Fire-Robust Structural Engineering:
A Framework Approach to Structural Design for Fire Conditions

by

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ABSTRACT

Thanks to significant worldwide research directed at understanding and predicting structural behavior at elevated temperatures, analytical methods are available to support a rational, performance-based approach to the structural design of buildings for fire conditions. To utilize these analytical methods effectively, structural engineers need guidance on reliable and appropriate approaches to dealing with a variety of factors, including the effects of fire protection measures, temperature-dependent thermal and structural properties, elastic and inelastic behavior of structural components and assemblies, and thermal and structural response of framing connections.

To meet the objective of guiding the structural engineer in appropriate analytical methods and parameter values for performance-based structural fire protection, this thesis proposes a comprehensive way of thinking about the design and analysis of structures for fire conditions. This integration of structural engineering and fire protection engineering into a functional framework is defined herein as *Fire-Robust Structural Engineering* (FRSE). The FRSE process, which is presented as a series of flowcharts, is designed to guide the structural engineer in executing the functions involved in the design of fire-safe structures and to help identify informational needs critical to these tasks.

Currently, mechanisms for identifying possible resources to fulfill fire-related informational needs are generally organized for the convenience of the fire research community. Identification of resources that provide appropriate information for fire-robust structural engineering, such as laboratory fire test results, parametric studies of analytical methods, and other sources of guidance, is often difficult because these resources are rarely organized and presented for the benefit of structural engineers. To begin to resolve this problem, this thesis has developed a prototype information management system (IMS) based on the framework of the FRSE process. The IMS addresses the critical challenge of organizing and presenting the available knowledge and data in a format that is consistent with the perspective and informational needs of the structural engineer. The prototype version of the IMS has been implemented using a Microsoft Excel® platform.

In addition to guidance in utilizing specific analytical methods and choosing appropriate parameter values, the structural engineer also requires an understanding of the input requirements and accuracy of various analytical methods in order to make informed decisions regarding which methods are appropriate for use with different structural configurations. Therefore, this thesis includes a model study as an example of a resource that could aid the structural engineer in making such decisions. The model study compares various analytical methods (simplified spreadsheet applications and advanced finite element techniques) to published laboratory test data and discusses concerns that the structural engineer must keep in mind when using each method. Conclusions are drawn regarding the appropriateness of each analytical method to the analysis of a fully restrained, spray-protected steel beam. Given this type of information, the structural engineer can make decisions regarding the types of analytical methods and the level of analytical sophistication required to solve a given design problem.

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1 INTRODUCTION

In reviewing the current state of the field of structural design for fire conditions, one can make numerous observations:

- More is known about the performance of structural frames under fire conditions than most other aspects of fire protection engineering;

- Relatively few structural engineers are familiar with the analytical techniques and scientific findings that the fire research community has developed to support the practice of structural design for fire safety;

- Fire endurance ratings based on simple laboratory test methods developed in the early twentieth century dominate building code requirements and the thinking of designers; and

- A shared perspective of structural fire protection does not exist between structural engineers and fire protection engineers.

This thesis defines a comprehensive framework, the Fire-Robust Structural Engineering (FRSE) process, for the analysis and design of structures exposed to fire conditions. Also, it proposes methods of connecting structural engineers with information that may be critical in designing fire-robust buildings. In doing so, it stresses that performance-based design is necessary to ensure that a given structure is truly safe from the effects of fire. Integrating the research of the fire protection community with the knowledge of the structural engineer is vital to protecting today's buildings, their contents, and their occupants from structural failure during fires.

The simplified life cycle of a building is shown in Figure 1.1. Also shown are ways that the impact of fire is tied into this cycle.

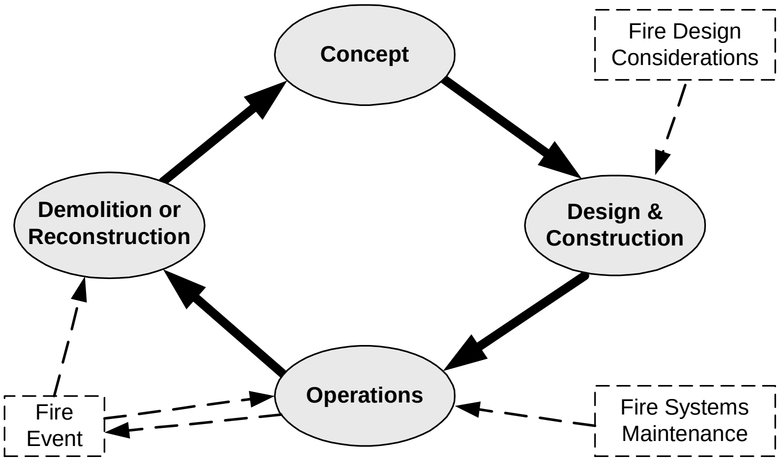


Figure 1.1. The Building Life Cycle

Consideration of fire can occur at three different positions in the life cycle of a building. First, during the design phase, the structural configuration can be analyzed for response to expected fire conditions. This is the task of the fire-robust structural engineering process. Next, the maintenance of fire systems, such as member protection methods and automatic sprinkler systems, has an impact on the operations of the building. As with all building systems, appropriate maintenance of the structural fire protection systems is necessary to ensure continuation of the performance predicted in the design phase. Third, the possible occurrence of fire events is included. Depending on its severity, the impact of a fire event occurring during the operational phase could range from not affecting operations to requiring reconstruction or demolition of the building. The goal of the fire-robust structural design process is to help minimize the impact of a fire event on a structure such that operational interruption is minimized.

The fire-robust design process combines the steps currently used in the design of building structures with available techniques for predicting fire conditions and analyzing the effects of these conditions on structures.

1.1 Definitions

This thesis approaches the subject of structural design for fire conditions from a combination of standpoints. Cooperation between the fields of fire protection engineering and structural engineering is necessary to effectively protect structures from the effects of fire. In order to define the process of performance-based structural design for fire conditions, a series of key definitions must first be set forth. These formal definitions will help define the roles of the engineers in this process. Also, a succinct definition of the design process for fire conditions is provided.

Various professional societies have formally defined the terms *Structural Engineer* and *Fire Protection Engineer*. For example, the Society of Fire Protection Engineers has established a definition of the term *Fire Protection Engineer* [1]. However, the process set forth herein for the performance-based design of structures requires an understanding of the specific roles of these engineers within this process. The definitions provided by professional societies may be too general to achieve this requirement. The definitions provided here are designed to define these roles in the context of the process presented in this thesis.

1.1.1 Structural Engineer

The structural engineer is a professional trained in the design of structural systems for the support of building loads, including material weights, occupant loads, furnishing and partition loads, and external loads such as wind and earthquake-induced forces. On an increasingly frequent basis, the structural engineer is also called upon to incorporate consideration of loads caused by extreme events (fires, explosions, floods, etc.) into structural designs, although the structural engineer may not have extensive training with regard to these phenomena. A structural engineer uses principles of static and dynamic systems, as well as solid mechanics, to determine appropriate structural details (member sizes and materials, connection details, assembly configurations, etc.) to support the loads imposed on the structure and to ensure the structural safety and serviceability of the building. The structural engineer also takes into account appropriate local or regional regulatory codes designed to establish a threshold for structural safety by defining minimum requirements for structural details, components, and assemblies. The products of a structural engineer's labor include building specifications and design drawings for use in construction.

1.1.2 Fire Protection Engineer

The fire protection engineer generally receives advanced training in fire science (fire physics and chemistry) and develops an understanding of techniques for the prediction and analysis of fire and explosions in the built environment. Fire protection engineering utilizes concepts of chemistry, heat and mass transfer, fluid flow, and physics to make reasonable predictions of fire behavior (including ignition, growth, decay, and suppression) and its impact on a given environment. The fire protection engineer is generally trained in the design of building system details (structural fire protection measures, occupant protection measures such as egress considerations, fire suppression systems, etc.) intended to reduce the risk of fire or explosion and to minimize the impact of these events. The fire protection engineer may or may not have formal training in the normal (non-fire) design of building structural, architectural, and utility systems.

1.1.3 Fire-Robust Structural Engineering

Fire-robust structural engineering (FRSE) involves the combination of the skills of the structural engineer and the fire protection engineer in an effort to design structural systems that minimize the impact of fire on building occupants, contents, and operations. The FRSE process involves the detailed consideration of the response of structural elements to fire conditions. Necessarily, this process also involves the prediction of expected (design) fire conditions within the building environment. Time-temperature relationships are defined for critical fires in specific locations within a building, physical loading conditions and structural failure modes of concern are identified, and a description of the structure's response to these conditions is developed. The structure's fire performance can then be judged, and appropriate measures to improve this performance, if necessary, can be devised, evaluated, and implemented. The intended result of this process is the design of structural systems that perform favorably under fire conditions.

1.2 Problem Statement and Proposed Reactions

In order to perform the fire-robust design of a building, an engineer must have an understanding of what the fire-robust structural engineering process involves. Therefore, one objective of this thesis is to develop a functional description of the FRSE process. A functional description facilitates communication because it clearly identifies what the structural engineer must do to quantify, evaluate, and make decisions regarding structural fire performance.

A functional description of structural design for fire conditions makes evident the need for various types of information within the process. Topics such as design and analysis techniques, failure modes, and global structural response are all critical to the fire-robust structural engineering process. The engineer must have access to appropriate information regarding these topics in order to analyze a building's structural fire performance using the fire-robust structural engineering process.

A large amount of data exists worldwide regarding various aspects of the behavior of structural components under fire conditions. However, this data is not organized or linked together in a way that provides structural engineers with easy access to appropriate answers for specific questions that arise during the design and analysis of structures exposed to real fire temperatures. Also, many research efforts do not get published for public use, so an engineer may not be able to use the information they contain. Thus, an engineer may not have access to state-of-the-art information regarding the specific functions the engineer needs to perform, such as those that make up the fire-robust design process. As building design becomes ever more innovative, and regulation and design move towards a performance basis, a direct link between the structural engineer and the fire safety engineer is necessary for the effective and efficient protection of structures against fire.

While much research has been completed on structural fire protection topics, and more is currently under way, the vastness of the topic can result in a lack of full understanding in critical areas. By defining the functions involved in a fire-robust structural design and discussing the types of information required to perform these tasks, a functional description of FRSE can serve to identify key areas of future research. The result may be more organized and focused research activities with the goal of contributing to the comprehensive understanding of complex structural response to fire.

In order to begin to deal with the issues described above, this thesis formulates in detail a functional description of the fire-robust structural engineering process. It then develops a database format intended to aid the structural engineer in filling the various informational needs inherent in the FRSE process. Future full-scale implementation of this database concept could serve to organize the available knowledge regarding structural fire protection and to make it available to those practicing FRSE, as well as to identify gaps in the body of knowledge represented by existing research. Lastly, this thesis provides a model study demonstrating the type of research that would be considered useful to the structural engineer using the FRSE process.

1.3 Thesis Objectives and Solution Elements

The objective of this thesis was to describe the basic framework of a process for the design of buildings that are robust to fire events. The integration of structural engineering and fire protection engineering for the analysis and design of structures for performance under fire conditions is defined here as *fire-robust structural engineering* (FRSE). To achieve the main objective of this work, a conceptual framework for the practice of fire-robust structural engineering was developed to provide a context for understanding the perspective and informational needs of a structural engineer. The framework for the FRSE process describes a functional approach to the analysis of thermal and structural performance of building structures, and the framework is intended to supplement current structural design practices.

With the necessary functions defined by the FRSE framework, this thesis moves on to a second objective of assisting the structural engineer in finding sources of information. To accomplish this, a computer-based information management system (IMS) was proposed and developed in detail. This system provides the structural engineer with a link to available sources of knowledge regarding the functions of FRSE. Also, it serves to identify the types of knowledge available within given resources such that the structural engineering can quantify the current level of knowledge in structural design for fire. Thus, research needs can be identified.

The final objective of this thesis was to describe the type of research that is appropriate to populate the IMS, and thus is critical to the practice of fire-robust structural engineering. To accomplish this objective, a model study was carried out as an example of the type of research that can directly benefit the FRSE practitioner. The model study investigated different analytical methods for performing a given function and points out important considerations for the use of each analytical method. This type of information can contribute to a body of resources to help a structural engineer identify and implement a comprehensive but efficient method for achieving a fire-robust structural design.

2 FUNCTIONAL APPROACHES TO PROBLEM SOLVING

Solving engineering problems is rarely a brief, simple process. The inherent complexity of the built environment results in complicated situations that must be dealt with to accomplish various goals. However unique an individual situation may be, it generally will fall into a particular category of concern. Some examples of categories of concern may be:

- Design for structural capacity and safety;
- Design for rare event (fire, explosion, earthquake, etc.) protection and mitigation;
- Design for functionality, operations efficiency, and continuity; and
- Design for aesthetic quality.

These concerns apply to many aspects of the engineered world, from buildings and facilities, to transportation systems, vehicles, and commodities. To start every new engineering project from scratch – first exploring all possible concerns and deciding which of these apply to the given situation, and then dealing with each of these concerns in turn – is highly impractical and inefficient. The engineering process also requires high levels of experience and education of those individuals undertaking the project. The concept of a functional framework can help eliminate this efficiency by defining an appropriate methodology for achieving a desired result.

Functional framework approaches must be precise in their definition of tasks, but must also be flexible enough to apply to a wide range of situations with similar ultimate concerns. For example, a framework appropriate for designing high-rise buildings for performance during earthquakes must incorporate all of the tasks that may be required to protect any tall building (within a reasonable range of building configurations) from earthquake damage. Specific approaches may only apply to certain situations, but they must be included in the general framework to ensure its completeness and usefulness.

The great benefit of functional approaches to problem solving lies in their ability to help guarantee that important concerns are addressed and critical considerations are not ignored or passed by. As the built environment grows more complex with each new innovation, engineers are forced to deal with a growing range of concerns. Also, as design for performance requirements becomes common practice, methods for guiding and regulating the design process are required. The functional framework approach defines a methodology for achieving a given result and helps ensure that appropriate and correct steps are taken during the engineering process.

This section discusses functional approaches to solving engineering problems; examples are derived from the highway engineering and chemical development industries. Concepts described here have served as the foundation for the fire-robust structural engineering framework.

2.1 Highway Design: A Functional Approach to Engineering Problem Solving

Much like structural design, highway design is a field that is based on tradition. While this field has kept up with technology in terms of advances in drawing tools, the actual process of designing highways has remained unchanged for decades. Highway engineers often rely on experience and accepted standards as guidance through the entire design process. Some may argue that these tendencies result in acceptable designs and prevent major (and publicly visible) engineering failures, such as road surface failures. However, general operational shortcomings, such as lack of capacity, go largely unnoticed. It may take a given commuter longer to get to work, but the story doesn't exactly make the evening news. In the long run, a highway that is unable to support its traffic volume is a failure, although the consequences are not as catastrophic as for a building that is unable to support its occupant loads.

Traditionally, highway engineers design highways with the goal of a 20-year service life [2]. It is assumed that it is possible to rather accurately predict traffic loads 20 years into the future. One cannot ignore the fact that a 20-year forecast is an approximation, and it should be more of a guide than an absolute rule. However, many highway designers use such numbers as a rigid basis for design. The result is a design that may not adapt to unforeseen changes in traffic loads or patterns. It might be noted that a parallel exists between these 20-

year forecasts in highway design and fire resistance ratings in structural design. Tradition has given both the status of design guides, yet many engineers who use them do not have complete understanding or evidence of their appropriateness. Engineers need to go beyond such numbers in order to produce successful and flexible designs.

In much the same way that the interaction of structural and fire protection engineers can greatly benefit the structural design of buildings, highway engineers can benefit from the inclusion of traffic engineers in the highway design process. To accomplish this, some suggest a functional highway design process that utilizes the skills of both the highway engineer and the traffic engineer [2].

2.1.1 The Functional Highway Design Process

The functional highway design process alters the traditional highway design process by giving the traffic engineer an important role. In this process, the highway engineer works to ensure is responsible for designing the overall geometry of a given highway element and ensuring that it can support its intended loads, while the traffic engineer defines flow patterns and capacity requirements to help ensure that the highway element will be able to serve its users well. The process starts with concept master planning, a step that involves consideration of capacity, safety, and the interconnected nature of roads. The next step is systems planning, which considers how a new design may impact the existing highway network.

Systems planning is immediately followed by a process known as functional design. Generally, traffic engineers perform the previous tasks, and the development of a functional design is the stage of the process when they connect with highway engineers. The functional design step produces numerous possible solutions to a given problem, each of which includes general details regarding travel direction, right-of-way, and other critical details. These alternatives do not yet include detailed geometrical design. They do, however, include sufficient detail to be evaluated, and the best design is chosen to continue through the next phases of the functional design phase. Designs are evaluated qualitatively in terms of safety, efficiency, flexibility, and cost, among other factors.

At this point, the highway designer becomes active in the process, developing geometrical details for all aspects of the functional design. They fit the design into the proposed site and consider vehicle speed, sight distances, and drainage concerns. The result is a highway design that is safeguarded against both engineering and operational failures.

2.1.2 Comparison to the Fire-Robust Structural Engineering Process

Trimming both the functional highway design process and the fire-robust structural engineering process down to their basic components, one can see that they each essentially bring together the skills of different fields to produce robust designs. Figure 2.1 helps to illustrate this comparison.

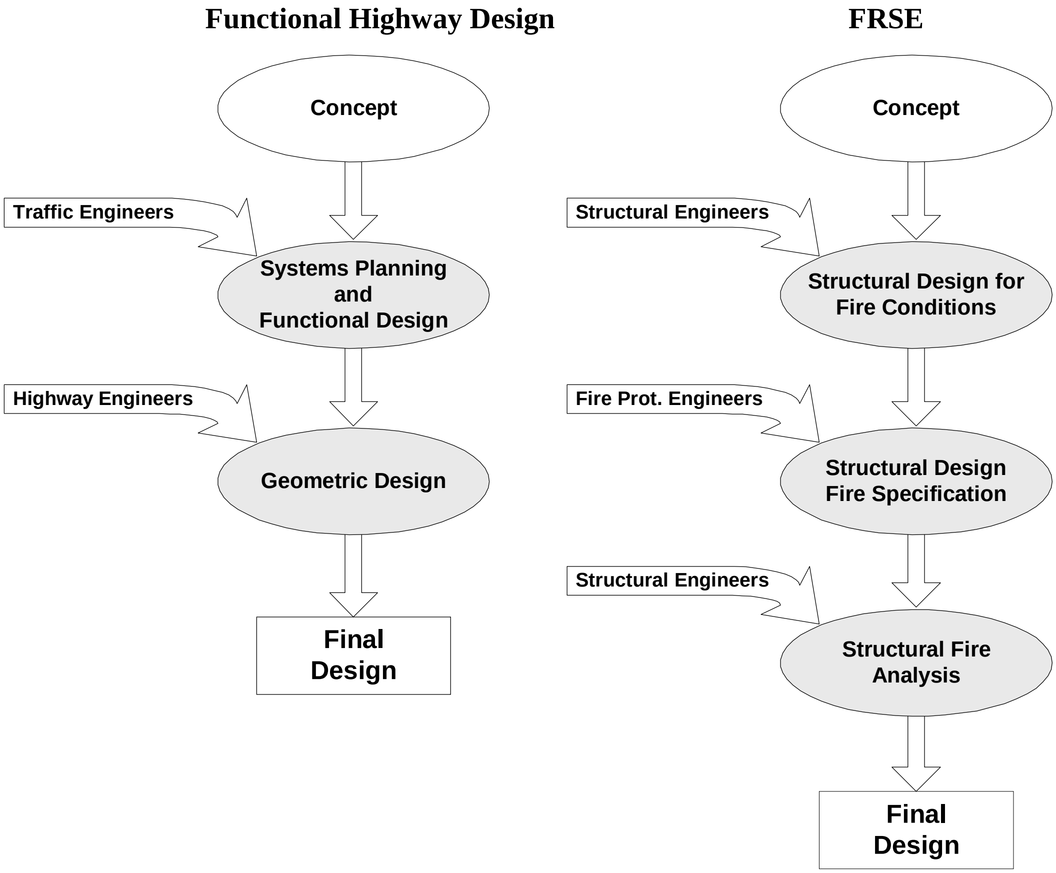


Figure 2.1 Highway Design And FRSE Process Comparison

The functional highway design process couples the fields of traffic engineering and highway engineering by specifically defining the tasks that must be carried out by the two groups of engineers. Initial tasks, such as concept master planning, systems planning, and functional design, are carried out by the traffic engineer. The traffic engineer helps to ensure that the highway component being designed will handle traffic efficiently and will be incorporated into the existing highway system in a seamless manner. The highway engineer is then presented with a refined highway design that can be used in the specification of components of that design and to evaluate its performance in carrying traffic.

The fire-robust structural engineering process is designed to combine the skills of the structural engineer and the fire protection engineer in a similar manner to that observed in the functional highway design process. In the fire-robust structural engineering process, the fire protection engineer is responsible for the accurate prediction of fire conditions within the building being designed. The structural engineer's responsibility lies in the development of a basic design, the analysis and evaluation of that design's response to predicted fire conditions, and the improvement of the design's performance, if necessary. This coordinated effort results in a structural framework that is designed to withstand the specific high-temperature conditions that it may experience during its service life.

2.1.3 Conclusion

By specifically defining the tasks, or functions, that must be carried out by each type of engineer in order to achieve a desired result, be it a highly efficient highway design or a structure designed to withstand the high temperatures of a fire, both the functional highway design process and the fire-robust structural engineering process offer a protocol for engineers to work together to contribute various skills to a design job. The functional highway design process, versions of which have already been adopted by numerous state highway departments (including Arizona, Colorado, Florida, and Georgia) [2], is an excellent example of a functional approach to problem solving in the engineering world. It efficiently links to skills of different engineers and results in better-performing highway designs than could be produced otherwise. A great deal of inspiration for the fire-robust structural engineering process is derived from this observation

2.2 Function-Based Database Design

Numerous situations exist in the scientific world in which a function-based approach may be the most efficient means of achieving a goal. An example of this is evident in the pharmaceutical field of drug development. Often in the development of new drugs, the need arises for molecules that perform certain known functions. The chemical engineer may set out to find candidate compounds able to perform specific functions and to meet the geometric constraints of the overall drug. Greene *et al.* [3] have proposed an advanced search mechanism that can better identify candidate molecules than simpler search mechanism based on topological features. Much like the fire-robust structural engineering process, the function-based chemical search approach is an example of the use of a functional solution to aid scientific professionals in their work.

During the development of a drug, the chemical engineer is faced with the goal of defining the components that will eventually comprise the drug. The chemical function to be served by a given topographical feature of a drug may be theorized, but specific molecules to be bound to a ligand (a molecule with one or more unshared pairs of electrons that can attach to a central metallic atom or ion [4]) to result in the necessary topographic feature may need to be identified. Given the vast number of molecules available to the chemist, an automated search mechanism able to call out potential molecules is required.

The need for an advanced chemical function query mechanism arose because it was noted that simpler query mechanisms typically reference highly specific atomic topologies and incorporate tight constraints for topographical measurements. This results in a very strict database structure - one that allows little flexibility in the identification of candidate compounds for inclusion in new drugs. Because of the strict nature of the search, novel chemical structures can often be missed. Since most search queries of this type define molecular features by atomic topographies such as nitrogen, a phenol ring, or a carboxyl oxygen [3], they do not have the ability to accurately describe all groups that can be used to perform a given function.

Instead of searching based solely on topographic requirements, the search mechanism proposed by Greene *et al*. [3] employs a three-dimensional methodology to identify all possible molecules able to serve a specific purpose (function) in a given atomic topography. The query structure that they suggest is based on the three general forces involved in selective molecular binding. These are as follows [3]:

- Hydrogen bonding;

- Electrostatics; and
- Hydrophobic interactions.

Greene *et al.* [3] define generalized function-based definitions for molecular groups able to take part in these interactions. This allows queries to define candidate molecules based on the functions that those molecules can perform. The record format in this case includes a list of the functions that may be performed by a given molecular group. As will be described in Chapter 5 of this thesis, the information management system proposed for use with the fire-robust structural engineering process involves a record format that also includes a list of functions that a given resource may cover, which is analogous to the approach of Greene *et al.* [3]. Assuming records are accurately characterized when they are input into the database, the function-based approach helps ensure that records that are identified as a result of a query apply to the function upon which that query was based.

Greene *et al.* [3] performed a comparison between the performance of their functional database and that of more traditional search mechanisms based on topographical features. In one example, they found that the function-based search identified more than 3 ½ times more potential compounds than the traditional database. Additionally, they noted that about 15% of the compounds identified by the topological query were not appropriate for use in the example situation. The latter observation is also seen when searching for structural fire protection information with currently available search tools. Generally, these tools result in lists of possible resources, yet only some of these resources may be appropriate for the given situation. Unfortunately, it is up to the engineer to sort through these lists to identify appropriate resources. In both the structural fire protection field and the drug development process, the time required to identify and reject inappropriate query results can be better used for other tasks.

3 THE PROPOSED FIRE-ROBUST STRUCTURAL ENGINEERING PROCESS

The current level of knowledge in room fire behavior, heat transfer, and structural engineering is sufficient to allow analysis of structural frameworks under fire conditions, thus providing a greater understanding of structural fire performance than could be achieved previously. The combination of structural and fire protection engineering will result in an advanced structural design process that can be used to greatly improve structural fire performance of new or redesigned buildings. The integration of these two engineering disciplines for the analysis and design of structures exposed to fire conditions is defined here as *fire-robust structural engineering* (FRSE). While this integration has been made difficult in the past by the lack of a shared perspective between the two disciplines, gaps in the body of knowledge or structural design for fire, and limited computing capabilities, the potential benefit greatly outweighs the effort required to overcome this difficulty. This work will contribute to the linking of structural and fire protection engineering by detailing a comprehensive process that can be used to design fire-robust structures. Additionally, the development of the comprehensive fire-robust structural engineering process will contribute to the teaching and practice of structural design for fire conditions, and will identify informational and knowledge needs placed on the engineer by the process.

3.1 Impetus for Development

The design and construction of buildings that are robust to extreme loading and environmental conditions, such as those created by high winds, earthquakes, fires, and blasts, has become a critical goal of the building design community over the past several decades. Thorough consideration of wind and earthquake loading conditions is included both in modern building codes and industry standards for structural design and disaster mitigation. These guidance resources reflect the combination of scientific research efforts and experience from actual events. By considering the results of modern research and observations of structural behavior under these extreme conditions, current design techniques allow the structural engineer to design structures that are resilient under extreme wind and earthquake loading conditions

On the contrary, while the pace of research exploring the effects of fire on structural frameworks and the development of analytical tools to determine structural response to elevated temperatures has been brisk over the past two decades, most structures are not designed with specific consideration of performance in real fire situations. Relatively few structural engineers are familiar with current structural fire protection research efforts, advanced analytical tools, and state-of-the-art structural fire analysis methods developed recently to support the practice of structural design for fire safety. Traditionally, structural elements are selected and detailed in terms of general fire resistance ratings (i.e. 3/4-hour, 1-hour, 2-hour, etc.). These ratings are based on performance in highly controlled standard furnace tests. Numerous conditions in these tests, including restraint details, construction quality, and fire severity, may not reasonably represent conditions within a real building at the time of a fire. Ratings derived from standard tests do not take into account the actual conditions that a structural element may experience in a fire. Therefore, a traditionally designed structure may not be robust to all fire situations it may face over its operational life. To allow the design of truly fire-robust structures, modern advancements in fire science and structural fire protection must be integrated into the teaching and practice of the widely accepted structural design process.

This chapter presents a comprehensive function-based framework for designing structures to be robust under real fire conditions. In addition to greatly benefiting the efforts to design fire safe structures, this functional framework may also serve as a template for future development of a structural design processes for other extreme events, such as blasts (blast-robust structural engineering) and floods (flood-robust structural engineering).

3.2 Performance-Based Design of Structures for Fire Conditions

The fire-robust structural engineering process is, generally speaking, a performance-based, multi-step procedure intended to supplement the traditional structural design process. Much like the in-depth consideration of earthquake impact, the fire-robust structural engineering process requires structural engineers to investigate the fire performance of individual structural components and of a structure as a whole. The event in this case is a fire. The skills of the structural engineer and the fire protection engineer are combined to analyze the response of a structural configuration to expected fire conditions, and to make decisions regarding the acceptability of this performance.

The traditional structural design process is essentially the first phase of the fire-robust structural engineering process. Traditional methods of planning and design must first be used to take into account gravity and lateral loads to obtain a general structural configuration represented in structural drawings and specifications. Consideration of member protection methods and in-service (pre- or post-fire) can be included next. State-of-the-art tools and knowledge can then be used to predict the fire conditions that may be expected to occur within the building, to calculate the response of the structure and its elements to these fire conditions, and to evaluate the resulting structural performance. Five basic functions must be performed to accomplish a fire-robust design. These functions are:

- **Structural Design by Traditional Methods.** This results in a reference set of structural drawings and specifications (materials, geometric layout, member sizes, connection details, etc.) for which fire performance can be determined.

- **Consideration of Member Protection or Events that Change the Structural Configuration.** Member protection may change the fire performance of a structural design, both locally and globally. Also, the as-built conditions may differ from the original design drawings and specifications, so the actual performance may differ from the performance of the system and its elements predicted by the initial design. Additionally, events occurring during the life of the building (i.e. earthquakes, blasts, fires, accidental damage to protection materials, etc.) can also change the subsequent fire performance of a structure. These possibilities should be considered to help ensure that the structural design is truly robust.

- **Prediction of Fire Conditions within the Building.** A task likely performed by a fire protection engineer, this step utilizes available tools to predict and describe a fire event, including the behavior of a fire and the associated conditions within a fire compartment.

- **Analysis of Structural Response to Predicted Fire Conditions.** The structural engineer must determine the response of a given structural configuration to predicted fire conditions. Analysis of the effects of the expected fire conditions on a structural design, as well as the impact of these effects on the structure's performance (load-carrying capacity, serviceability, etc.), is accomplished through modern analytical tools and techniques.

- **Determination of the Acceptability of the Predicted Performance.** Given a prediction of structural performance under expected fire conditions, the engineer can determine failure criteria and judge the acceptability of the structural configuration.

The combination of the five tasks outlined above can result in the development of a fire-robust structural design. The tasks are listed above in their basic order of occurrence, but the links existing between them should be emphasized. Figure 3.1 below visualizes the process that can be followed to create a fire-robust structural design.

In Figure 3.1, the fire-robust structural engineering process begins with the development of an architectural concept, or schematic design. Schematic design drawings and architectural elevations act as input to the fairly routine process of determining suitable dimensions for structural members, connections, and details based upon the predicted strength and serviceability performance of these elements under foreseen physical loading conditions. These loading conditions fall into two basic categories in the traditional design process: gravity loads, which include dead, live, and snow loads, and lateral loads, which may include forces generated by wind, earthquakes, and earth pressure. The term *Normal Structural Design* refers to the fact that the response of the structure and the assessment of the governing design criteria are conducted assuming normal temperature conditions.

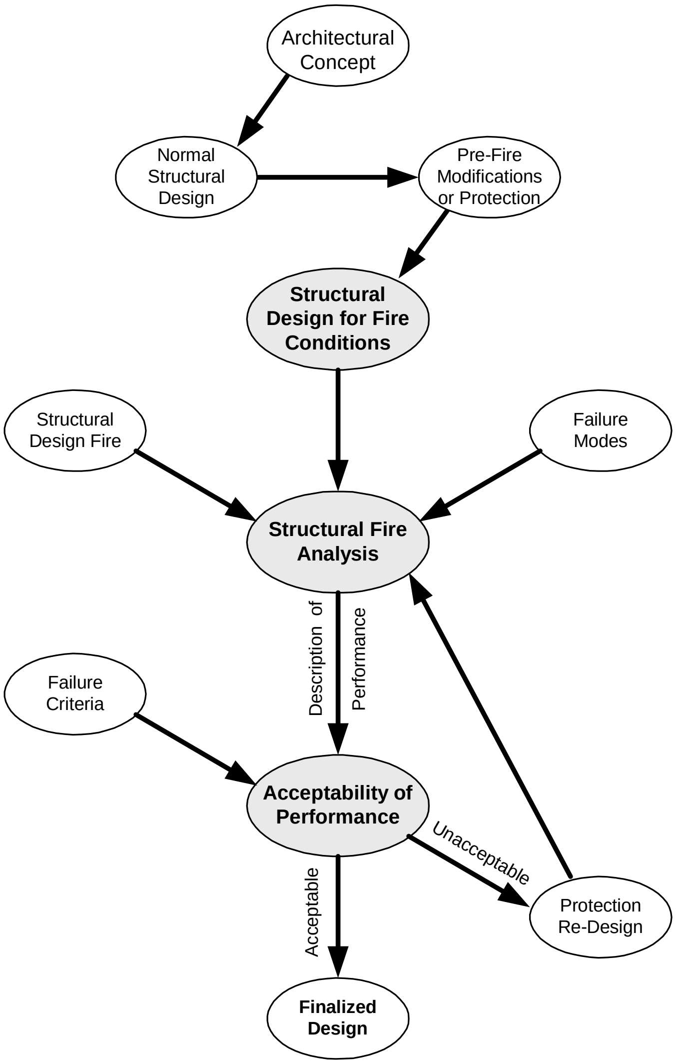


Figure 3.1. Fire-Robust Design Thought Process

Improvement of structural fire performance generally involves one or more of several available techniques, including adjustment of design details (increasing the size, and therefore the thermal mass, of members, for example), application of protective materials, insulation, or fire resistive coatings to structural members and connections, and the construction of physical barriers (passive fire resistance systems). Such techniques can result in what Figure 3.1 refers to as a *Structural Design for Fire Conditions*. This state can also include any changes to the normal structural design resulting from pre-fire events. Such events can range from the accidental scraping off of a fire-resistive coating to an earthquake that may partially cripple the structure. These types of events may change the performance to be expected during a fire, and thus may be considered to ensure that a structural design is indeed robust.

From this point, the fire-robust structural engineering process is developed. A structural design fire, which describes the conditions within the building during a fire, mainly in terms of time-temperature relationships describing the state of the heated gases in the vicinity of given structural members, is established. This set of time-temperature relationships is used to determine the response of structural systems to fire conditions. Such response takes the form of various mechanical reactions that are based on the loading conditions experienced by the structure. All possible mechanical reactions must be considered to determine the failure modes that are of concern, and the contribution of these modes must be quantified. The structural behavior observed in the analysis can then be compared to stakeholder-defined design criteria in an effort to determine the acceptability of the design. An unacceptable design may require additional implementation of fire safety techniques described in the previous paragraph. The fire analysis process would then be repeated for the new structural configuration. Iteration of this process is required until acceptable performance is achieved, at which point the engineer may finalize the design drawings and specifications for the structure.

The fire-robust structural engineering process involves numerous specific functions necessary to accomplish the tasks discussed above. The process is broken down in the following subsections and the individual functions are discussed in detail. The detailed description of the fire-robust structural engineering process presented here includes five summary flowcharts that interact with each other to produce a robust design. This discussion makes apparent the engineer’s need for a substantial amount of knowledge and information during the performance-based design of structures for fire conditions.

3.2.1 The General Fire-Robust Structural Engineering Process

The fire-robust structural engineering process involves the integration of advanced techniques for predicting fire behavior and analyzing structural response to fire conditions with current (normal temperature) structural design procedures. Chart 1 (Figure 3.2) shows the overall process of incorporating the consideration of the effects of fire on structures into the current structural design process.

CHART 1: THE FIRE-ROBUST STRUCTURAL DESIGN PROCESS

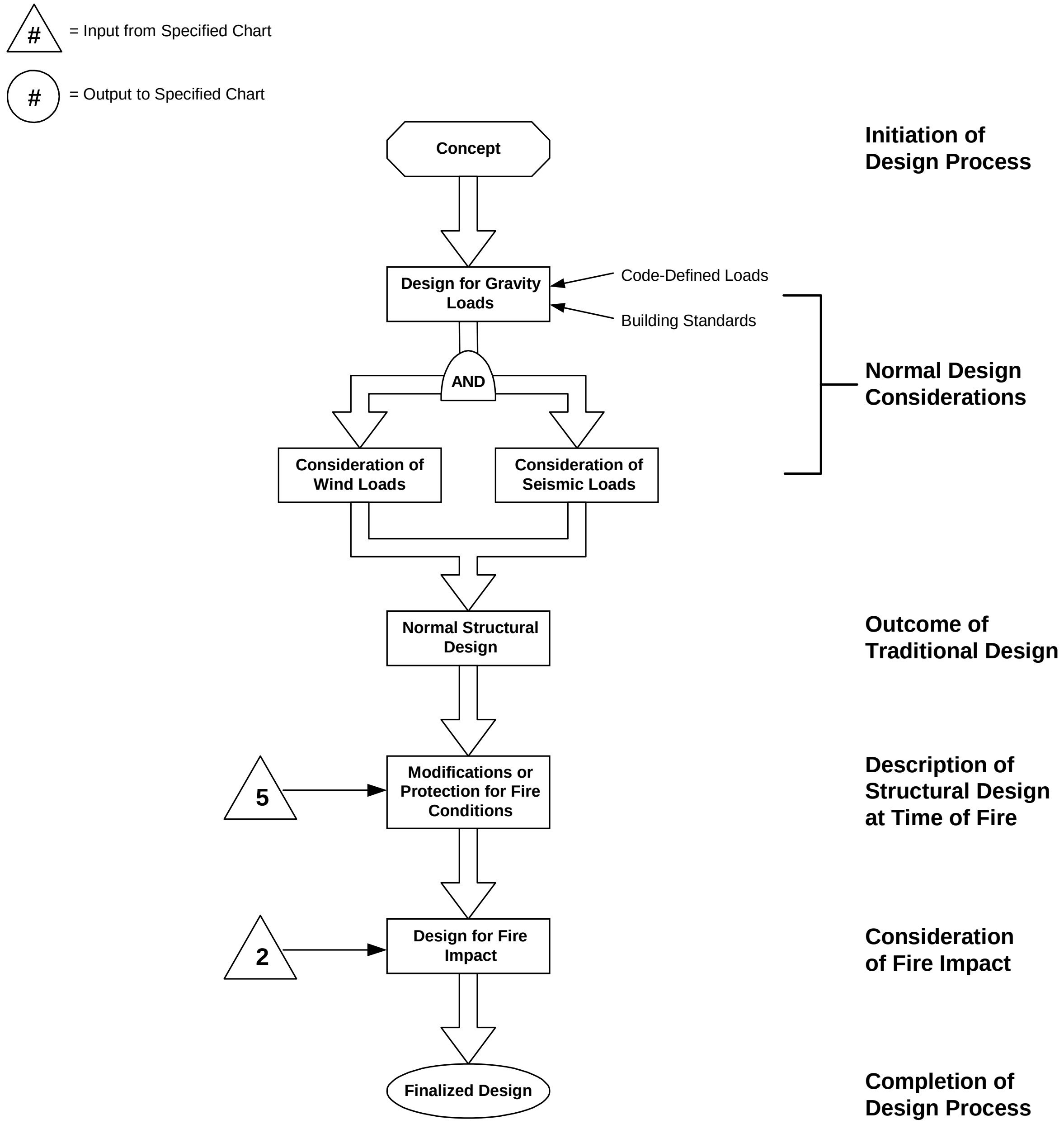


Figure 3.2. The Fire-Robust Structural Engineering Process

Given an architectural concept (schematic design), the structural design process is first carried out for normal operating temperatures. The result is full set of structural drawings and specifications based on normal temperature operation (gravity and lateral loads). Allowance is then made for the possibility of modification of the initial design. Modifications may include:

- The protection of members (insulation, coatings, barriers, etc.),
- Differences between the originally specified structural configuration and the as-build condition,
- Changes to the structural configuration caused by pre-fire events (earthquakes, blasts, accidental loss of protective material, etc.),
- Changes to the structural configuration subsequent to a fire (post-fire condition)

Chart 1 allows a normal structural design to be modified based on the possible events listed above. In-service conditions (the latter three bullets above) are covered in detail by Chart 5 (Figure 3.9). Thus, the output from Chart 5 acts as input in Chart 1. Modifying the normal structural design in these ways allows the engineer to analyze the actual structural conditions expected at the time of a fire.

After the structural configuration expected to be in place at the time of a fire is defined, the process moves to the fire analysis phase. Chart 2 (Figure 3.3) is the master roadmap for the structural fire analysis process. The product of Chart 2 is an acceptable, robust structural design. This design is brought back to Chart 1, where it is finalized and the structural design process is concluded.

Chart 1 presents a general overview of the fire-robust structural engineering process. While the first chart summarizes the process from start to finish, it cannot stand alone, and must be supplemented by additional functions. These functions are performed in Charts 2 through 5, which are discussed in Sections 3.2.2 through 3.2.5.

3.2.2 The Structural Fire Analysis Process

While Chart 1 offers a general overview of the fire-robust structural engineering process, Chart 2 (Figure 3.3) defines the specific procedure for analyzing a particular structure’s response to fire conditions.

CHART 2: THE STRUCTURAL FIRE ANALYSIS PROCESS

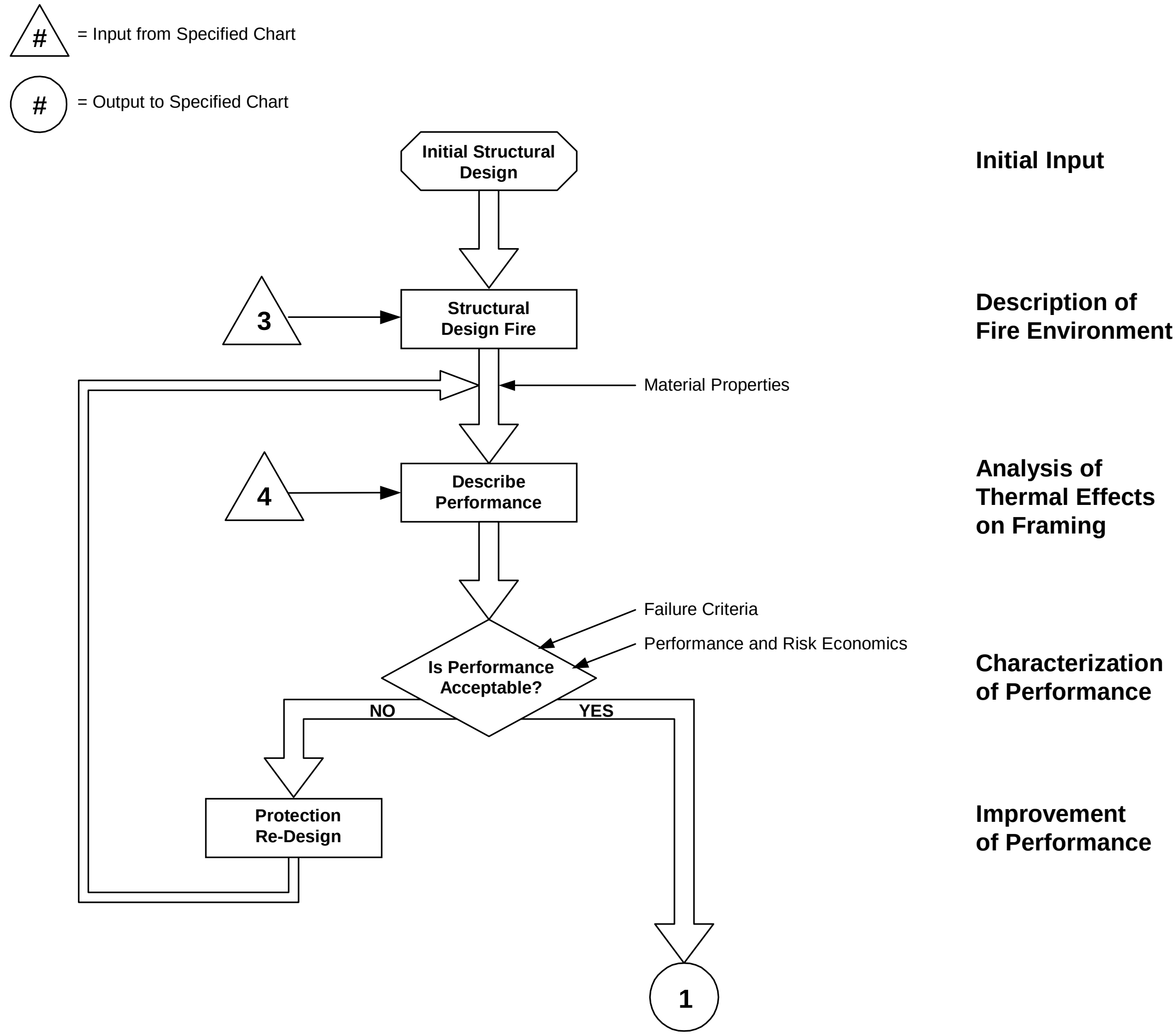


Figure 3.3. The Structural Fire Analysis Process

The initial structural design, based on load-carrying performance in normal operating conditions and modified as discussed in the previous section, is the primary input in this analysis. Additionally, the engineer must input expected fire conditions by specifying an appropriate structural design fire (Chart 3, Figure 3.4). The design fire includes predictions of the conditions that the structural will be exposed to during a fire. The actual performance of the structure under real fire conditions can be determined by analyzing the structure's response to the conditions predicted by the design fire. Fire conditions impact upon the structure and may vary the performance of the structure from that observed for normal operating temperatures. The analysis used to determine these changes to behavior is detailed in Chart 4 (Figure 3.7), which provides input for the task of describing the structure's fire performance.

Once the structural fire performance has been described, it must be compared to appropriate performance criteria. Stakeholders (building owners, authorities-having-jurisdiction, etc.) may place limits of the various types of responses a structure may have to fire conditions. A *limit state* is defined as a condition of set of conditions for which a structure ceases to fulfill its intended function [5]. Failure occurs when a given limit state is reached or surpassed. Limit states may include:

- Limitations on member deformation or requirements for serviceability,
- Requirements for load-carrying capacity (prevention of collapse),
- Time to failure requirements (to allow occupant egress and suppression activities),
- Fire containment requirements (limitations on the impact of a fire on structural members distant from the fire)

Predicted performance can be compared to the defined failure criteria in order to determine the acceptability of the structural design. A design that fails to meet the performance criteria requires modification and re-evaluation. This modification may include resizing of members, protection of members, redesign of connections, or addition of passive fire barriers. After these modifications have been implemented in the design, the process of analyzing the structures response to design fire conditions must be repeated in order to evaluate the performance of the new configuration. A design is deemed acceptable when it meets all defined performance criteria. Such a design can then be finalized and specifications for the structure can be completed.

Chart 2 provides a general description of the structural fire analysis process, but it is largely just an organizational tool. It organizes the analytical functions necessary for the quantitative prediction of a structure's response to fire. These functions are incorporated into two additional processes: the *Design Fire Quantification Process* (Chart 3), and the *Identification of Expected Structural Fire Performance* (Chart 4). Through Chart 2, the structural engineer utilizes the output from these two processes to evaluate a structure's fire performance.

3.2.3 The Design Fire Quantification Process

A key step in determining the performance of a structure under fire conditions is the prediction of a fire's impact on the ambient conditions of the spaces within a structure. Generally speaking, a fire burning somewhere in a compartment releases superheated products of combustion (gases and unburned fuel particles) into the fire compartment. The heat produced by the fire reaction rises and collects at the vertical limit of the compartment. Heat and smoke (the unburned fuel particles) collect into a hot upper layer, essentially dividing the compartment into two different regions, one superheated, and the other at essentially ambient temperature. The interface position between these two regions at any given point in time depends on the state of the fire up to that time. The state of the fire can be described in terms of:

- Rate of fire growth,
- Total rate of heat release into the compartment,
- Modes of heat transfer to compartment contents (convection, radiation)

All three factors listed above depend largely on the nature of the fuel being burned. Different fuels burn at different rates and produce different amounts of heat, and the overall fire will grow at a rate based on the combustion characteristics of the fuel(s). Also important is the amount of air (oxygen) available to the fire. Combustion cannot occur without oxygen. At a certain point, the maximum amount of oxygen that the fire can use for combustion may be present. This is referred to as the stoichiometric fuel-air condition. The addition of oxygen beyond this level will not increase combustion. Between the point where a total lack of oxygen prevents combustion and the stoichiometric fuel-air condition, a fire's size is controlled by the actual amount of oxygen available. Since most structures have walls with limited openings to act as vents, fires within structures are often oxygen-controlled.

The transfer of heat from a fire to objects within a compartment depend on both the nature of the fuel being burned and the location of the objects being heated in relation to the flames. Convection is always present in a fire because of the heated gases produced during combustion. These gases rise in a buoyant plume and collect below the ceiling, where they can heat any target objects they surround. Fuels that do not combust efficiently produce large amounts of unburned particles (smoke). This smoke can affect the fire's ability to transfer heat to nearby or distant objects by interrupting the heat flow path. A fuel resulting in a smoky fire would be expected to reduce the amount of radiative heat transfer occurring within the fire compartment, and thus objects (such as structural members) may be heated to a lesser extent than in the case of an efficiently-burning fuel that produces little smoke, and therefore higher levels of radiation. On the other hand, a smoke-filled upper layer can absorb heat and radiate it back down to the floor of the compartment and to unburned fuel packages, thus potentially increasing the fire's size and heat production rate. Heat transfer modes are also affected by the position of target objects in relation to the fire. If an object (structural member) is physically surrounded by flames, heat transfer by conduction becomes important.

All of the factors discussed above must be considered in the prediction of compartment fire conditions. Generally, specification of the design fire for structural fire safety includes prediction of time-temperature relationships for the heated gasses surrounding structural members or heat flux levels to these members. Fire is a highly complex chemical reaction, and accurate prediction of a fire's behavior is extremely difficult. Various tools are available to aid in the prediction of fire behavior, and their appropriate use can give the fire protection engineer a good understanding of the conditions that can be expected in a compartment during a fire. Chart 3 (Figure 3.4) provides a general process that can be used to determine time-temperature conditions during a fire for use in the analysis of structural elements within a particular compartment.

Required input for the design fire quantification process includes all details of compartment geometry, ventilation conditions, and material properties, including those of possible fuels. The definition of these details comes partially from the schematic design phase, when room dimensions and vent openings may be specified. Often, room materials are not specifically identified in the schematic design phase. Compartment usage is generally known, however. Statistical data can often be used to determine fuel types and amounts for various types of occupancies. Also, boundary thermal properties can be assumed based upon the occupancy of the space and the construction type of the building.

CHART 3: The Design Fire Quantification Process

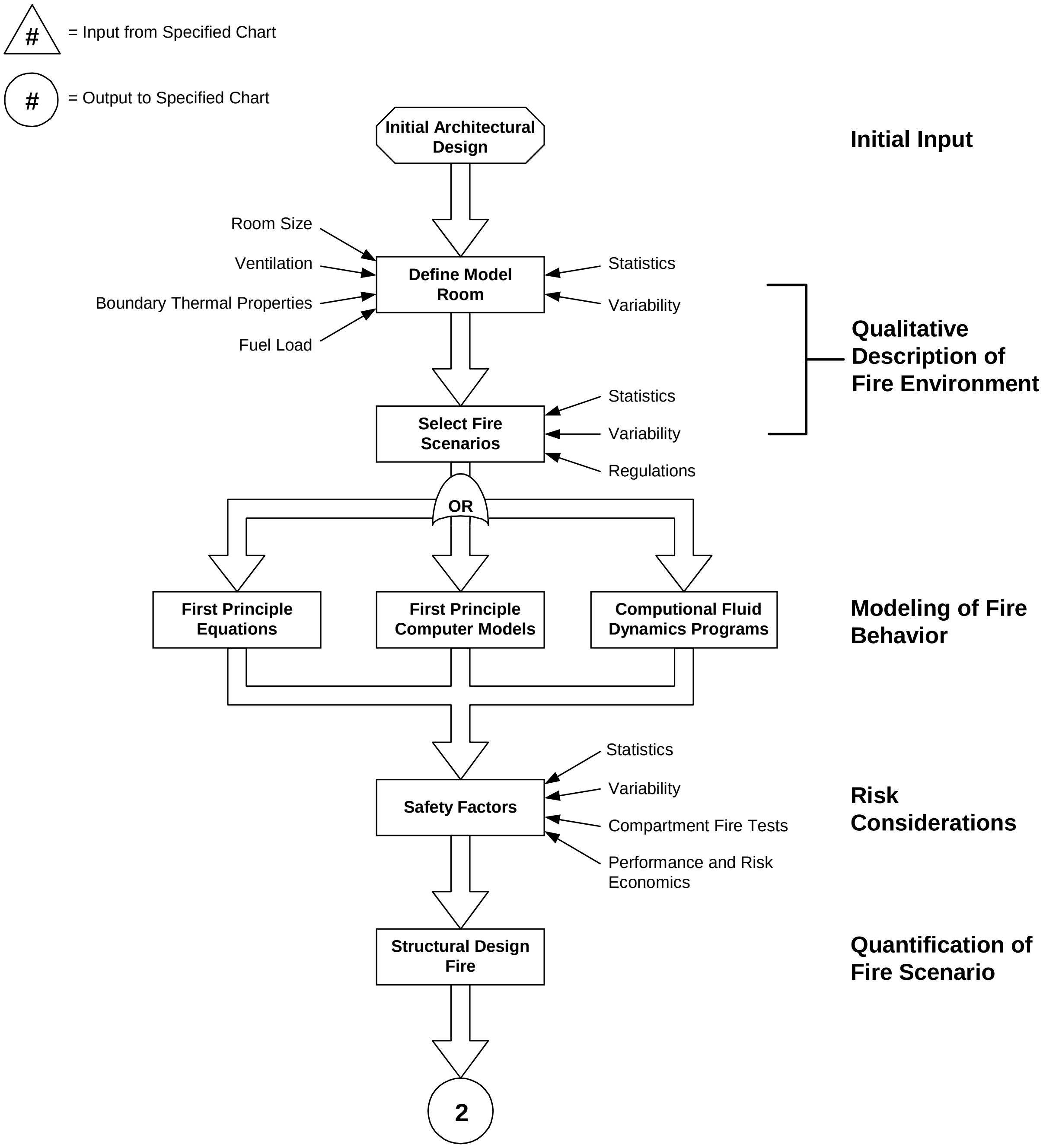


Figure 3.4. The Design Fire Quantification Process

After the model room has been completely specified, appropriate fire scenarios must be defined. Critical fire conditions must be considered in order to produce a truly robust structural design. The term *critical* refers to situations that will produce the most severe conditions within the given compartment. Basically, critical fire conditions represent the worst-case scenarios for the compartment under consideration. Generally speaking, fire scenarios can include the details listed in Figure 3.5 [1]:

Building Characteristics	**Occupant Characteristics**	**Fire Characteristics**
Architectural Details	Number of Occupants	Ignition Source(s)
Structural Components	Occupant Locations	Available Fuel Sources
Fire Protection Systems	Alertness	Growth Characteristics
Building Services/Processes	Physical and Mental Capabilities	Decay Characteristics
Operational Characteristics	Familiarity	
Fire Department Response	Physical and Physiological Condition	
Environmental Considerations		

Figure 3.5. Possible Design Fire Scenario Details

In performance-based design, fire scenarios can take numerous forms and serve various purposes. A design fire is generally chosen based on the phenomena of concern in the given situation. The details that must be included in the description of the design fire depend on the ways the fire will affect the systems being considered. For instance, a design fire that will be used in an analysis solely considering the fire's effect on structural elements may not need to include occupant characteristics. Generally, structural design fires include a complete description of the building characteristics, as well as details of the fire ignition, growth, and decay or suppression.

Any given compartment may have hundreds of possible fire scenarios. Consideration of all of these fire scenarios is not feasible, nor is it necessary. By considering critical fire scenarios, the engineer has confidence that less-severe fire scenarios will be indirectly accounted for because the structure will be designed to withstand the most severe fire conditions expected. At this point in time, the fire protection engineer must use knowledge, experience, and intuition to determine critical fire scenarios. It is foreseen that, in the future, guidance for the process of identifying appropriate fire scenarios based on occupancy, construction type, and other building details may be a beneficial component of building codes or other regulations.

Once the details of the critical fire scenario(s) are defined, they can be used to calculate important values, such as temperature levels at specific positions in the compartment at various points in time. Numerous tools are available to perform this task, including equations and models based on first principle concepts, as well as more complicated fluid dynamics techniques. Current technology has brought about the computerization of these techniques, thus greatly increasing the efficiency of this process. Available computer models include the first principle models CFAST [6] and ASET-B [7] and the computational fluid dynamics model Fire Dynamics Simulator [8].

The design fire description should include details for all phases of a fire. Structural member performance can be affected by the way a fire grows, how long it burns steadily, and how it decays. Figure 3.6 below gives a general description of the phases of a compartment fire [9].

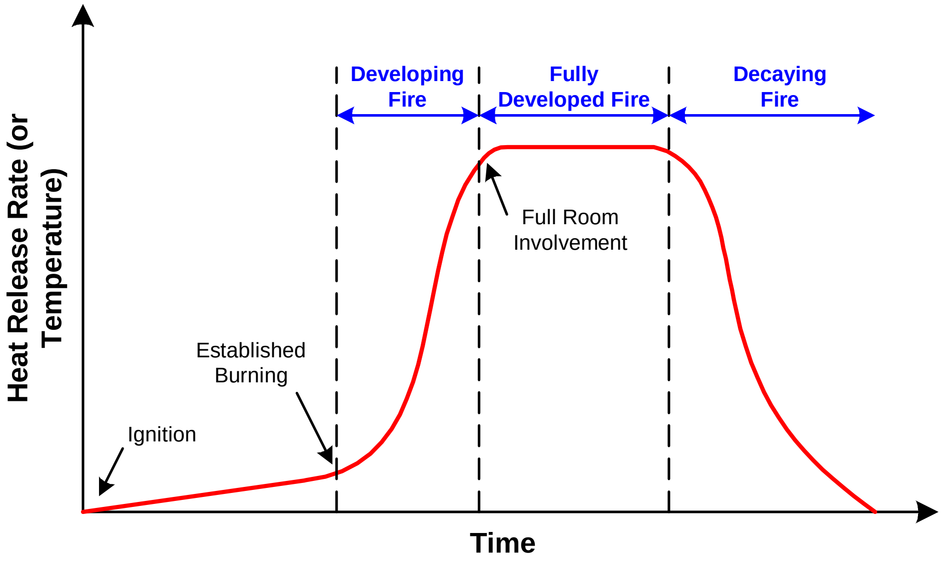


Figure 3.6. Burning History for Representative Compartment Fire

It is important that the structural design fire represent the most severe impact to the structure possible. This ensures that the structure is designed to withstand the most severe conditions that may be imposed upon it by a fire. While worst-case fire scenarios are chosen in an effort to ensure that the subsequent analysis considers critical conditions, factors of safety are often applied to the structural design fire quantification. Because fire behavior is so difficult to accurately predict, some method of allowing for inaccuracies in the prediction of fire behavior must be included; that is, the design must consider overload fire conditions. Safety factors allow consideration of overload fire conditions in the fire-robust structural engineering process much like load factors in probability-based AISC Load and Resistance Factor Design (LRFD) specifications [10] help ensure that structural steel details are designed to support loading levels beyond those reasonably expected in the building's service life. The deviations in the structural configuration that may result in understrength are considered in Chart 5 (Figure 3.9).

Because of the highly complex nature of fire, completely accurate prediction of fire behavior is nearly impossible. A skilled engineer using appropriate tools can produce a reasonable estimate of expected fire behavior. However, this requires extensive knowledge of the principles governing fire behavior, as well as experience with and some level of intuition for real fires. Because of these facts, this thesis recommends that the process shown in Chart 3 be carried out by a fire protection engineer, and that the predicted fire behavior be output from this process in a form that can be directly input into the structural fire analysis process. Efficient communication between the fire protection engineer and the structural engineer at this point is crucial. The fire protection engineer can provide the structural engineer with time-temperature curves, which can be used in the structural analysis to evaluate a structure's response to the conditions predicted by the fire protection engineer.

3.2.4 Identification of Expected Structural Fire Performance

Given input in the form of a schematic design and a structural design fire, the process of determining structural response to fire conditions can commence. The analytical functions utilized in this process are shown in Chart 4 (Figure 3.7).

CHART 4: IDENTIFICATION OF EXPECTED STRUCTURAL FIRE PERFORMANCE

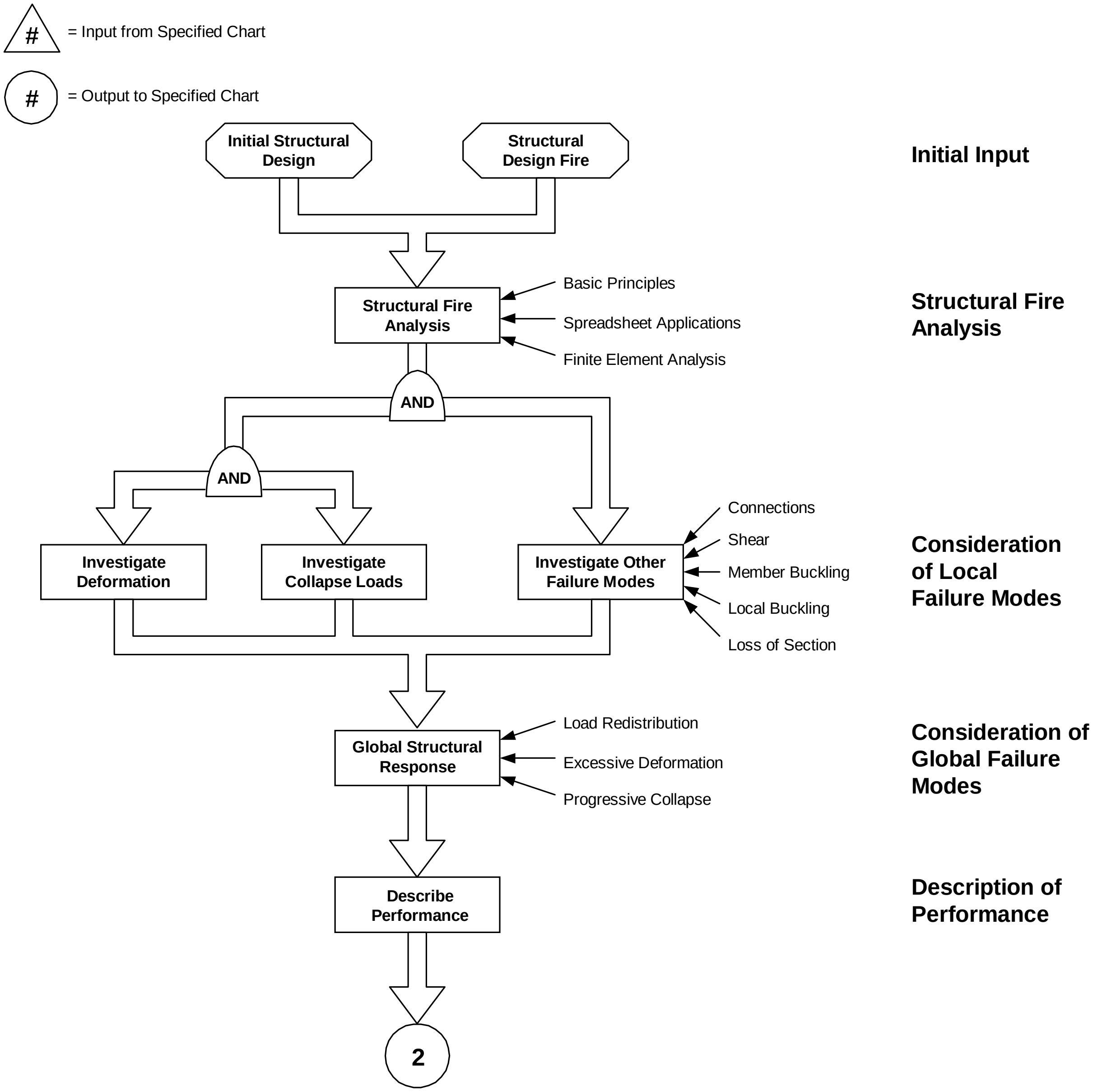


Figure 3.7. The Process of Identifying Expected Fire Performance

The tools used to analyze the response of structural elements to a given set of fire conditions are of several forms: basic principles, spreadsheet applications, and finite element analyses. Basic principles and spreadsheet applications are relatively efficient for the determination of the performance of individual structural elements.

These techniques may not be appropriate for more extensive analysis of structural systems, such as frames, or of global structural response.

Regardless of the technique used to determine structural fire performance, certain specific failure modes must be considered. Failure modes are mechanisms through which defined limit states may be reached, thus causing failure. These fall into two separate but related categories:

- Local Failure Modes, and
- Global Failure Modes.

3.2.4.1 Local Response to Fire

The term *local failure mode* refers to the response of an individual structural member or detail to a given loading or thermal condition. An example of a local failure mode may be the crushing of a concrete column, or the buckling of a steel column. Local failure modes are specific to the various types of structural elements included within a structure. In the previous example, buckling is noted for a steel column, but it would not be expected in a concrete column. The structural engineer must determine which behavioral phenomena are of concern for each critical element within a structure (critical elements are those that would be expected to fail first under a given loading condition). Exploration of the failure modes of critical individual members and details is crucial in determining the overall response of a building.

Local failure modes are specific to the configuration and behavior of a given member. Loading conditions determine the failure modes that must be considered. Numerous different types of members comprise a structural system, and many different loading conditions may be present in such a system. Additionally, support conditions also affect the fire performance of a member. Different failure modes need to be considered for different types of members or loading conditions. Figure 3.8 shows the failure modes that must be considered when analyzing different types of structural members [5,10,11]. Note that combinations of different types of stresses are also of concern in structural analysis, and must be considered when determining structural performance.

Member Configuration	**Possible Failure Modes and Design Considerations**
Pure Tension Members	Excessive strain Fracture across cross section Fracture of net section at connections (for bolted connections) Block shear failure
Simply Supported Beams	Deflection Development of a plastic hinge Lateral torsional buckling Shear Flange local buckling Web local buckling Web crippling
Continuous Beams	Deflection Development of multiple plastic hinges Lateral torsional buckling Shear Flange local buckling Web local buckling Moment redistribution
Pure Compression Members	Flexural buckling Torsional buckling Flexural torsional buckling Inelastic buckling and crushing
Beam-Columns	Flexural buckling Torsional buckling Flexural torsional buckling Inelastic buckling and crushing Lateral deflection Second order moments (eccentric loading)

Figure 3.8. Failure Modes Based on Member Configuration

3.2.4.2 Global Response to Fire

Global failure modes are the result of the actions of local failure modes. As individual members are exposed to changes (gradual or sudden) in physical loading and thermal conditions, their response can alter the overall performance of the structure by contributing to large-scale response mechanisms. These global failure modes can include:

- Excessive deformation of structural elements or systems, and
- Progressive collapse.

Additionally, load redistribution between different structural elements is an example of a response mechanism that may lead to global failure through the modes given above.

Having investigated possible local failure modes and the resulting global responses caused by a given structural design fire, the engineer can summarize the performance of a structure under fire conditions. Summary performance descriptions can include various predictions of structural response, including:

- Load-carrying capacities of individual members or connections,
- Deformation,
- Time to failure of individual members or systems, and
- Time to collapse of all or portions of the structure.

The above performance descriptions are used to describe the overall performance of a structural design. These act as output from Chart 4, which feeds back into Chart 2, where they are compared to performance criteria in an effort to determine the acceptability of the design.

3.2.5 Identification of In-Service Conditions

A wide variety of events may affect or change a structural configuration during its lifespan. In addition to fires, these can include earthquakes, blasts or explosions, windstorms, snowstorms, and floods. Also, normal operation and deterioration can affect a structure. Examples of this include rust, corrosion, and other environment-related deterioration mechanisms, as well as aspects of building operation that may cause inadvertent damage or long-term wear to structural members or protective coatings or encasements. Sometimes, variations can exist between design specifications and as-built conditions. All of these factors can impact the performance of a structure by altering the originally specified structural configuration.

A structural design cannot be considered robust if it does not consider the events that the structure may be exposed to during its service life. For example, an office building located over a fault line should be designed with consideration of the effects of an earthquake. A research facility built in the middle of flat plains land should be designed with consideration of the impact of high winds. These are normal design considerations for such structures. The events of interest to the fire-robust structural designer are more rare. They are occurrences for which the structure has not been specifically designed, and which may change the structural configuration, and thus the performance, of the building.

Chart 5 (Figure 3.9) shows how events occurring during the service life of a building can be considered during the design process.

CHART 5: IDENTIFICATION OF IN-SERVICE STRUCTURAL CONDITIONS

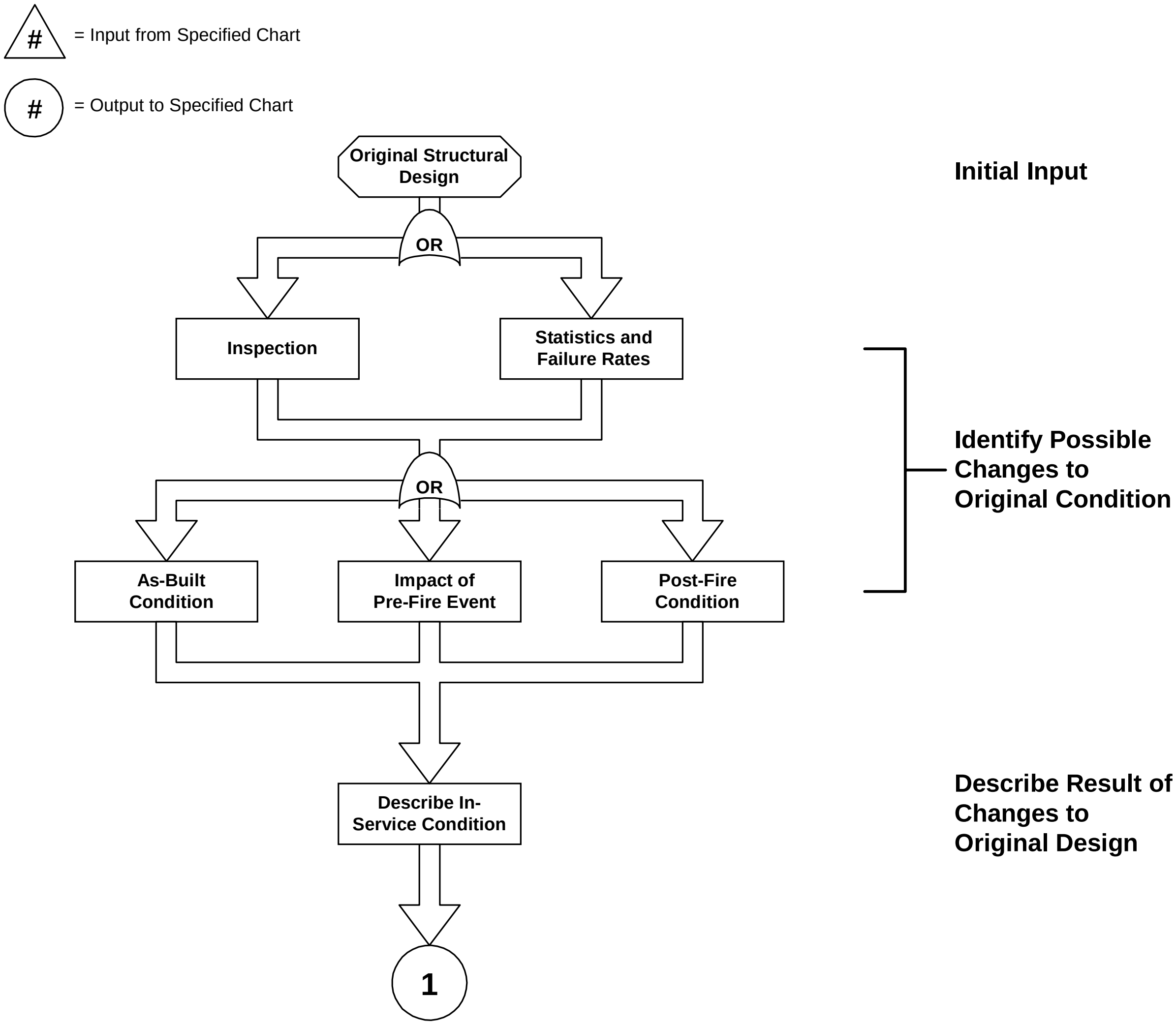


Figure 3.9. The Process of Identifying In-Service Structural Conditions

The first step in determining the in-service structural design of a building is to determine the ways in which the structure can be or has been impacted by various events. This can be done either through inspection of the structure subsequent to such an event, or through probabilistic means prior to such an event. The fire-robust structural engineering process, when being used to develop a new structure, requires a probabilistic approach since the structure is still being designed and possible events have not yet occurred. Statistics and failure rates can be used to predict the size and frequency of earthquakes, maximum wind forces expected over the life of the building, and percentage loss (through both accident and deterioration) of protective coverings applied to members. Also, deviations in construction and workmanship, as well as material properties, must be considered. All of these factors can change the performance of the structure prior to a fire, and thus the fire performance may differ from that predicted in the analysis of the original design.

It may also be important to consider the performance of a structure subsequent to a fire event. A fire can change a structural configuration by removing individual members, both critical and non-critical, or by causing entire sections of the structural system to collapse. Such losses result in load redistribution that can cause remaining members to be exposed to loading levels they've never been exposed to previously. Thus, the structural capacity subsequent to a fire can be different than before the fire. If a goal of the design process is to prevent total structural loss and allow salvage of portions of the structure and rebuilding after a fire, then the engineer must consider how the fire may affect even those members it didn't destroy.

The description of in-service conditions produced through Chart 5 can act as input in Chart 1 by altering the original structural design before it is analyzed for response to fire conditions. Consideration of as-built conditions, pre-fire events, and post-fire conditions can increase the robustness of a structural design by allowing the structural engineer to ensure that the structural configuration present at the time of a fire can perform acceptably.

3.3 Roles of the Engineers

The fire-robust structural engineering process has been developed for use by structural engineers. Wherever possible, tasks and functions have been described in a fashion oriented toward the training and experience of most structural engineers. However, it is not the intent of this thesis to suggest that the fire protection engineer is not a necessary contributor to this process. Advanced training is necessary to understand fire behavior to the degree required by the fire-robust structural engineering process. The process divides tasks into five different functional groups (Charts 1 through 5). Each of these functional groups (excepting Chart 3, *Structural Design Fire Quantification*) should be carried out by qualified structural engineers. The process of identifying fire conditions, as outlined in Chart 3, should be reserved for the fire protection engineer. Alternatively, standard structural design fire scenarios may one day be specified by building codes, although much development of this concept remains to be done.

Techniques commonly utilized in the structural design field have been applied here to help meet the goal of a fire-robust design. For example, classic structural analysis methods and concepts must be used to analyze the global effects of a fire impacting on critical members. A fire's impact on the structure has been represented as a series of mechanical stresses. The approach to analyzing a fire-exposed structure focuses on these stresses much like traditional structural design techniques do. Such analysis techniques are well known to the structural engineer, and most structural design offices are well equipped to carry out such work.

In some portions of the fire-robust analyses, methods not common to traditional structural design must be used in order to predict the impact of high heat levels on structural members. Here, the fire-robust structural engineering process helps to make structural engineers aware of the tools available to perform such analyses and provides guidance for this work. The combination of available structural analysis tools, such as finite element methods and spreadsheet applications, with advanced methods for predicting member or frame response to fire conditions, which are available in the literature, can enable the structural engineer to carry out a full fire analysis of a structure.

Until a time when thorough and appropriate design fire scenarios become available in regulatory documents, structural design fires should be developed and quantified by qualified fire protection engineers. Fire is a highly complicated chemical mechanism, and accurate prediction of ignition, development, and spread behavior is difficult. Fire protection engineers are trained in the chemical and thermo-physical processes of combustion, and are generally experienced in the use of basic principles and computer models for the description of expected fire behavior. Additionally, fire protection engineering, more so than most other engineering fields, is highly performance-based. The input of fire protection engineers to the fire-robust structural engineering process can help ensure that structures are designed to perform well in real fires.

3.4 Requirements for Implementation

Various tools and resources must be available to engineers to carry out the fire-robust structural engineering process. Additionally, certain knowledge of the appropriate use of these tools and resources is also required to properly perform the tasks of the design process. The process is intended to be performed by traditionally trained and fully qualified structural and fire protection engineers, and highly specialized training may not be required. However, various resources must be available to the engineers to allow fire considerations to be added to the design process. This section identifies the resources that the engineers may require access to during the fire-robust structural engineering process.

As stated in the introductory chapter, the fire-robust structural engineering process is made possible by state-of-the-art knowledge, information, and methods in the areas of structural analysis, fire protection engineering and fire science. Thus, the practitioners of this process must also have access to and knowledge of state-of-the-art analytical tools. These tools may include:

- First principle equations;
- Theoretical and analytical correlations;
- Simplified approaches; and
- Advanced computer methods (e.g., computational fluid dynamics, finite element methods).

While in most cases this thesis does not define a single tool as the sole method for achieving a desired result, the engineer must still know how to utilize certain appropriate tools in order to perform the various functions involved in the process. Several tools are often available to achieve a desired result. The engineer has the ability to choose amongst appropriate tools through application of his/her knowledge and experience to the details of the situation being analyzed and the level of information available.

The primary requirements for the implementation of the fire-robust structural engineering process take the form of informational needs. As has been described previously in this chapter, the fire-robust structural engineering process involves a large number of individual functions designed to work together to produce a robust design. To carry out these functions effectively, the engineer must have access to various kinds of information. This information may include:

- Analytical approaches and methodologies;
- Equations and correlations for determining local and global structural response;
- Variable and parameter values;
- Material properties;
- Structural and fire test data;
- Guidance resources;
- Failure mode and criteria definitions;
- Member protection techniques;
- Parametric studies of available methodologies.

Given sources for the types of information listed above, the structural engineer can decide which tools are appropriate for a specific task and can find guidance in the appropriate use of these tools to achieve the required outcome.

3.5 The Need for an Advanced Information Management System

Previous sections in this chapter have described the design process in detail, and have made clear the wide range of functions necessary for achievement of the overall goal of a robust structural design. This functional description facilitates communication because it focuses on what the structural engineer must do to quantify, evaluate, and make decisions about structural fire performance. It also helps to identify the various informational needs within the process. For the fire-robust structural engineering process to be implemented, sources for these informational needs must be available

In general, the fire protection engineering community holds a significant amount of research regarding various aspects of the behavior of structural components under fire conditions. The valuable information contained within this research is often not easily accessed by the structural engineer searching for guidance in the design of structures for fire. This is because the data is not organized or linked together in a format designed to serve the structural engineering community. Also, many research efforts do not get published for public use, so an engineer may not be able to use the information they contain. The functions of the fire-robust structural engineering process benefit greatly from state-of-the-art engineering knowledge and analytical methods. Consequently, it is critical that the structural engineer have access to this information.

Numerous information search mechanisms are currently available, including Internet search engines, library catalogues, and electronic databases. However, these do not provide a direct link to efficiently organized, function-based, accurate lists of resources. An inappropriately chosen keyword entered into one of these search tools, be it a general purpose search engine or a database dedicated to fire protection or structural engineering specifically, can result in a daunting list of resources, leaving the searcher unsure of where to look for appropriate and technically justified answers. Even an accurate keyword choice does not necessarily guarantee that the listed references will provide suitable answers to specific questions. Also, these databases rarely include state-of-the-art, unpublished research efforts. Chapter 4 provides a specific discussion of some available search tools and their use with the fire-robust structural engineering process, noting their benefits or shortcomings. Chapter 4 is included to make clear the need for an advanced information management system dedicated to use with the fire-robust structural engineering process.

4 CURRENTLY AVAILABLE SEARCH TOOLS

This section is included as a brief review of computer-based tools that are currently available to engineers searching for sources of information to meet various needs. This is not intended as an exhaustive review of all available fire- or structural-related information search mechanisms, but rather an outline of ways an engineer may commonly access information within these topic categories. Current computing capabilities have allowed more engineers and researchers to access a greater amount of information than ever before. Presented here is a study of information management tools commonly used by engineers and researchers, the driving forces behind the development of these tools, and the ways they are used by the engineering community. Also included are discussions of any major benefits or shortcomings in terms of the use of these tools in fulfilling the informational requirements of the fire-robust structural engineering process. Lessons learned in this study will be used to help develop the architecture of the information management system architecture proposed in this thesis. These lessons will help ensure that the information management system is designed to meet the needs of the designer of fire-robust structures.

It is common to provide users with multiple search methods for a given database. For example, the general engineering search engine *Engineering Village 2* [12] allows users to perform a “Quick Search” or an “Expert Search.” However, expert or advanced searches are often oriented toward information management and retrieval professionals who may have training or understanding not possessed by most civil engineers. For the purposes of this study, it is assumed that most structural engineers will use simple search mechanisms to look for information on the functions of fire-robust structural engineering. This assumption is made valid by one of the requirements identified in the development of the fire-robust structural engineering process: in order for the process to become widely accepted and utilized, access to information should be efficient and easy for all structural engineers. Where databases offer both simple and advanced search options, this study will focus on simple search tools.

4.1 Basic Database System Concepts

By definition, a database, or more appropriately, a database-management system, is a collection of interrelated data coupled with a set of computer programs used to access those data [13]. The set of data is called a database, although most users casually refer to the overall system as a database. Database systems are designed to provide rapid access to large collections of information. Management of this data involves the definition of structures to categorize the information and formulation of mechanisms to access these structures. Components of the system can be designed to help ensure informational security and stability and to allow multiple users to access the information concurrently.

Over the last four decades, database usage has expanded greatly. Early in the history of database use, database systems generally operated in support of various common operations, including banking, airline reservation systems, and payroll activities [13]. Generally, users (other than database administrators) did not interact directly with these systems. An example of this is a printed credit card report. Purchases listed on such a report are tracked and stored through the use of a database system, but the buyer does not interface directly with this system.

Human-database interaction grew rapidly with the Internet revolution of the late 1990’s, when web interfaces for many business applications became prevalent. Through simplified user interfaces, the Internet allows users to interact efficiently with complex database systems. These interfaces hide many of the technical details of database operation, such that many users do not realize they are accessing a database. An example of this is an online purchase system, in which buyer information is stored in a database.

Database-management systems are extremely useful because they allow the complex workings of a computer database system, operations such as physical storage and logical structuring, to be hidden from users. Users interact with an interface component that allows them to access specific information and limits the types of information that is displayed.

This helps provide the system with security and stability, and means that advanced computer knowledge is not required of the user.

The core of a database structure is the data model. A data model is a collection of conceptual tools for describing data, data relationships, data semantics, and consistency constraints [13]. Several types of models are available, with two main types being most common: the *entity-relationship model* and the *relational model*. An entity–relationship model is a collection of basic objects (entities) linked together by a series of relationship definitions. Attributes define the entities, and the system uses the relationships among these attributes to fill user requests. The relational model, which is most common in modern database systems, uses a collection of tables to represent different types of data and their relationships to each other. The first version of the information management system developed in Chapter 5 of this thesis is an adaptation of a relational database. Data attributes are defined based on the location of the data within the tables. The system uses algorithms to access data in the correct location based on user input.

A third type of data model is becoming increasingly common. This is the object-oriented data model. The object-oriented data model extends the concepts of the previous models through the use of encapsulation, object identities, and functional relationships. In theory, the information management system developed in this thesis is an object-relational database, which combines the features of the object-oriented model and the relational model. For more information on the structure of database proposed by this thesis, refer to Chapter 5.

4.2 Use of Database Standards

The various subsections of this chapter will make apparent the fact that different database systems often use different methodologies. Each methodology includes software details, access requirements, user interfaces, and record formats. However, a guideline exists to attempt to standardize some of these elements such that communication with database systems is efficient and use of such systems does not require advanced knowledge. This standard, approved by the American National Standards Institute, is known as *Information*

Retrieval (Z39.50-1995): Application Service Definition and Protocol Specification (ANSI/NISO Z39.50). The current version was approved in 1995 [14].

Z39.50 was developed to deal with various problems associated with worldwide searching of database systems. Specifically, the goal of the standard is to eliminate the need for specific knowledge of different menus, command languages, and search procedures necessary to utilize different database systems. Basically, Z39.50 specifies a procedure for allowing a remote user easy access to the information stored within a given information management system. While not all database systems follow this standard exactly, many use it as the basis for their architecture, often simply hiding various aspects of the standard form from the user in an effort to simplify the interface [15,16].

The Z39.50 standard is based on a client/server model. Tasks are divided between a pair of computers: one acting as the client, and one as the server. The client initiates a search, and the server responds by returning a series of records that are appropriate for the given search. The query is transmitted to the server in a standardized format (as defined by Z39.50). After the search is executed, the resulting information is returned to the client in standardized form, and then translated into the appropriate local form for presentation to the user.

Many database systems require knowledge of command languages. Examples of command language include the identifiers AU (author) and TI (title). Traditionally, these may vary from system to system, and a remote user may require advanced knowledge of a given database to obtain results. Z39.50 eliminates this problem by allowing different systems to communicate with each other through the use of a standard language that does not need to be understood by the user.

While the Z39.50 standard is extremely efficient because it defines a protocol for communicating with a database, extensive use of the Internet has made the standard somewhat unnecessary. The use of most current versions of Internet-based search tools starts at an associated website. This website acts as the standard user interface for the system, providing a portal for the user to input various approved types of information. The information input at the website is transformed into a standard form that is then delivered to the database, which performs the search and then returns the appropriate records. This type of interface is not precisely what the Z39.50 standard is designed to control because the database administrator develops the interface website to work with the database system. The interface is not local to the client computer. This system simply uses the Z39.50 concept of a standard information transmittal format used for every record.

Many database developers hide the majority of the record fields used by their systems from the users. For example, a user may be able to search for title or subject terms, keywords, author names, or document type, while the actual record format includes many more categories of information, such as publisher, classification codes, etc. Search fields are limited in the interface in an effort to make the search process as straightforward and simple as possible for most users. Often, alternate advanced searches are made available for those familiar with more advanced search techniques. These advanced searches generally make use of more record fields than do simple searches.

The Z39.50 standard will not specifically be used in the development of the fire-robust structural engineering information management system. This is necessary because the FRSE IMS is a highly specialized database designed around the framework of the FRSE process. It requires a specialized record format and search algorithms. However, a standardized record format will be used to facilitate query communication and record identification. A standard set of possible record descriptors will be developed, and records will be classified based on these descriptors. Users will not necessarily need to be familiar with the workings of this standard format, but it will add to the efficiency of the search process and in the delivery of descriptive information to the user.

4.3 FIREDOC

The Internet search tool FIREDOC, provided by the National Institute of Standards and Technology (NIST) (fire.nist.gov), is possibly the most widely accessed tool of its type in the fire protection engineering field. This is justified, given that FIREDOC provides access to bibliographic information for over 55,000 fire-related publications listed in the Fire Research Information Services (FRIS) of the Building and Fire Research Laboratory (BFRL) [17]. Using this tool, an engineer can search for books, published reports, journal articles, conference proceedings, and audiovisual items stored in the FRIS catalog.

4.3.1 Development

FIREDOC was developed in 1983 when the National Bureau of Standards' (NBS, now NIST) Center for Fire Research (CFR, now BFRL) assigned a team, headed by Nora H. Jason, to the task of developing a system to provide easy access to the FRIS literature collection.

From the start, the creators of FIREDOC wanted to tailor the system to the needs of the individuals who would use it. The developers assumed that the principal users of this system would be CRF staff, however availability to the general fire community was also an original intention. FIREDOC's creators started with a literature review of documentation for other database systems, as well as a review of other databases that were in service at the time. They also completed a needs assessment to determine what features should be included in the system. This needs assessment resulted in the identification of a series of questions that would later guide the development of FIREDOC. These questions deal with various key considerations for system development, including access issues, record format decisions, hardware and software requirements, and expected maintenance needs. The questions identified by the needs assessment are listed below in Figure 4.1 [17].

FIREDOC Development Concerns

a. Should the database be made available to the general public, or kept restricted or classified (for use by CFR staff only, for example)?

b. Should the system present the user with the complete document, or is a bibliographic reference sufficient? If just a bibliographic reference is presented, should it include an abstract?

c. Are the management records currently being kept for the FRIS collection of the appropriate form, or should they be more detailed? Can certain details be eliminated?

d. What specific records should be kept for each document? Which records will be most beneficial to the user?

e. What types of hardware and software are available for implementation of the database? What limitations (in terms of service capacity) are inherent in the use of such hardware or software?

f. How much support could the CFR staff provide for the database on a 24-hour basis, and is this support sufficient, or should some sort of outside maintenance source be considered?

g. Will management support the project during the development, implementation, and future maintenance of a system that meets the objectives of the project? Do the objectives of the developers match those of the management?

h. What level of monetary support will be provided during the first and subsequent years of implementation of the system? Will the system be maintained as appropriate and upgraded when necessary?

Figure 4.1. Concerns Identified during FIREDOC Development

These questions were asked in an effort to bound the development of FIREDOC based on the foreseen needs of the users and the available support within NBS. The feasibility of the project was based on the needs of the fire community, the capabilities of the available technology, and the expected future benefit and maintenance requirements of the system. These are all logical questions to be asked during the development of any information management system.

Regardless of the degree of sophistication desired by the developers and future users of a system such as FIREDOC, in the mid 1980’s, database development was controlled largely by the available computing technology. The developers considered the hardware and software technologies available at the time, and compared them to the anticipated functional requirements of the system. Of concern to the developers were topics such as:

- Integration of data from outside sources (other than FRIS);
- Flexibility of search and retrieval capabilities;
- Password security requirements;
- Multiple-user capability;
- Thesaurus control options;
- Performance level of available hardware; and
- System cost.

A developer of an information management system today, in 2002, has access to a vast amount of computing power. Generally, the sophistication of a modern database is limited by the need for it to be user friendly [16]. Most modern server computers are powerful enough to run highly sophisticated database software, so the availability of computing power no longer limits the complexity of a database program. Modern servers can permit a large number of users to access a database concurrently without an obvious decrease in performance.

FIREDOC was initially implemented using the bibliographic search program STAR on an Alpha Micro computer [17]. The system required all users to log into a rather complicated interface, and to understand the use of various search fields in performing a search. A User's Manual [18] was made available that listed these search fields and other commands in the STAR program. Because of this complicated interface and the requirement that users have specific knowledge of the use of the database platform, the system's benefit to those not familiar with search techniques was severely limited. The system was eventually upgraded to a Unix platform by 1993, and has remained in virtually the same form since then. The Unix version is much more intuitive, and does not require special knowledge of search fields or other commands.

4.3.2 Record Format

Consideration of all of the issues discussed in Section 4.2.1 could result in an operational automated information retrieval system. However, the developers were additionally concerned with how the database would be used by the fire protection engineering community. They wanted the system to be efficient and beneficial to the individuals who would rely on it. To this end, the NBS team held a workshop in April of 1985 to determine the types of information people in the fire community would need from the system, and how such information could best be presented to these individuals. The workshop included professionals from the fields of fire service training, research, education, and fire protection engineering, thus representing the majority of people working in fire-related fields. By using suggestions from this workshop, the system designers felt that the "best" record format could be defined and developed.

The record format developed as a result of the April 1995 workshop included the details listed below in Figure 4.2 [17]:

FIREDOC Record Fields

Stamp
Staff Initials
Accession Number
Staff
Author
Title
Document Type
Document Distribution
Form
Corporate Source
Sponsor
Journal Title
Volume
Number or Part
Book or Conference Title
Place
Publisher
Editor
Report Page Count
Book or Conference Page Count
Journal Page Count
Publication Year
Journal Publication Date
Report Publication Date
Order Number
Language
Contract Number
Keywords
Abstract

Figure 4.2. FIREDOC Record Fields

It was not the intention of the developers that all of these fields be completed for each reference, but rather that this list would include all possible reference details that may need to be presented to the user when characterizing a variety of different types of records. For instance, only certain fields would be appropriate for a paper published in a journal, while other may only be used in records of conference proceedings.

4.3.3 Application of FIREDOC to Fire-Robust Structural Engineering

Having clearly designed FIREDOC based on a great deal of research and study of pertinent issues, the CFR released it for use by its employees and the fire community in general. FIREDOC presents users with basic, complete information outlining potential sources of information to meet their needs. People often rely on FIREDOC because of its ability to link them with the vast amount of fire-related literature available in the industry. It has stood the test of time and remains one of the most popular methods of identifying sources during the fire protection research process. There are numerous reasons for FIREDOC's success.

The developers of FIREDOC designed the system from the point of view of their target user group: engineers and researchers looking for informational sources. They also talked with engineers and researchers to determine how they would use a comprehensive database, and what they would look for in terms of an appropriate record format. Thus, the system was tailored to the people who would use it on a daily basis throughout their careers.

The original version of FIREDOC was rather complicated, and a good deal of understanding of search techniques and the mechanisms of the database software were required. An upgrade in the early 1990's resulted in a more user-friendly version that could be accessed by a very wide audience. The user interface is straightforward and not confusing, and the output is comprehensive. A recent addition to the system includes links to a limited number of NIST publications that are available in electronic form, thus providing the user with direct and immediate access to resources. Note that one of the questions originally posed by the developers involved the presentation of entire documents to the user (see Figure 4.1), and at the time of initial development, the decision was made not to include this feature. Since then, advances in scanning technology and file compression have made such a task much more feasible.

FIREDOC represents a huge library of references, and it has been kept largely up-to-date through the years. Thus, engineers and researchers are provided with access to a wide range of modern literature. To search through this data bank to find resources covering specific topics, users have some degree of knowledge in efficient search techniques. Otherwise, huge lists of possible resources can be presented, and it is left to the user to pare these lists down to records useful for the given topic. Because users cannot limit their searches based on the functions for which they are searching for information, FIREDOC is not efficient when considered in the context of the fire-robust structural engineering process described here. The proposed design process requires very specific types of information, and a comprehensive search tool such as FIREDOC is not oriented towards the identification of such narrow groups of resources. The FIREDOC user must be experienced in different types of search techniques to obtain a limited list of appropriate resources, and even then, the records provided for these resources may not be sufficient to judge their usefulness in providing information for the fire-robust design process.

A specific example may clarify this point. An engineer looking for information on finite element analysis of structures under fire conditions may enter the keywords “finite element structural analysis” into FIREDOC. This will result in no matches, and the engineer will have to refine the keywords. Removing the word “analysis” and searching for the keywords “finite element, structure” also results in no references. The engineer is forced to remove the term “structure” and then to search for the more general topic “finite element.” This search results in 20 references, some of which refer to structural modeling. Other records, however, refer to other uses for finite element modeling techniques. Even those that seem to refer to structural modeling are referenced only by their titles, so the engineer may be unsure of their actual content and the appropriateness of that content for the task at hand.

Much of the reason why FIREDOC is too broad for use with the fire-robust design process is owed to the fact that it was designed for the use of the entire fire protection community, including researchers, educators, the fire service, and engineers. While this makes FIREDOC extremely comprehensive and applicable to the entire fire protection community, fire-robust structural designers require a limited portion of the information represented by FIREDOC. If FIREDOC is used to find information regarding the functions of the fire-robust structural engineering process, the user is responsible for determining the appropriateness of the resources identified by the system because both appropriate and inappropriate resources may be identified. For these reasons, FIREDOC, as well as many other standard databases, do not work efficiently in serving the practitioners of functional approaches to engineering problem solving, in which informational sources for a wide range of highly specific topics may be required. The efficiency of a functional approach can depend on the efficiency with which informational needs are met, so database systems that do not allow highly accurate and specific searches can greatly slow the analysis process.

4.3.4 Conclusion

While FIREDOC is an extremely comprehensive database, and was designed with its users in mind, its wide reach may be its most limiting attribute in terms of application to the fire-robust structural engineering process. It is feared that if the process of finding specific and appropriate information on the functions involved in structural design for fire conditions is difficult or inefficient, then the fire-robust design process might not be widely accepted for general use. This process requires a more refined search mechanism – one designed specifically to deliver structural fire protection information to the engineer. The new system’s intended audience is greatly limited, unlike that of FIREDOC. However, the developers of FIREDOC went to great lengths to ensure that the system would be as beneficial to its users as possible. The development of the fire-robust structural engineering information management system shares this goal, and thus can benefit from a similar development process. The techniques used in the development of FIREDOC have been kept in mind during the development of the fire-robust structural engineering information management system described herein because they resulted in the creation of a system that met the requirements of its developers and served (and continues to serve) its users well.

4.4 ASCE Civil Engineering Database

The American Society of Civil Engineers (ASCE) provides free access to a database on its website (www.asce.org). This Civil Engineering Database (CEDB) is oriented towards all aspects of civil engineering, and provides access to all ASCE documents published since 1972. Thus, even more so than FIREDOC, the CEDB represents a huge number of resources – more than 100,000 at the current time. The ASCE database can be used to search for various types of civil engineering resources, including books, articles within journals, magazines, and newspapers, conference proceedings, standards, and manuals.

4.4.1 Development

The ASCE database was first introduced in 1990 when the Society recognized the value of the large number of publications it held. The database was released to the public on the Internet immediately, and never occupied a non-public form. It is designed to be helpful to anyone interested in the field of civil engineering, and is not necessarily limited to civil engineers.

4.4.2 Record Format

The record format for the ASCE database did not go through an extensive development phase, as did that of FIREDOC [15]. It was judged that a standard database format based on ANSI/NISO Z39.50 would be most efficient in capturing the wealth of information available in ASCE publications, and in delivering this information to potential users. The Internet user interface allows users to search for the following details:

- Document Type;
- Full Text;
- Author;
- Title;
- Keyword Term (from list of approved terms); and
- Publication Year Range.

Users can search with one or more of the above tools, and comprehensive search tips are available for each.

The ASCE database utilizes a proprietary software program called Bluesky [15]. This program enables collection of all common bibliographical access points, although only those listed above are made available on the Internet version. While this may limit the amount of confusion experienced by an inexperienced searcher, more experienced users may wish for more flexibility. The current management of the database has expressed interest in expanding the online capabilities of the database by making more details available to the user [15]. It is expected that if this move is approved, input from the public would be used to determine which search fields are most useful.

4.4.3 Maintenance

The ASCE database is constantly expanding. New publications are added on a daily basis. However, the Internet interface is updated monthly. ASCE's Internet service provider handles many of the technical details of this maintenance. Two ASCE employees are responsible for adding new records to the database whenever they are published. Once a month, the Internet service provider upgrades the online interface to incorporate new records.

4.4.4 Application of the CEDB to Fire-Robust Structural Engineering

A database intended to cover the entire civil engineering field must necessarily be extensive due to the wide variety of different topics included in this field. Figure 4.3 provides a list of subjects covered by the CEDB. Note the lack of specific mention of any fire-related topic.

CEDB Subjects

Aerospace Engineering
Architectural Engineering
Bridges
Cold Regions
Computer Practices
Construction
Earthquake Engineering
Education
Engineering Mechanics
Environmental Engineering
Forensic Engineering
Geotechnical Engineering
Highways
Hydrology
Irrigation and Drainage
Management
Materials Engineering
Structural Engineering
Transportation
Urban Planning
Water Resources
Waterway, Port, and Coastal Engineering

Figure 4.3. Civil Engineering Fields Covered by the CEDB

It is important to note the CEDB is not segregated according to the topics listed in Figure 4.3 at this time. The list simply shows the wide range of topics covered by the CEDB. One cannot, for example, perform a search that only considers documents categorized under the subject of Computer Practices. One can, however, enter “Computer Practices” as a limiting keyword phrase. While this may not limit the search to only those records appropriate to the specific query, it can reduce the number of possible records presented to the user.

Currently, ASCE is considering developing a browse function for its online database that would allow users to explore specific topic areas that are covered in the database. In theory, this would allow users to focus their search to a given topic area (bridges, hydrology, urban planning, etc.) instead of having to search the entire database. If this plan were carried out, the resulting database would function much like the information management system developed here for use with the fire-robust structural engineering process. Given that each of the topics listed above probably represents a quantity of information on the same order as that represented by the subject of structural fire protection, the large scale of the CEDB can be appreciated.

Much credit is due to ASCE for assisting CEDB users in the search process. The online database is user friendly and straightforward, and in-depth search tips and techniques are provided. These help topics provide descriptions of all of the different searchable fields in the database, along with suggestions for their use. Given this overview, an inexperienced searcher can perform a relatively efficient search. However, even good search techniques cannot always sufficiently narrow a search in such a large database.

To demonstrate the above observation, the example first presented in the discussion of FIREDOC will be repeated using the CEDB. The topic of research is finite element structural analysis, and the researcher first views the provided tips and techniques for help in beginning the search. The CEDB includes a list of possible Keyword terms, and this is often the best place to start. Using Keywords from this list that were thought to be appropriate, the researcher would obtain the following results.

- “Finite Element Method” – yields 1921 records;
- “Computer Analysis” – yields 870 records,
- “Computer Models” – yields 1746 records,
- “Structural Analysis” – yields 1782 records; and
- “Structural Models” – yields 512 records.

Note that only the first 100 references are actually displayed by the system, so some potentially valuable resources may never be presented to the user. Exploring the references resulting from the narrowest search listed above, “Structural Models,” the researcher is presented with a list of titles that serve as electronic links. Choosing a link provides access to additional information on the given reference, including descriptive abstracts. However, it is clear from an exploration of numerous records at the top of the list that is presented in this search that a great deal of time is needed to identify appropriately specific references.

It should be noted that, unlike in the general topic list given in Figure 4.3, the Keyword list includes several specific references to fire topics. Authorized fire-related Keywords include:

- Fire Control (23 titles)
- Fire Exposure (15 titles)
- Fire Hazards (11 titles)
- Fire Protection (65 titles)
- Fire Resistance (80 titles)
- Fire Resistance Materials (9 titles)
- Fire Safety (54 titles)
- Fire Tests (35 titles)
- Fires (76 titles)

While the number of references resulting from these searches is much smaller than those discussed in the previous example, and thus exploration of the resulting topics is reasonable, these Keywords are not necessarily specific enough such that the example topic falls under any given one. Exploration of the results of each Keyword deemed to be related to the search might be necessary.

Next the researcher may try to enter a "Full Text" topic. Other than the keywords discussed above, this is likely the only other viable search mechanism for this type of search, since specific titles, author names, or year ranges are not known. Searching the Full Text field for the topic "Finite Element Structural Analysis" results in 638 records, and thus the search has not been further narrowed.

The most efficient search identified here results from combining the Full Text and Keyword search methods. Searching for the Full Text topic "Structural Analysis" with the Keyword "Finite Element Method" yields 329 possible references. This may be a small enough list for the researcher to peruse, but it would still take some time to winnow all appropriate references out of the list by identifying possible candidates (based on their titles) and reading their abstracts. If a method such as fire-robust structural engineering is ever to be commonly accepted for use, a more efficient means of obtaining the necessary information must be implemented, because a structural engineer simply does not have enough time to search through hundreds of possible resources for information appropriate to each of the numerous functions involved in the process.

4.4.5 Conclusion

The ASCE database proves that the size of an engineering discipline must be observed relative to engineering as a whole. Technically speaking, civil engineering is a relatively narrowly defined field when viewed in relation to engineering in general. However, a database covering all of civil engineering must actually include information on more than 20 individual topics (refer to Figure 4.3), many of which are unrelated to structural design for fire conditions. Such a database represents a large amount of information, and as with FIREDOC, effort is required to sort through this information in order to find specific details. The ASCE Civil Engineering Database provides numerous ways for its users to perform efficient searches, but the presence of a wide range of topics still makes it difficult to narrow a search down to resources that are appropriate for the fire-robust structural engineering process. Additionally, the lack of abstracts or summaries describing each resource makes the process of identifying appropriate information difficult.

4.5 Engineering Village 2

The Engineering Village 2, provided by Elsevier Engineering Information, Inc. (Ei), is designed as a single interface that links users with scientific information stored in multiple databases. The system provides a subscribing user with access to information on over 6,000,000 journal articles, technical reports, and conference proceedings published since 1970, as well as more than 10,000 website summaries and 80 full-text handbooks [12]. Engineering Village 2 is considered by many to be a one-stop source for all scientific research.

4.5.1 Development

Ei's involvement in scientific information management can be traced all the way back to 1884, when their first database was produced (in paper form). Originally called the *Index Notes*, it covered a small number of journals, and was published annually. Since then, it has expanded enormously, and now consists of six individual databases covering more than 8 million resources [12].

Index Notes was conceived in 1884 when Dr. John Butler Johnson of Washington University saw the need for a method of accessing information in an effective, efficient, and timesaving manner. To accomplish this, he compiled, indexed, and published a series of abstracts of technical publications. He called this modest database *Index Notes*. This was the birth of what, in 1896, would come to be known as the *Engineering Index*. By 1919, the *Engineering Index* was extensive enough to warrant monthly publication.

The initiative to make the *Engineering Index* easily available to a wide audience began in 1963 with the introduction of the Current Awareness and Document

Retrieval for Engineers (CADRE) program [12]. This effort was designed to explore the possibility of computerization of databases. While CADRE focused mainly on the fields of plastics and electrical and electronic engineering, its impact spread to all disciplines represented in the *Engineering Index*. By 1969, Ei had begun making plastics and electrical/electronic bulletins available in a machine-readable form (considered state of the art for the time). The rest of the *Engineering Index* would soon follow.

Beginning in 1969, Ei made a monthly tape service known as Compendex available online. This service gave engineering professionals electronic access to information in all engineering disciplines. Compendex still exists today as part of the Engineering Village.

The first Internet-based service offered by Ei was introduced in 1995. Known as the Engineering Village, the service required a subscription (as it still does), but promised access to "the entire world's technical literature" [12]. Several years later, Ei was combined with the scientific publisher Elsevier Science, and acquired *PaperChem*, an already established database for the paper and forest industry. The service was next expanded to the oil and gas markets with the addition of the American Petroleum Institute's publishing resources. The current version of the database, known as the Engineering Village 2, is a compilation of six different databases, as listed in Figure 4.4 below.

Engineering Village 2 Databases

a. Ei Compendex: Interdisciplinary Engineering Database

b. United States Patent and Trademark Office Resources

c. CRC Press: Engineering Handbooks Online

d. Industry Specifications and Standards

e. Website Abstracts

Figure 4.4. Databases Represented by Engineering Village 2

Ei Compendex is a traditional database designed for use in all engineering fields. It contains over 6 million records, and represents documents published since 1969. Compendex is Engineering Village 2's version of the standard scientific information management system. It incorporates references to books, journals, articles, and other paper documents that comprise the general body of engineering literature. Compendex is not limited to any individual publishers, and thus theoretically includes all published material. Thus, it is a very comprehensive source.

Other tools that a civil engineer might use include the CRC Press and industry specifications and standards. The CRC Press provides full text versions of more than 80 engineering handbooks, but requires an additional subscription to access. Ei's collection of more than 20,000 industry specifications and standards can be useful in many cases, but fees are charged for access.

Engineering Village 2 is the only service of its kind that offers efficient search capabilities for scientific websites on the Internet [12]. Many search engines are available for the purpose of identifying Internet sites that may be applicable to a given topic, but these generally offer little descriptive information about websites, and allow any websites to be listed in their databases. Ei evaluates the websites offered through their system based on technical value and the presence of relevant information, as well as ease of use, organization, and presentation. This greatly simplifies the process of identifying useable information on Internet websites because, as most individuals who use websites as sources of information, verification of such informational sources is often difficult. Ei attempts to give its users confidence in these sources by evaluating them before they are presented to the Engineering Village user.

4.5.2 Record Format

The Engineering Village 2 system uses a standard record format based on ANSI/NISO Z39.50 specifications. It includes the fields listed in Figure 4.5:

Engineering Village 2 Record Fields

Title
Subject
Abstract
Author
Author Affiliation
Publisher
Publication Year
Classification Code
CODEN Code
ISSN Number
ISBN Number
Conference Code
Document Type
Language
Number of References Cited
Treatment Type

Figure 4.5. Engineering Village 2 Record Format Fields

Possibly the most significant field listed in Figure 4.5 is the abstract, which is provided for each reference listed. An abstract can be extremely useful when one is attempting to determine if a possible reference contains information that is appropriate to the topic being explored. Engineering Village 2 is the only service discussed in this thesis that provides an abstract for every reference. Generally, the author provides the abstracts that are presented in the database.

Engineering Village 2 offers two general search options. The first is a simple search (Quick Search). The Quick Search uses an interface that is much like an Internet search engine, although the user is able to choose to search specific fields from a portion of the list given in Figure 4.5. Searches can be limited to subject terms, author, author affiliation, title, serial title, publisher, or abstract. It is also possible to search all of these fields at once. A search can also be limited by type of document, language, or publication date range.

Engineering Village 2 also provides an Expert Search that “caters to librarians and other information retrieval specialists” [12]. This tool allows the use of complex queries and Boolean techniques in the search process. Advanced users can use nesting and combine various search fields to efficiently identify possible resources.

4.5.3 Maintenance

Unlike FIREDOC and the CEDB, Engineering Village 2 is provided and maintained by a company that specializes in engineering information management. Elsevier Engineering Information employs staff members dedicated to maintenance of the Ei database. Compendex, the most extensive portion of the system, is updated on a weekly basis, with more than 250,000 new records added each year. Given the extent of the record format discussed in Section 4.3.2 and the range of fields represented within the database, Ei must dedicate a large amount of time and effort to keep the system up to date.

4.5.4 Application of Engineering Village 2 to Fire-Robust Structural Engineering

Ei does not segregate its database based on engineering disciplines. The search tools do not allow a user to search within defined engineering fields, and thus a great deal of crossover between different disciplines can occur. However, the system does provide the user with extremely detailed record information, as well as full text abstracts describing each reference. This is useful in judging the value of possible resources during a given search, but it requires time and effort. When presented with a moderate or large number of possible resources, an engineer may not have time to explore all of their records. Finding appropriate sources amongst over 6 million documents can be challenging.

The example carried out for FIREDOC and the ASCE Civil Engineering Database will again be used here to demonstrate the use of Engineering Village 2. As discussed in the introduction to this chapter, this study will focus on simple search methods by assuming that most civil engineers will use quick or simple search tools to look for information. Thus, Engineering Village 2's Expert Search option will not be explored here. The Quick Search tool will be used to recreate the example used in the previous two database studies.

In this example, the topic of research is “finite element structural analysis.” Entering this phrase in a simple search of the Compendex database without limiting the search to specific fields, document types, languages, or publication date ranges results in 194 possible resources. The user can explore the details of all of these records (the number of displayed records is not limited [12]). Each contains a full description of the given document, including a full text abstract. While the abstracts can be used to accurately identify appropriate resources, the time required to read the abstracts may be prohibitive.

Engineering Village 2 includes a useful tool to help alleviate this situation. The user has the option to browse the titles of the references identified by the Quick Search, and to check those with titles that imply their appropriateness for the given topic. The user can then redisplay only the results that have been checked, and begin exploring the associated abstracts.

Searching for the entire phrase “finite element structural analysis” results in the most narrowly defined query output (fewest references presented). Separating the search terms (in other words, searching for the terms “structural analysis” with the limiting terms “finite element”) results in many more possible references (12,503).

4.5.5 Conclusion

Engineering Village 2 is by far the most comprehensive database system discussed here. It goes beyond the field of civil engineering to include resources from all engineering disciplines. By doing so, it has the potential to present the user with staggering numbers of potential resources. Engineering Village 2 combats this problem to a certain degree by providing extensive record details, most notable of which are full text abstracts for all references. However, the time required to review the abstracts of all resources identified in a given search can make this process highly inefficient and thus not ideal for the fire-robust structural engineering process.

Unlike FIREDOC and the ASCE Database, Engineering Village 2 requires a subscription. Limited trial subscriptions are available, but frequent use requires the purchase of a subscription from Elsevier Engineering Information. The use of CRC Press and Industry Specifications and Standards databases incur additional fees.

4.6 General Conclusions and Lessons Learned

The study of available search tools presented here has identified numerous attributes that can help result in the development of a successful information management system. The previous sections have been designed to explore FIREDOC, the ASCE Civil Engineering Database, and the Engineering Village 2 and to identify positive and negative aspects of their development, performance (in regard to fire-robust structural engineering), and maintenance. The lessons learned here will be used in the development of the fire-robust structural engineering information management system developed later in this report. These lessons include the following:

- The desired audience should be identified in the early stages of database development. This audience should be directly (through surveys, focus groups, etc.) or indirectly considered during the development of both the record format and the user format, as this audience will use the database on a regular basis.

- No matter how narrow a given search, multiple records will almost always be identified. An efficient search tool provides the user with methods for first narrowing a search, and then choosing between the potential records that are identified. A search can be narrowed greatly by allowing keywords to be combined with full text search fields, or by allowing the user to search for information on a functional basis. Once a limited number of potential resources are identified, full text abstracts or summaries enable to user to make informed decisions regarding the appropriateness of resource content.

- While the available computer hardware and software can bound the development of an information management system, the current state of the art can allow extremely complicated system architecture and user interface designs.

- The available support (time, effort, financial, etc.) is a key controlling factor in database development. Generally, more effort is required to initially implement a new information management system than at later points in the life of the system. Additional effort is required to maintain, update, and upgrade the system during its service life. To be kept current, new records must be added on a regular basis. Complicated record formats or software programs make this process require large amounts of time and effort. The available support must be sufficient to provide the required levels of commitment.

The fire-robust structural engineering process requires highly specific information. The designer of fire-robust structures requires a means of efficiently accessing this information based on the functions that must be performed to achieve a fire-robust design. The study of database systems performed here suggests that a tool is not currently available to achieve this goal. However, the lessons learned in this study can greatly benefit the development of a refined and efficient information management system for use with the fire-robust structural engineering process.

5 INFORMATION MANAGEMENT SYSTEM DEVELOPMENT

The previous chapters of this thesis have pointed out the need for an efficient way of combining the knowledge, methodologies, and tools of the structural engineer and the fire protection engineer to design fire-robust structures, and have proposed a new framework for accomplishing this goal. They have also noted the difficulties currently inherent in the task of finding the information needed to perform the functions of the fire-robust structural engineering process. This chapter begins the development and initial implementation of an information management system designed to allow the engineer to efficiently search for structural fire protection resources.

This chapter begins by discussing the use of dedicated databases in the engineering community. With so much information compiled and represented in each general genre of engineering (mechanical, electrical, civil, etc.), databases dedicated to a small portion of literature are somewhat rare. The fire-robust structural engineering database is one such system, and its development will benefit from lessons learned from the study of the development of a similar established system. The remainder of the chapter is devoted to the development of an information management system designed to support education, research, and practice in fire-robust structural engineering.

5.1 State of the Art: The Dedicated Database

Relatively few dedicated databases exist in the engineering world. FIREDOC could be considered a dedicated database given the relative youth of the fire protection industry, although the ever-growing scope of this field has resulted in great expansion of the material covered by the database. Thus, a database covering the entire field can no longer be considered to be highly dedicated. The fire-robust structural engineering database discussed in this report is an example of a dedicated system that incorporates limited portions of the larger fields of structural and fire protection engineering. To aid in the development of this database, an exploration of another dedicated database, the Earthquake Engineering Abstracts, has been carried out and is included below.

5.1.1 National Information Service for Earthquake Engineering

Many parallels can be drawn between the fields of structural engineering for earthquakes and structural engineering for fire conditions. A great deal of research has been conducted and is available on each topic, but it can sometimes be difficult to extract pertinent information out of general engineering databases. For many of the same reasons why a database dedicated to structural fire design is being developed here, the Earthquake Engineering Research Center (EERC) at the University of California at Berkeley has made available a database focusing on earthquake engineering information [16].

5.1.1.1 Development

In 1971, a comprehensive source for civil engineering information was difficult to find. The American Society of Civil Engineers' (ASCE) Civil Engineering Database (previously discussed in Section 4.3 of this thesis) did not exist yet, nor did any source dedicated to earthquake engineering. However, there had been a significant public investment in earthquake engineering research, especially from the National Science Foundation (NSF), and thus a large amount of information on the subject existed. Given the value of this information as an engineering tool, the decision was made to maintain it in an organized form for public benefit.

The EERC database, known as the Earthquake Engineering Abstracts (EEA), was originally released in 1971 as a biannual publication called the *Abstract Journal in Earthquake Engineering*. At that time, it was available only in paper form. Eventually, an electronic version of the database was made available along with the paper version. Researchers at U.C. Berkeley later collaborated with their colleagues at the State University of New York (SUNY) at Buffalo in the development of a CD-ROM version of the database to be sold by a distributor for commercial use.

In 1995, the EERC database was implemented on the Internet for the first time as the National Information Service for Earthquake Engineering (NISEE). Through the efforts of the U.C. Berkeley staff, this version remains in use today, and is available to the general public. The database is used by engineers in more than 100 countries [16] and is generally considered to be the most comprehensive source for earthquake engineering information.

5.1.1.2 Record Format

The original EEA database was implemented with a standardized library citation format. During the upgrade of the EEA from paper to electronic form, it was desired that the large number of documents recorded only in paper form be included in the electronic database. The format of the printed database used in the original version of the EEA prevented the developers from designing a new record format based on user needs or preferences. Reformatting of the entire collection of records in the EEA to follow a new record format was considered to be an excessive expenditure of time and money, so the new database was designed to work with the original record format of the EEA. Because of this, the EERC database record format is largely identical to other standard database record formats, such as those of FIREDOC, the ASCE database, and the Engineering Village (see Chapter 4).

The EERC database allows users to search for any combination of the following:

- Author Name;
- Document Title;
- Keywords; and
- Year of Publication.

The software that resides at the heart of this database closely follows the American National Standards Institute (ANSI) accredited, National Information Standards Organization (NISO) approved standard database record format, known as ANSI/NISO Z39.50. The standard format includes options for additional record fields beyond those listed above. When the EERC database was implemented electronically on the Internet, the decision was made to hide the majority of these record fields from the general user. It was felt that limiting the record format in this way would produce a fast and efficient search and would avoid undue complications for the user while supporting much of the existing structure of the EEA [16].

5.1.1.3 Database Maintenance

The EERC, in addition to originally implementing the EEA database on the Internet, is also charged with the task of keeping the database current. Each year, between 6,500 and 10,000 new records are added. Selected documents are entered into the system on a daily basis using proprietary software developed within the EERC. A single editor, who is supervised by the EERC librarian, performs the majority of such maintenance.

Since its original inception, the EEA database has maintained a policy of selectivity in the addition of new records. Potential documents are screened for applicability to the fields of structural and geotechnical engineering for earthquakes, as well as engineering seismology. In general, the topics of geology, geophysics, and pure seismology are not included in the database because the database is not oriented toward practitioners of these sciences, but rather to civil engineers practicing earthquake engineering of structures (buildings, highway components, earth structures, etc.). The purpose of the database is to aid in the design of structures for protection against earthquakes, so the topics covered by the database are limited to the functions performed during the earthquake engineering process. This selective nature is a common aspect of the EEA database and the fire-robust structural engineering database developed here.

5.1.2 Conclusion

The Earthquake Engineering Abstracts database is a highly specialized system catering to a specific portion of the design, research, and education communities. It was conceived at a time when the available computing power greatly limited the development of a customized, user-friendly database interface. The database's original inception in paper form was based on a standard library records format. In order to avoid the loss of valuable previously catalogued records, the Internet version of the database was also developed using a standard library record format, unlike various other databases (including FIREDOC and the fire-robust design database developed here) for which record formats were tailored to the needs and preferences of potential users. The selective nature of the EEA database ensures that appropriate information is available to the target audience. This is also a goal of the fire-robust design database.

5.2 Goals of the Proposed Information Management System

While the fire-robust structural engineering process can greatly aid in the design of fire-safe structures, the informational demands for use of the process are significant. Much like the traditional structural design process, where various regulations and design aids are frequently utilized to provide information such as methodologies, parameter values, and other forms of guidance, the fire-robust design process requires that the engineer have sources for numerous types of information. For example, a structural engineer, having performed an analysis of a structural design exposed to a defined design fire, may need guidance in defining failure criteria against which the observed performance can be measured.

Successful implementation of the fire-robust structural engineering process in the engineering community depends on the availability of information covering the topics included in the process. Engineers who cannot obtain the required information will not be able to utilize the process. The goal of the information management system (IMS) being developed here is to help ensure that structural engineers can find sources for filling informational needs experienced during the fire-robust structural engineering process such that they can successfully incorporate the process into their design procedures.

It is intended that the user will interact with the IMS by focusing a search on individual functions of the FRSE process. As the user requires information on a given function, the user will interact with the IMS by choosing to search for resources providing information viewed as specifically valuable to that function. This functional system design will most efficiently deliver appropriate information to the engineer, and will reduce the amount of time and effort required to sort through possible resources.

To achieve the general goal of allowing for the use of the fire-robust structural engineering process by providing sources of information, a series of more specific goals have been defined.

a) The IMS should be designed to specifically serve the needs of structural engineers performing fire-robust design activities.

b) The IMS should hold records relating to the specific functions performed during the fire-robust structural engineering process.

c) Record information should be accurately recorded to help ensure that the presence of all valuable information in a given resource is noted by the record format.

d) Records should be presented to the users of the IMS in such a way as to make apparent the range of functions covered, as well as the level of coverage provided, by each individual reference.

e) For the fire-robust structural engineering process to be widely accepted and utilized, the IMS must be made widely available.

Goals a) through d) have been directly addressed by this thesis. The subsequent sections in this chapter discuss the ways in which achievement of these goals has been approached. Goal e) has been left as future work. In order to make the IMS widely available, implementation on the Internet would likely be necessary. This would require a large amount of effort and support, and lies beyond the scope of this thesis. However, Chapter 8 includes a discussion of the foreseen future of the IMS and possibilities for its worldwide use.

5.3 Record Format

Given the functional basis of this information management system and its specialized goals, a standard record format, such as those discussed in Chapter 4, cannot be used. The goals of the system require the accurate and thorough description of the ways a resource provides information that is useful to the fire-robust structural engineering process. In order for a function-based search to be performed, resources must be classified according to the functions they cover. The record must also interact correctly with the functional search process. For these reasons, the specialized record format described here has been developed. Note that the record format is independent of the IMS architecture, and has been designed to efficiently deliver a full description of the information that a given record can provide to an engineer for use in the fire-robust structural engineering process. Certain aspects of the database architecture, as will be described in Section 5.4, will be designed to interact with the record format defined here.

In general, the fire-robust structural engineering information management system's record format includes three main parts. Each record includes the following:

- a full bibliographic reference,
- a series of descriptors designed to characterize the content, and
- a full text summary.

When combined, the three components listed above fully describe a reference and its contents in terms of application to fire-robust structural engineering. The search mechanism of the system utilizes the second component by looking for records listed as containing given types of content. The other two components are included to provide the system's users with a full description of each resource. The three components listed above are described in detail in the following sections.

5.3.1 Bibliographic Reference

Each record includes a full bibliographic reference designed to provide the user with all information necessary to identify the source. A traditional bibliographic format has been followed for this portion of the record. At this time, the information management system (like many other database systems) is not designed as a direct link between the user and the viewable versions of the referenced documents. Future upgrades may potentially include such capabilities, but the present design relies on the availability of library catalogs and the like as sources for access to referenced publications.

Each bibliographic reference includes the fields listed below in Figure 5.1, where applicable:

Bibliographic Reference Fields

Author Name(s)
Title
Journal/Magazine Title
Conference Title
Volume
Release, Edition or Version
Type of Document
Place of Publication
Publisher
Publication Date
Language
Page Count

Figure 5.1. Bibliographic Reference Fields

A standard bibliography format has been adopted for this portion of the record format. An example of such a bibliographic reference is included below in Figure 5.2.

Johann, M. Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions. Thesis Report. Worcester, MA: Worcester Polytechnic Institute. December, 2002.

Figure 5.2. Example Bibliographic Reference

The goals of the information management system do not require that the individual portions of the bibliographic references be individually searchable. The primary search mechanism will not directly utilize any part of the bibliographic references. However, an author search feature will be made available to increase the functionality of the system. If desired, a user will be able to view the records of documents included in the fire-robust structural engineering database based on individual authors.

5.3.2 Resource Descriptors

The key to the functional search mechanism used here is a series of descriptive topics that correspond to specific functions included in the fire-robust structural engineering process. During a query, the IMS searches for records containing content that has been characterized by the descriptor(s) corresponding to the given function. When input into the database; each reference is reviewed for applicability to one or more of these topics.

Two types of topic descriptors are used in this information management system. They can be generally described as follows:

- Primary topics, and
- Secondary topics

These two types of topics are discussed in detail below.

5.3.2.1 Primary Topics

Primary topics are used directly by the search mechanism of the information management system. The range of primary topics is intended to cover all functions needed to carry out the fire-robust structural engineering process. When the system is called upon to provide resources on a given function, it will do so by identifying individual resources that have been categorized using descriptor topics corresponding to that function (see Section 5.4 for details of the system architecture).

Primary topics are divided into six general headings, corresponding to the general functions of the fire-robust structural engineering process. These headings are:

- Structural Design Fire Specification
- Structural Fire Analysis
- Local Structural Response
- Global Structural Response
- In-Service Conditions
- Member Protection

The general headings are the titles of the five process flowcharts presented in Chapter 3, with the exception of *Member Protection*, which is not represented by a dedicated flowchart but is still considered to represent an independent category of topics.

All functions in the fire-robust design process fall within the bounds represented by the above headings. Note that the list does not include the heading “Traditional Structural Design.” As mentioned previously, this database is not intended as a resource for the traditional structural design process, since such resources are widely available. The headings listed above correspond to the separate tasks that must be carried out subsequent to the traditional design process in order to produce a fire-robust design.

Each primary heading includes a series of primary topics that cover the scope of that heading. These topics are derived directly from the specific functions performed during each phase of the fire-robust structural engineering process. See Section 3.2 for a detailed discussion of the individual functions (primary topics) in the fire-robust structural engineering process. Because the engineer may require information on any or all of the functions used during the fire-robust structural engineering process, the information management system must include references to cover the entire range of functions. To accomplish this, references are classified based on their applicability to individual functional topics included in the design process. Each function in the fire-robust design process is considered to be a topic to which resources may apply. Included references provide information that is useful to one or more of the functions in the fire-robust structural engineering process. The matrix in Figure 5.3 shows these primary topics organized based on the primary headings to which they apply.

Note that the entry “Not Covered” in the matrix shown in Figure 5.3 is a placeholder used by the system to make apparent a record’s lack of information on the corresponding general heading of topics.

	Primary Topics					
	Structural Design Fire Specification	**Structural Fire Analysis**	**Local Structural Response**	**Global Structural Response**	**In-Service Conditions**	**Member Protection**
Possible Categorizations	Computational Fluid Dynamics Models	Basic Principles	Calculation of Deformation	Load Redistribution	Inspection	Board/Slab Protection
	First Principle Equations	Finite Element Analysis	Calculation of Collapse Loads	Progressive Collapse	Statistics and Failure Rates	Spray-On Protection
	First Principle Computer Models	Spreadsheet Applications	Connections	Excessive Deformation	Impact of Pre-Fire Event	Membrane Ceilings
	Compartment Fire Tests		Shear	Global Failure Criteria Definition	Post-Fire Conditions	Flame Shield
	Fuel Load Calculation		Local Buckling	Performance and Risk Economics		Concrete Encasement
	Regulations		Lateral Torsional Buckling			Heat Sink
	Ventilation Effects		Column Buckling			
	Statistics		Web Crippling			
	Variability		Spalling			
	Performance and Risk Economics		Charring			
	Safety Factors		Combined Stresses			
			Local Failure Criteria Definition			
			Performance and Risk Economics			
			Crushing			
	Not Covered	Not Covered	Not Covered	Not Covered	Not Covered	Not Covered

Figure 5.3. Primary Topic Descriptors

5.3.2.2 Secondary Topics

In addition to the primary topics discussed above, a series of secondary topics that provide additional information regarding the content of a given resource are also included in the database. These secondary topics are used by the system in identifying possible resources in certain instances (such as when searching for information on analysis of specific materials or types of members), but are primarily included in the record format to provide the user with an additional level of understanding of the content of a resource. The system includes four secondary topic headings.

- General Focus of Document;
- Type of Structural Material;
- Type of Element; and
- Data Presented.

The heading *General Focus of Document* is included to summarize the content of a resource. Because the system identifies resources based on individual functions, it does not utilize the summary field in the search process. This helps to ensure that a record identified as a potential resource for a specific functional topic (e.g. Finite Element Analysis, etc.) will contain information that is appropriate to that topic. The system searches for records classified as providing information on that specific function, rather than identifying records containing topics under the same general heading as the function being explored. The record format includes the heading *General Focus of Document* simply to make the scope of a resource apparent to the user. Refer to Figure 5.4 for a list of the topics included under the heading *General Focus of Document*.

Because different structural materials generally require different concerns for analysis and design, the heading *Type of Structural Material* is included in the system. This heading, which includes the fields *steel*, *concrete*, *wood*, and *composite*, is utilized by the system in the identification of resources that are appropriate to the structural materials of interest. These headings will also help the user decide among various possible resources by showing the breadth of a resource's coverage (i.e. focused coverage of a single material versus general coverage of multiple materials). Note that the term *composite* is used in the initial version of the IMS to represent any combination of materials composing a single structural element or assembly. Future versions of the IMS will likely include more specific coverage of different combinations of materials.

The heading *Type of Element* allows the user to specify the type of structural member under consideration such that appropriate resources can be identified. This is crucial since different types of stresses are of concern for different types of members. For example, drastically different information is required to analyze a concrete column than is needed to analyze a steel truss. The system allows the user to identify the type of member being analyzed (see Figure 5.4 for a list of possible member types). Coupling of this feature with the identification of material type, as discussed above, allows the system to present the user with resources that are appropriate to the specific structural configuration being considered.

The final secondary heading is *Data Presented*. This heading group allows the system to identify the types of information provided by the included resources. This allows the user to make decisions about the utility of possible resources based on the function being performed. The *Data Presented* heading includes useful topics such as material properties, which are generally needed for the functions of the fire-robust structural engineering process. Identification of sources for this information is a crucial step in the design process. Figure 5.4 includes the complete list of topics listed under this heading.

Again, the entry “Not Covered” in the matrix shown above is a placeholder used by the system to make apparent a record’s lack of information on the corresponding general heading of topics.

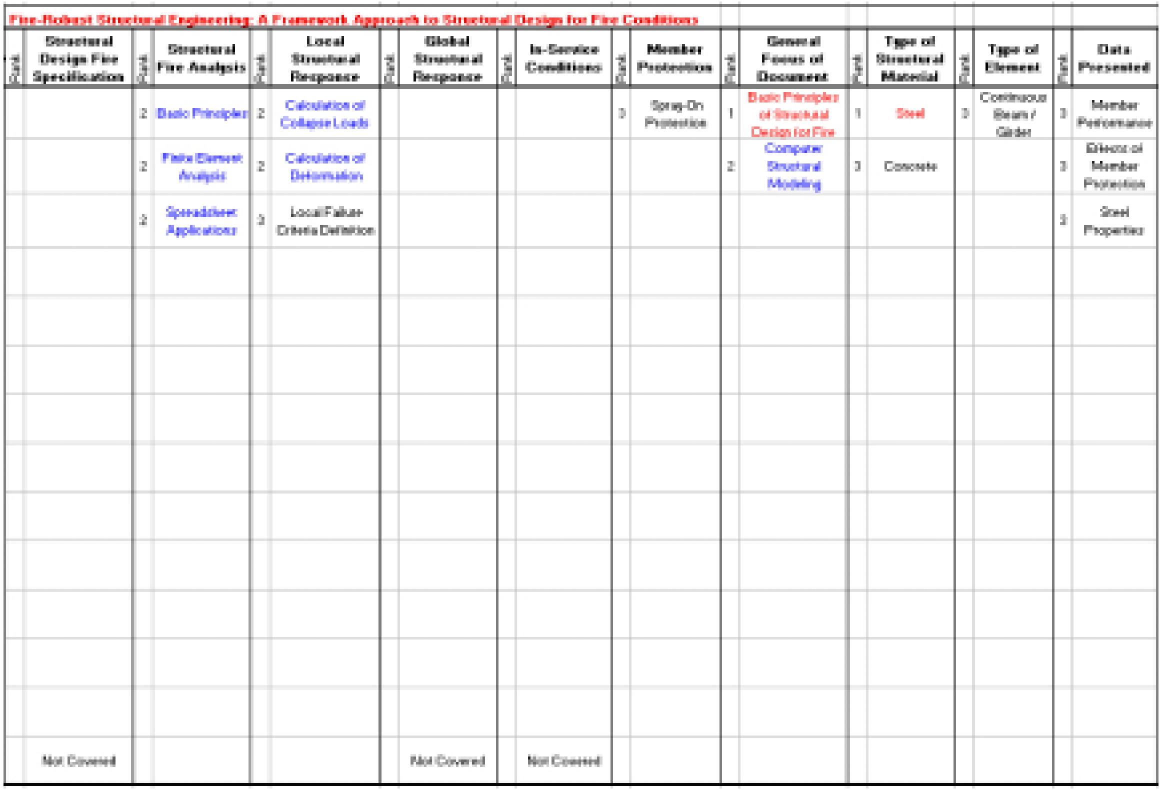
	Secondary Topics			
	General Focus of Document	Type of Structural Material	Type of Element	Data Presented
Possible Categorizations	Basic Principles of Structural Design for Fire	Steel	Rigid Frame	Member Performance
	Steel Design for Fire	Concrete	Braced Frame	Protection Material Properties
	Concrete Design for Fire	Wood	Simple Beam / Girder	Effects of Member Protection
	Wood Design for Fire	Combination of Materials	Continuous Beam / Girder	Steel Properties
	Protection of Members		Column	Concrete Properties
	Computer Structural Modeling		Connections	Wood Properties
	Computer Fire Modeling		Floor / Ceiling Assembly	Boundary Material Properties
	Material Properties		Truss	
	Standard Test Methods		Roof Assembly	
	Failure Modes		Slab	
	Design Criteria			
	Risk and Decision Making			
		Not Covered	Not Covered	Not Covered

Figure 5.4. Secondary Topic Descriptors

Classification of a resource involves recording all topics, both primary and secondary, for which the resource provides information. The user is presented with a summary of these applicable topic descriptors in the record format. Additionally, topics are ranked according to their coverage in a given resource. This is accomplished with a numbered ranking scheme that is implemented at the time of original record compilation. In this scheme, Level 1 topics represent the primary focus or strongest points of the given resource. Level 2 topics are considered to be secondary, but are still strongly covered. Level 3 topics are considered to be ancillary information included to supplement the primary and secondary topics. This extra information may not represent complete coverage of a function, but may still provide useful information. This ranking scheme allows the user to identify strong sources for a given topic. For example, assume two different resources are identified during a search on a given topic. If that topic is listed as a Level 2 topic in the first record and a Level 1 topic in the second, then the user would likely choose the latter because the topic is more thoroughly covered in that document. Note that rankings are not made in relation to information contained in other documents, but instead only to the other information covered by the document in question.

For rapid identification of ranking levels during review of records, the ranking levels are also color coded in the record format. Level 1 topics are presented in red text, Level 2 topics are presented in blue text, and Level 3 topics are presented in black text. Since this color-coding scheme cannot be used if records are printed using a black-and-white printer, the record format also includes level numbers (1, 2, or 3) to the left of each topic descriptor.

An example of a resource categorized using the primary and secondary topics discussed above is included in Figure 5.5.



Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions

Rank	Structural Design Fire Specification	Rank	Structural Fire Analysis	Rank	Local Structural Response	Rank	Global Structural Response	Rank	In-Service Conditions	Rank	Member Protection	Rank	General Focus of Document	Rank	Type of Structural Material	Rank	Type of Element	Rank	Data Presented
		2	Basic Principles	2	Calculation of Collapse Loads					3	Spray-On Protection	1	Basic Principles of Structural Design for Fire	1	Steel	3	Continuous Beam / Girder	3	Member Performance
		2	Finite Element Analysis	2	Calculation of Deformation							2	Computer Structural Modeling	3	Concrete			3	Effects of Member Protection
		2	Spreadsheet Applications	3	Local Failure Criteria Definition													3	Steel Properties
	Not Covered						Not Covered		Not Covered										

Figure 5.5. Example Reference Categorization

5.3.3 Document Summary

While not used directly by the search mechanism of the information management system, a full text summary is a key component of this record format. A primary goal of this record format is the efficient and complete delivery of references to the fire-robust structural designer, and the summaries help the system meet this goal. While, in general, the series of descriptors used to characterize a given document, as discussed above, fully describes the content of the document and is a necessary part of the system architecture, document summaries provide the majority of the benefit for the user.

The example used in the previous two subsections is extended below in Figure 5.6 to provide an example of a document summary registered in the information management system.

> Presented is a functional framework for the integration of fire protection concerns into the structural design process. The process of producing a "fire-robust structural design" is described in detail. Technical aspects of the computations and analyses involved in this process are not covered in depth, but the roles of these functions in the design process are described. An exploration of previously available information search tools reveals the lack of an efficient means for finding the information needed by the engineer during the fire-robust structural design process. A new function-based information management system designed to cope with this problem is proposed and developed in detail. Future possibilities for the expansion of this system are offered. Lastly, a model study comparing different computer-based methods for calculating structural member performance during fire is included. Conclusions regarding the level of computational complexity required to achieve reasonably accurate predictions of fire performance are included.

Figure 5.6. Example Reference Summary

Once a user has been presented with a series of references that are appropriate to the function for which the user is seeking information, the document summaries presented with each record are the primary decision tools for choosing appropriate references. Each summary will describe the range of information included in the corresponding document, allowing the user to get a sense of the information available within a given document when considering from a series of possible resources.

The summaries included in this information management system are not intended to be traditional abstracts. In some ways they are expanded abstracts, but they may be more accurately described as concise executive summaries. Each document summary includes the following details:

- Topics covered (scope);
- Levels (ranking) of topic coverage;
- Methodology;
- Primary conclusions.

The author of this thesis has compiled the summaries for all records included in the initial version of the information management system. These summaries are not intended as opinions or reviews of the included references, but rather concise overviews of the information provided within each. Future additions to the list of references included in the system will likely be made through author submissions using a standard submission form (see Section 6.4). In this case, the authors of individual documents will be responsible for supplying reference summaries.

No part of the summary included with each record is searchable. By utilizing the descriptors discussed in Section 5.3.2, the functional search mechanism will generally result in a limited number of possible resources, each of which relates to the topic of interest in some way. The full text summaries can then be used to determine the ultimate utility offered by each reference in regard to the topic of interest.

5.4 System Architecture

Due to the specialized nature of the fire-robust structural engineering IMS, it is difficult to use a standard database format as the foundation for the system. To accomplish the goals of the system, as discussed in the previous section, queries for different functions must utilize specific search algorithms, each of which may differ from those of the other functions covered. The system must interact with a specific portion of the record format described in Section 5.3 for each different query. This means that a single search algorithm cannot be applied to all queries. The system must be specialized in order to serve the user efficiently.

The IMS is being implemented as a modified object-oriented database. Such a database uses various controls to define how a query is carried out in a given situation. Records in an object-oriented database are assigned identifiers and stored based on these identifiers. During a query, buffers and other controls are used to limit a search to a given function. A traditional object-oriented database is shown in Figure 5.7 (adapted from [19]).

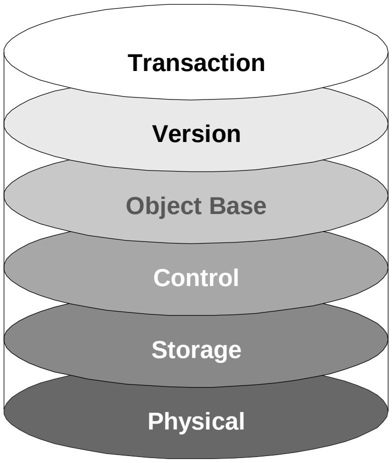


Figure 5.7. Traditional Object-Oriented Database Architecture

In the above figure, the various layers serve the following functions:

- The *Physical* layer represents a storage medium (disc, hard drive, etc.) on which data is saved.
- The *Storage* layer defines different objects based on identifiers and locates data on the *Physical* layer based on these identifiers
- The *Control* layer groups objects and controls buffering and other storage activities.
- The *Object Base* layer provides definitions for different objects, thus allowing for object-based queries.
- The *Version* layer allows for parallelism of activities by managing different versions of objects.
- The *Transaction* layer allows execution of multiple concurrent transactions by different users.

The first version of the fire-robust design IMS is not intended for use by multiple users concurrently. This means that the *Version* and *Transaction* layers are not needed. However, a layer is needed to control user input and organize it based on the function being explored. The traditional object-oriented database structure has been modified as shown in Figure 5.8.

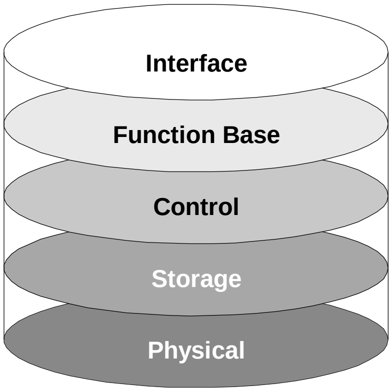


Figure 5.8. Modified Object-Oriented Database

In the modified architecture, the layers serve the following functions:

- The *Physical* layer represents a storage medium (disc, hard drive, etc.) on which data is saved.
- The *Storage* layer defines different objects based on identifiers (record descriptors), and allows the system to search for records based on these identifiers
- The *Control* layer defines provides a given query with the corresponding search algorithm to achieve a given search objective.
- The *Function Base* layer provides definitions for different objects (functions performed during the fire-robust structural engineering process), thus allowing for function-based queries.
- The *Interface* layer allows the user to initiate queries based on the functions defined by the *Function Base* layer.

During a query, the system starts at the top (*Interface*) layer, where the user initiates the query by choosing a function to explore. The system then defines an appropriate search algorithm based on the chosen function, and determines which objects (record descriptors, see Section 5.3.2) characterize records that are appropriate to that function. The IMS next searches specific portions of the data stored in the *Physical* layer and identifies records that have been labeled with the previously defined descriptors. These records are then displayed to the user. This procedure is outlined in Figure 5.9.

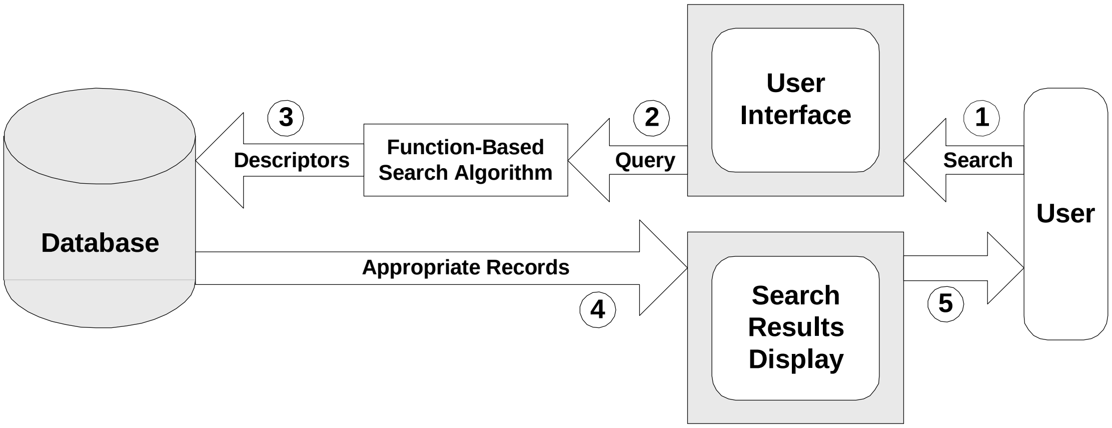


Figure 5.9. IMS Search Process

5.5 Computer Implementation

The initial version (Version 1.0) of the IMS has been implemented using the spreadsheet program Excel®, available from Microsoft. Excel was chosen for its ease of data entry and because of the author's familiarity with the Visual Basic® programming language, which can be used to develop macros in Excel. In Excel, macros are programs that automate tasks within a given spreadsheet. Version 1.0 of the IMS makes extensive use of Excel macros to:

- prompt for user input;
- perform search-and-retrieve functions;
- sort records based on user input; and
- present search results to the user.

The macros interact with the content of a source worksheet, where all records are listed according to the record format described in Section 5.4. The other worksheets in the IMS comprise the user interface.

The interface of the IMS is based directly on the fire-robust design process and the functions therein. When implemented in computerized form, the graphical user interface includes the process flowcharts first introduced in Chapter 3. This interface is necessary because the IMS performs a unique search for each different function involved in the fire-robust structural engineering process. The function-based architecture helps ensure that resources identified by a query are appropriate to the specific function under consideration. This feature also helps eliminate the need to systematically remove inappropriate records from a list of possible resources resulting from a simpler search. A highly efficient search results from this functional architecture.

As efficient as the IMS architecture is in theory, it relies heavily on accurate description of documents through the record format defined in Section 5.3. This is true of all database systems: a database cannot correctly identify a possible reference if that reference has not been accurately described by the record format. The IMS record format developed here is highly specific and is designed to help an author or IMS maintenance official register all topics in a given reference that relate to the fire-robust structural engineering process.

As mentioned previously, the architecture of the IMS is based directly on the five flowcharts used to define the fire-robust structural engineering process (refer to Chapter 3). Correspondingly, the IMS includes five separate interfaces, one for each flowchart. Each function in these flowcharts represents an individual and highly specific search action. These actions may include:

- Linking to different locations within the five interface flowcharts;
- Prompting for additional information (such as material or element type); and
- Performing a search of recorded documents and presenting possible resources.

Provided below is a description of the query actions corresponding to each individual function in the fire-robust structural engineering process.

The primary and secondary topic headings that were introduced previously in the discussion of the record format used for this database (see Section 5.3.2) each sit at the top of a column of topic descriptors. For the purpose of describing the computer implementation of the IMS, these columns have been numbered from left to right in the topic matrices shown in Figures 5.3 and 5.4. The headings are numbered as follows:

Column 1: Structural Design Fire Specification
Column 2: Structural Fire Analysis
Column 3: Local Structural Response
Column 4: Global Structural Response
Column 5: In-Service Conditions
Column 6: Member Protection
Column 7: General Focus of Document
Column 8: Type of Structural Material
Column 9: Type of Element
Column 10: Data Presented

Figure 5.10. Descriptor Matrix Column Numbers

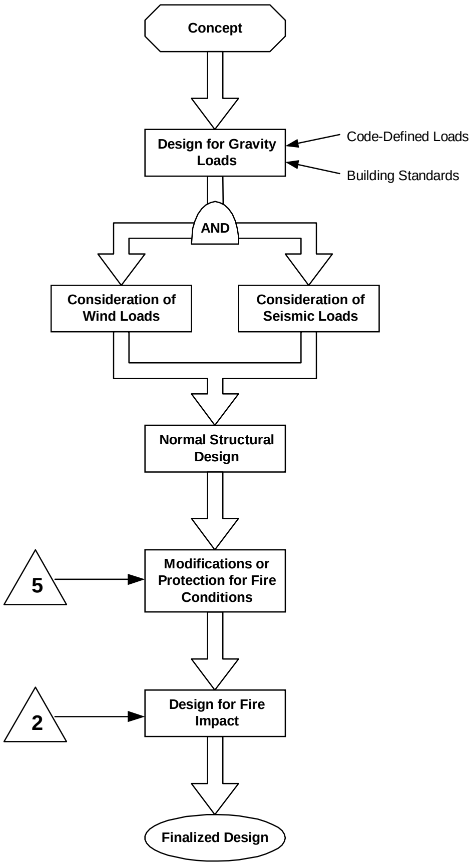


Figure 5.11.Fire-Robust Structural Design

Normal Structural Design

All tasks in Chart 1 up to and including *Normal Structural Design* are intended to be carried out according to accepted structural design standards and regulations. These tasks are not covered by this information management system.

Modification or Protection for Fire Conditions

- Link to Chart 5

Design for Fire Impact

- Link to Chart 2

Finalized Design

Finalized Design indicates a design that shows acceptable performance under the predicted fire conditions. In practice, this step includes finalization of the design drawings and written specifications as in the traditional design process. The information management system developed here does not include references to this task.

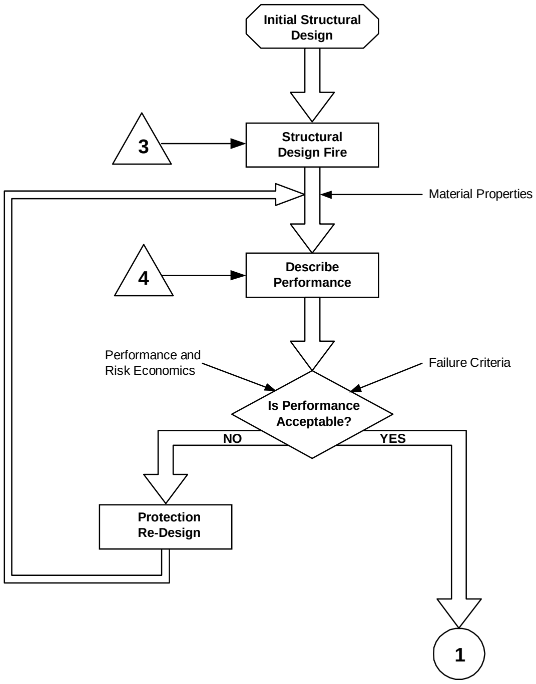


Figure 5.12.Structural Fire Analysis

Structural Design Fire

- Link to Chart 3

Material Properties

- Choose Material Type
  - Steel: Search Column 10 for *Steel Properties*
  - Concrete: Search Column 10 for *Concrete Properties*
  - Wood: Search Column 10 for *Wood Properties*
  - Protection Materials: Search Column 10 for *Protection Material Properties*
  - Boundary Materials: Search Column 10 for *Boundary Material Properties*

Describe Performance

- Link to Chart 4

Failure Criteria

- Choose Local or Global Failure Criteria
  - Local: Search Column 4 for Local Failure Criteria Definition
  - Global: Search Column 5 for Global Failure Criteria Definition

Performance and Risk Economics

- Choose Local or Global Response
  - Local: Search Column 3 for *Performance and Risk Economics*
  - Global: Search Column 4 for *Performance and Risk Economics*

Protection Re-Design

- Choose Protection Type
  - Board/Slab: Search Column 6 for *Board/Slab Protection*
  - Spray: Search Column 6 for *Spray-on Protection*
  - Membrane Ceilings: Search Column 6 for *Membrane Ceilings*
  - Flame Shield: Search Column 6 for *Flame Shield*
  - Concrete Encasement: Search Column 6 for *Concrete Encasement*
  - Heat Sink: Search Column 6 for *Heat Sink*

Finish

- Link to Chart 1

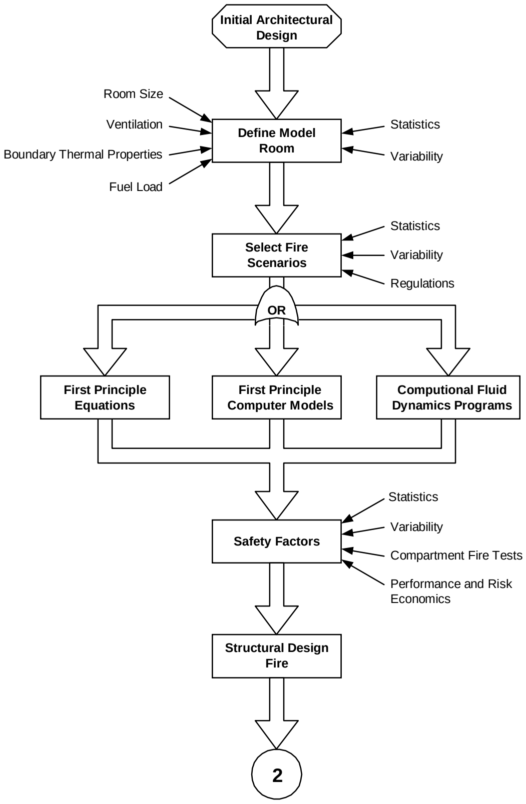


Figure 5.13. Structural Design Fire Quantification

Define Model Room

- ➢ Choose Factor
  - Room Size: No Search
  - Ventilation: Search Column 1 for *Ventilation Effects*
  - Boundary Thermal Properties: Search Column 10 for *Bound. Therm. Props.*
  - Fuel Load: Search Column 1 for *Fuel Load Calculation*
  - Statistics: Search Column 1 for *Statistics*
  - Variability: Search Column 1 for *Variability*

Select Fire Scenarios

- ➢ Choose Factor
  - Statistics: Search Column 1 for *Statistics*
  - Variability: Search Column 1 for *Variability*
  - Regulations: Search Column 1 for *Regulations*

First Principle Equations

- ➢ Search Column 1 for *First Principle Equations*

First Principle Computer Models

- ➢ Search Column 1 for *First Principle Computer Models*

Computational Fluid Dynamics

- ➢ Search Column 1 for *Computational Fluid Dynamics Models*

Safety Factors

- ➢ Search Column 1 for *Safety Factors*
- ➢ Choose Factor
  - Statistics: Search Column 1 for *Statistics*
  - Variability: Search Column 1 for *Variability*
  - Compartment Fire Tests: Search Column 1 for *Compart. Fire Tests*
  - Performance and Risk Economics: Search Column 1 for *Performance and Risk Economics*

Structural Design Fire

- ➢ No Search

Finish

- ➢ Link to Chart 2

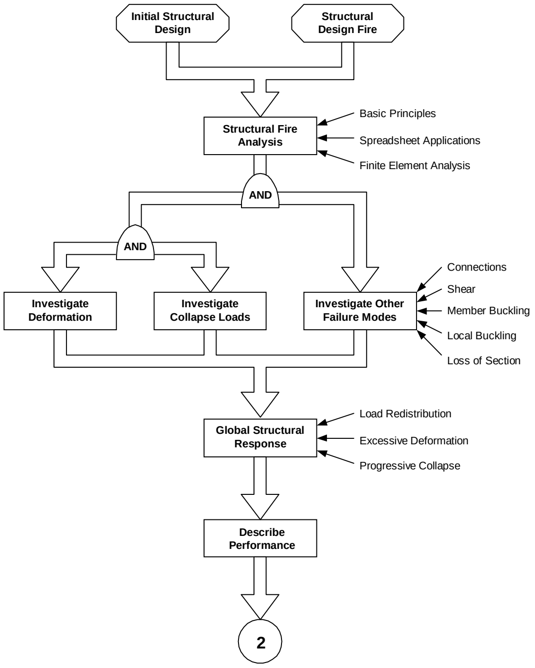


Figure 5.14. Structural Fire Performance Identification

Structural Fire Analysis

- ➢ Choose Methodology
  - <u>Basic Principles</u>: Search Column 2 for *Basic Principles*
  - <u>Spreadsheet Applications</u>: Search Column 2 for *Spreadsheet Applications*
  - <u>Finite Element Analysis</u>: Search Column 2 for *Finite Element Analysis*

Investigate Deformation

- ➢ Choose Material Type
  - <u>Steel</u>: Search Column 8 for *Steel*
  - <u>Concrete</u>: Search Column 8 for *Concrete*
  - <u>Wood</u>: Search Column 8 for *Wood*
  - <u>Combination of Materials</u>: Search Column 8 for *Combination of Materials*
- ➢ AND Choose Element Type
  - <u>Rigid Frame</u>: Search Column 9 for *Rigid Frame*
  - <u>Braced Frame</u>: Search Column 9 for *Braced Frame*
  - <u>Simple Beam/Girder</u>: Search Column 9 for *Simple Beam/Girder*
  - <u>Continuous Beam/Girder</u>: Search Column 9 for *Continuous Beam/Girder*
  - <u>Column</u>: Search Column 9 for *Column*
  - <u>Connections</u>: Search Column 9 for *Connections*
  - <u>Floor/Ceiling Assembly</u>: Search Column 9 for *Floor/Ceiling Assembly*
  - <u>Truss</u>: Search Column 9 for *Truss*
  - <u>Roof Assembly</u>: Search Column 9 for *Roof Assembly*
  - <u>Slab</u>: Search Column 9 for *Slab*
- ➢ AND Search Column 3 for *Calculation of Deformation*

Investigate Collapse Loads

- ➢ Choose Material Type
  - <u>Steel</u>: Search Column 8 for *Steel*
  - <u>Concrete</u>: Search Column 8 for *Concrete*
  - <u>Wood</u>: Search Column 8 for *Wood*
  - <u>Combination of Materials</u>: Search Column 8 for *Combination of Materials*

- AND Choose Element Type
    - Rigid Frame: Search Column 9 for *Rigid Frame*
    - Braced Frame: Search Column 9 for *Braced Frame*
    - Simple Beam/Girder: Search Column 9 for *Simple Beam/Girder*
    - Continuous Beam/Girder: Search Column 9 for *Continuous Beam/Girder*
    - Column: Search Column 9 for *Column*
    - Connections: Search Column 9 for *Connections*
    - Floor/Ceiling Assembly: Search Column 9 for *Floor/Ceiling Assembly*
    - Truss: Search Column 9 for *Truss*
    - Roof Assembly: Search Column 9 for *Roof Assembly*
    - Slab: Search Column 9 for *Slab*
- AND Search Column 3 for *Calculation of Collapse*

Investigate Other Failure Modes

- Choose Material Type
    - Steel: Search Column 8 for *Steel*
    - Concrete: Search Column 8 for *Concrete*
    - Wood: Search Column 8 for *Wood*
- AND Choose Element Type
    - Rigid Frame: Search Column 9 for *Rigid Frame*
    - Braced Frame: Search Column 9 for *Braced Frame*
    - Simple Beam/Girder: Search Column 9 for *Simple Beam/Girder*
    - Continuous Beam/Girder: Search Column 9 for *Continuous Beam/Girder*
    - Column: Search Column 9 for *Column*
    - Connections: Search Column 9 for *Connections*
    - Floor/Ceiling Assembly: Search Column 9 for *Floor/Ceiling Assembly*
    - Truss: Search Column 9 for *Truss*
    - Roof Assembly: Search Column 9 for *Roof Assembly*
    - Slab: Search Column 9 for *Slab*
- AND Choose Failure Mode
    - Shear: Search Column 3 for *Shear*
    - Local Buckling: Search Column 3 for *Local Buckling*

- <u>Lateral Torsional Buckling</u>: Search Column 3 for *Lateral Torsional Buckling*
- <u>Column Buckling</u>: Search Column 3 for *Column Buckling*
- <u>Web Crippling</u>: Search Column 3 for *Web Crippling*
- <u>Combined Stresses</u>: Search Column 3 for *Combined Stresses*
- <u>Spalling</u>: Search Column 3 for *Spalling*
- <u>Charring</u>: Search Column 3 for *Charring*

Note: See later in this section for a discussion about how specific failure modes are linked to different material and element types.

Global Structural Response

- ➢ Choose Failure Mode
  - <u>Load Redistribution</u>: Search Column 4 for *Load Redistribution*
  - <u>Excessive Deformation</u>: Search Column 4 for *Excessive Deformation*
  - <u>Progressive Collapse</u>: Search Column 4 for *Progressive Collapse*

Describe Performance

- ➢ No Search

Finish

- ➢ Link to Chart 2

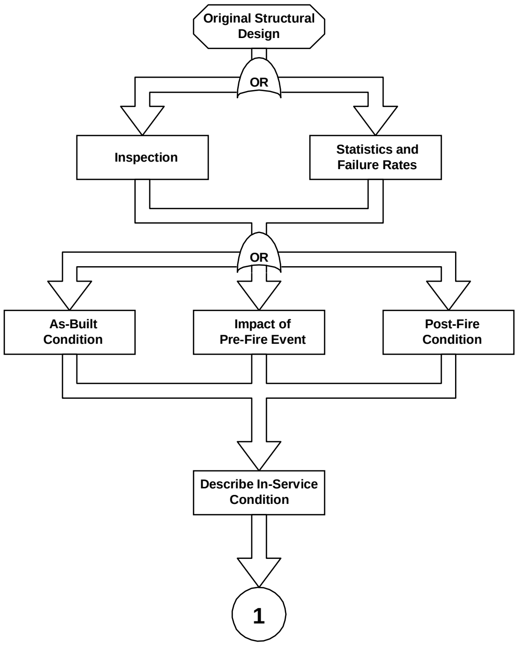


Figure 5.15. In-Service Condition Identification

Inspection

- Search Column 5 for *Inspection*

Statistics and Failure Rates

- Search Column 5 for *Statistics and Failure Rates*

As-Built Condition

- No Search

Impact of Pre-Fire Event

- Search Column 5 for *Impact of Pre-Fire Conditions*

Post-Fire Conditions

- Search Column 5 for *Post-Fire Conditions*

Many of the queries described above are very simple in form: when a given function is chosen, the IMS searches available records for coverage of that function. An example of this is the function “Computational Fluid Dynamics” within the *Structural Design Fire Quantification* flowchart. Initiation of a query for this function would simply instruct the IMS to search available records for the topic “Computational Fluid Dynamics Models” in Column 1 of the topic matrix. This simplest query is designated Order 1.

Not all queries are this simple, however. The next higher level of complication involves a choice between various options available to perform a given function. The figure below shows how a Level 2 query is structured.

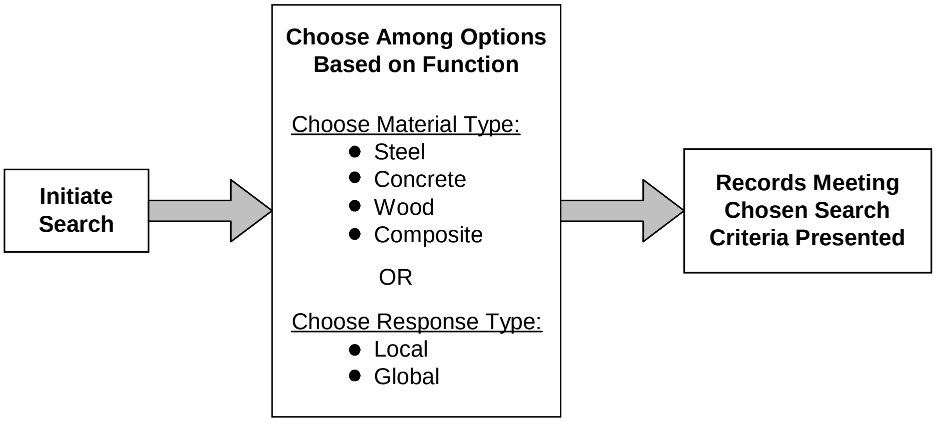


Figure 5.16. Level 2 Query Structure

Second Order queries are used in the *Structural Fire Analysis* flowchart for the functions “Material Properties,” “Failure Criteria,” and “Performance and Risk Economics.” Initiation of a query of the former prompts the user to choose which material type property data is needed for, while a query of the latter two topics asks the user to identify whether local or global response is being considered.

More complicated than Order 2 queries are Third Order queries, which are used with the *Structural Fire Performance* flowchart. Because different materials and element types may respond to fire conditions in different ways, the IMS must be prompted as to the material and element type of concern in order to identify appropriate records. For instance, a concrete column (compression member) will react to elevated temperatures in different ways than would a steel column, and different design and analysis considerations would be necessary for each. The functions "Investigate Deformation" and "Investigate Collapse Loads" both require that the user specify material type and structural element type. The results of a Third Order query are limited by the input of the user. For example, a user exploring the investigation of collapse loads in steel columns will be prompted to input these details. The system first collects all records including the topic "Investigate Collapse Loads," then, from this refined list, collects all records including the topic "Steel." Lastly, records covering the topic "Column" are collected from the second refined list. The user is then presented with records that have been categorized with the topic "Investigate Collapse Loads" in Column 3 of the topic matrix, the topic "Steel" in Column 8, and the topic "Column" in Column 9. The structure of a Third Order query is shown below.

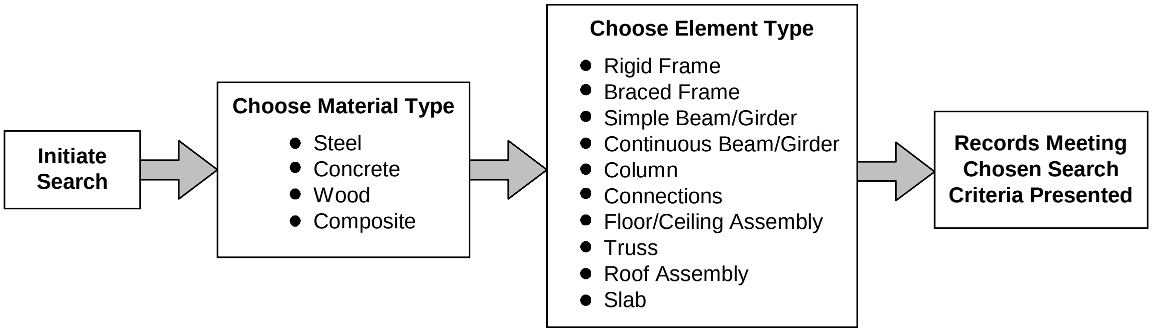


Figure 5.17. Level 3 Query Structure

The most complicated query type (Order 4) is utilized with the *Structural Fire Performance Identification* flowchart. The function "Investigate Other Failure Modes" can be used to identify failure modes that are of concern to different combinations of structural material and elements. Like an Order 3 search, the IMS prompts the user to specify material and element types. The system then uses the user's input to identify the failure mechanisms that are of interest. The user can choose from these and can obtain resources detailing how to analyze those failure mechanisms. The Figures 5.18 through 5.21 detail the algorithms used by the system to identify failure mechanisms that are of concern for different material/element type configurations.

Appendix D includes walk-through examples of search tasks with different orders of query complexity.

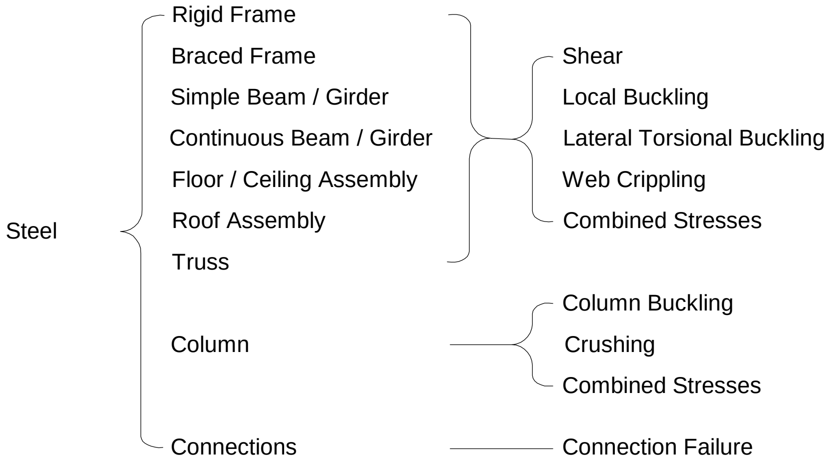


Figure 5.18. Other Failure Modes for Steel Members

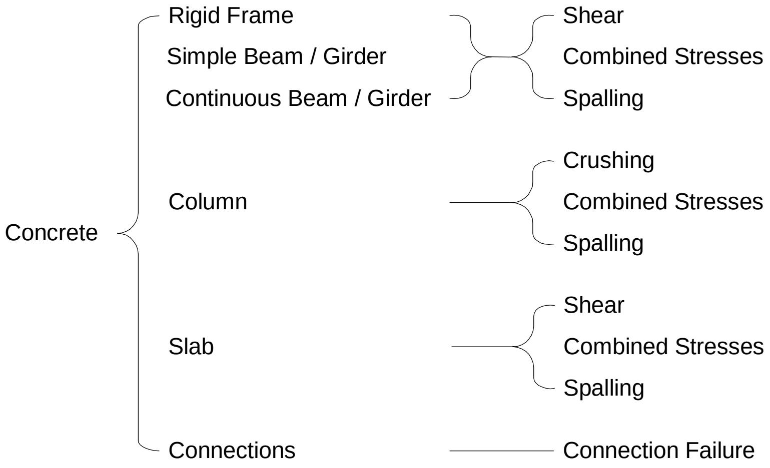


Figure 5.19. Other Failure Modes for Concrete Members

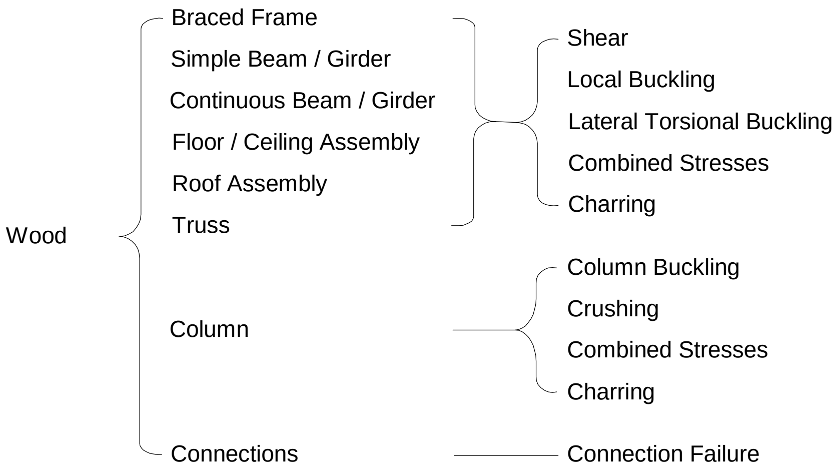


Figure 5.20. Other Failure Modes for Wood Members

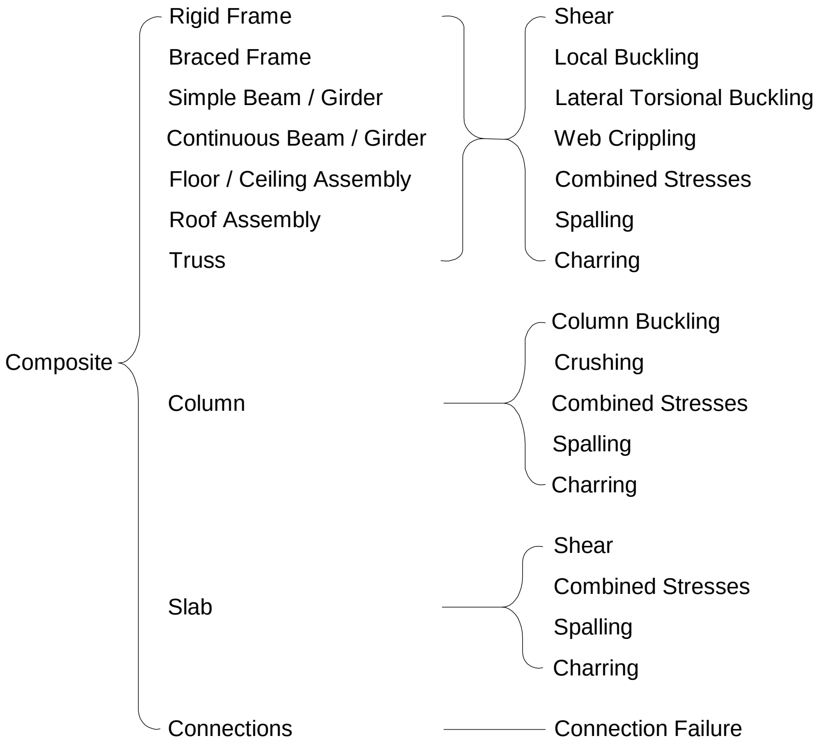


Figure 5.21. Other Failure Modes for Composite Assemblies

5.6 User Interface

The user interface of the IMS must accomplish two main goals:

- Clear description of the fire-robust structural engineering process; and
- User accessibility to all functions of the fire-robust structural engineering process.

The IMS accomplishes the first goal by including an interface that is based directly on the flowcharts developed to describe the fire-robust structural engineering process. The main interface consists of five different pages corresponding to the five FRSE flowcharts. This allows the user to follow the FRSE process during the search process, and points out functions that should be considered during different portions of the process. Additionally, the user can hover the cursor over any function within the FRSE process in order to display a definition or description of the given function. In these ways, the flowcharts tutor the user on the process of fire-robust structural engineering and identify the concerns and consideration that must be taken into account at each juncture in the process. This helps to ensure that the engineer will consider all necessary topics when performing a given function, and also allows the engineer to efficiently obtain references for these topics.

The latter goal listed above is also accomplished by basing the interface on the fire-robust structural engineering flowcharts. Within the charts, each function covered by the IMS is represented by a link that can be navigated by the user. Each link takes the user to a different portion of the process, prompts for additional information, or performs a search. Because all functions necessary to carry out a fire-robust design (excepting those tasks included in the traditional structural design process) are represented as links that result in queries, all functions are accessible to the user. The engineer can navigate the fire-robust structural engineering process through the flowcharts, stop at any function for which information is needed, and perform an appropriate query to identify sources for this information.

Screenshots of the IMS are included in Appendix C.

Appendix D includes walk-throughs of example search tasks to demonstrate the use of the FRSE IMS.

6 RESOURCE COLLECTION

Now that the full architecture of the information management system has been developed and the record format has been defined, the database will be partially filled with a series of documents. This activity will show how records are input into the system, how the record format supports function-based searching and record retrieval, how the system presents records to the user, and how resources can be accurately represented by the proposed record format.

6.1 Methodology for Identifying Potential Resources

While the information search tools discussed in Chapter 4 may not be ideal for frequent use in the practice of fire-robust structural engineering, they are useful here for identifying resources to include in the new information management system. By expending the effort required to sort through available resources now, less effort will be required of fire-robust structural designers during daily design work.

This thesis does not attempt to compile all available references that may be appropriate to the fire-robust structural engineering process. Instead, the information management system developed here will include a limited number of resources that are intended to demonstrate the architecture of the system and to show the benefit of the function-based approach to resource management. Full implementation of the system will require further compilation of resources, as well as author cooperation through the resource submittal form discussed in Section 6.3. Moreover, some level of support from technical committees, industrial organizations, and/or government agencies will be required to accomplish full public implementation.

For this thesis, potential resources for inclusion in the database have been identified in three primary ways: Internet-based databases, computer program documentation, and contact with individuals or groups active in the structural fire protection industry.

6.1.1 Resource Identification through Available Databases

The resources necessary to perform a fire-robust structural design originate from both the structural engineering community and the fire protection engineering community. Certain functions may only be covered by one of these disciplines, while information on other functions may be available from both. Because of this, two different Internet-based search mechanisms have been utilized here to ensure that work of both communities is taken into account. The fire protection engineering industry's contribution has been accessed through NIST's FIREDOC. Structural engineering resources have been identified using ASCE's Civil Engineering Database (CEDB). For some functions, only one of these databases may be utilized (for example, resources for most topics dealing with design fire specification are generally identified using FIREDOC). In other cases, resources may be identified using both databases (as in the case of the spalling of concrete).

Queries that resulted in appropriate resources were documented in files that also contain the bibliographic information for these resources. Query details include all search fields utilized. In most cases, simple searches utilizing primary and limiting search terms were used. These terms were based on the specific function being considered and the general heading that the function applies to.

6.1.2 Resource Identification through Computer Model Documentation

Because it is the current technology that allows advanced analysis of structural frameworks exposed to fire conditions, it is important that structural engineers have access to resources to guide them in the use of advanced analytical tools. Several types of information are necessary for the complete understanding and the appropriate use of advanced analytical models. These include:

- Users' manuals;
- Technical reference guides;

- Comparative or validation studies;
- Parametric studies of models; and
- Guidance resources.

The authors of the computer codes generally write users' manuals and technical reference guides. They are often provided with their associated programs at the time of purchase or download from the Internet. Depending on the complexity of the model and analytical approach, users' manuals and technical reference guides can be substantial, but they often contain large amounts of information about the appropriate use of the programs. Frequently, examples of correct usage are included in these documents. Computer models designed to predict structural behavior or fire conditions should never be used without first studying the accompanying literature, as this is how the author conveys to the user the correct ways to utilize the model and obtain appropriate results.

The documentation accompanying computer programs often contains references to works used in the creation of these programs. These works can contain valuable guidance on the workings of the model implemented by the code, and can often aid in the successful and correct use of these models.

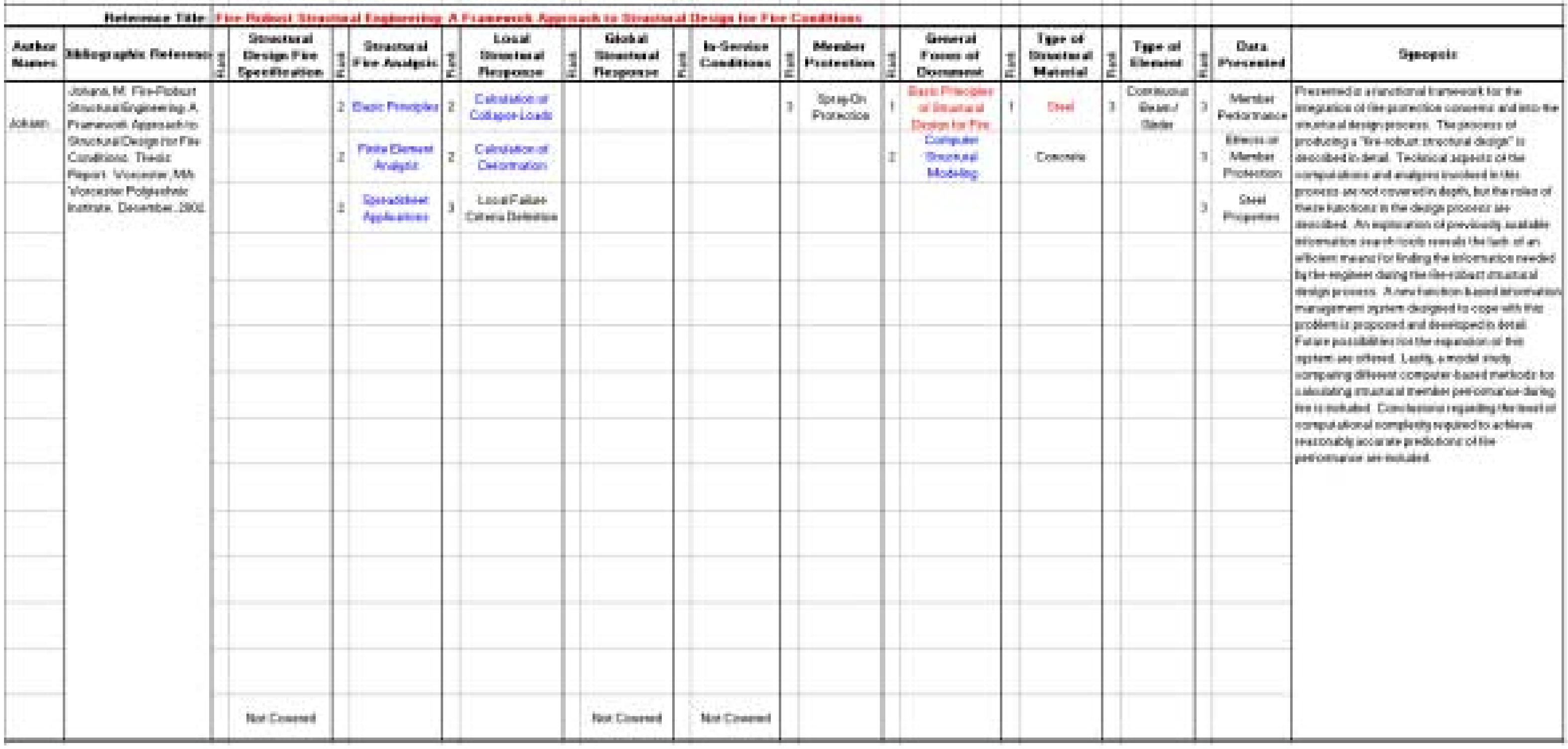
Any model that is developed and offered for general use by the engineering community must be validated before it can be thought of as appropriate for the situations it attempts to model. Validation can come in many forms, including comparison of models to physical tests, to other calculation methods, and to phenomena observed during real events (such as fires). Similarly, parametric studies are often performed to determine model sensitivities and appropriate ranges of values for given parameters, as well as levels of confidence in predicted behavior. Studies such as these can result in many resources that give guidance to the user of a particular computer model. These can generally be identified through the use of available search mechanisms, such as FIREDOC and the CEDB. In the fire-robust structural engineering process, which depends heavily on the use of technology to predict complicated structural behavior, the engineer must have access to all of these types of resources in order to use these tools appropriately.

6.1.3 Resource Identification through Contact with Active Engineers

In the modern research environment, new research is constantly under way, new documents are produced extremely often. Only a portion of these reports are officially published and reach the general engineering community. Because of this, many valuable resources may not be available to the engineer. A database that truly links active engineers with state-of-the-art research information must include non-published resources. While the field of fire protection is moderately small compared to other engineering disciplines, it is constantly growing. Communication between its members is vital in distributing information, and the implementation of the FRSE IMS must take advantage of the flow of information between individuals. Authors will be requested to submit useful information for possible inclusion in the database, and word-of-mouth regarding both current research accomplishments and the existence and objectives of the database will be relied upon to help make unpublished resources available.

6.2 Methodology for Compiling Resource Details

In order to make the collection of records as efficient as possible, a spreadsheet has been developed for use during the resource compilation process. This spreadsheet is based on the record format described in Section 5.3 and allows for the organization of bibliographic information, resource descriptors, and a summary abstract for each record. The compilation of record information in a spreadsheet form ensures that each record is recorded in the same way and that the same information is recorded for every record. It also allows the records to be directly fed into the initial version of the information management system, which is also implemented using a spreadsheet application. An example of a compiled record is provided in Figure 6.1.



Reference Title: Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions

Author Names	Bibliographic Reference	Rank	Structural Design Fire Specification	Rank	Structural Fire Analysis	Rank	Local Structural Response	Rank	Global Structural Response	Rank	In-Service Conditions	Rank	Member Protection	Rank	General Focus of Document	Rank	Type of Structural Material	Rank	Type of Element	Rank	Data Presented	Synopsis
Johann	Johann, M. Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions. Thesis Report. Worcester, MA: Worcester Polytechnic Institute. December, 2002.			2	Basic Principles	2	Calculation of Collapse Loads					3	Spray-On Protection	1	Basic Principles of Structural Design for Fire	1	Steel	3	Continuous Beam / Girder	3	Member Performance	Presented is a functional framework for the integration of fire protection concerns and into the structural design process. The process of producing a "fire-robust structural design" is described in detail. Technical aspects of the computations and analyses involved in this process are not covered in depth, but the roles of these functions in the design process are described. An exploration of previously available information search tools reveals the lack of an efficient means for finding the information needed by the engineer during the fire-robust structural design process. A new function-based information management system designed to cope with this problem is proposed and developed in detail. Future possibilities for the expansion of this system are offered. Lastly, a model study comparing different computer-based methods for calculating structural member performance during fire is included. Conclusions regarding the level of computational complexity required to achieve reasonably accurate predictions of the performance are included.
				2	Finite Element Analysis	2	Calculation of Deformation							2	Computer Structural Modeling		Concrete			3	Effects of Member Protection	
				2	Spreadsheet Applications	3	Local Failure Criteria Definition													3	Steel Properties	
			Not Covered						Not Covered		Not Covered											

Figure 6.1. Example Compiled Record

As can be seen in the example record above, all components of the record format are efficiently organized in the spreadsheet. Note that resource descriptors are listed in columns under their respective headings. The portion of the spreadsheet including the ten columns headed by the primary and secondary topic headings is the heart of the information management system search mechanism. The system uses these columns to identify resources that are appropriate for a given function. Accurate classification of resources based on these descriptors is critical.

The spreadsheet utilizes drop-down menus to allow the user to choose among the descriptors available under each primary and secondary heading. These drop-down menus are linked directly to the descriptor matrix presented in Section 5.3.2. Note also that the descriptors are color-coded. Those topics listed in red are considered to be the primary foci of the given document. Red topics are covered in depth. Descriptors listed in blue are also considered to be important topics that are covered well in the document. Topics listed in black are ancillary information included in the document that may be useful to the engineer but are not the foci of the document itself.

An important benefit of the spreadsheet form is the ability to expand the compilation file to include many resources. Adding new resources simply requires copying a blank entry field and inputting the resource's information. The initial version of the information management system can be easily adapted to scan large numbers of records over numerous worksheets in the resource compilation spreadsheet.

6.3 Blank Form for Resource Submittal by Authors

Once full implementation of the information management system has been achieved, the most efficient means of ensuring that the system includes current information is to allow authors to submit their work themselves, rather than requiring staff to review and record new records. For this purpose, a three-page form has been developed to allow an author to compile and submit a full record of a new resource. Upon submittal, support staff can easily add resources characterized using this form to the information management system because the input fields of the form are based on the record format fields. This requires minimal effort by system support staff. Also, by allowing the author to compose the document summary and choose appropriate resource descriptors from amongst those identified in the record format, the true intent of the given document will be conveyed in the record.

Not all records submitted using this form will automatically be added to the database. Some review by support staff will be required to ensure that the resource is appropriate for the fire-robust structural engineering process.

The resource submittal form is provided in Appendix E.

7 MODEL STUDY – COMPARISON OF ANALYTICAL METHODS

7.1 Introduction

Due to the relatively high level of activity in the development and advancement of analytical methods for the study of structural response to fire conditions in recent decades, the engineer has access to a wide range of different tools for the analysis of structural members exposed to fire. Some of these tools, such as laboratory fire tests, have been used extensively for over half a century. Others, such as advanced numerical methods, are still in their infancy in terms of widespread use in the structural fire protection field. Empirical tests and advanced numerical methods represent two different ends of a spectrum encapsulating numerous analytical approaches.

To properly utilize the various analytical methods available to them, structural engineers need an understanding of these different methods. In addition to guidance in utilizing specific analytical methods and choosing appropriate parameter values, the structural engineer also requires an understanding of the input requirements and the accuracy of the various analytical methods in order to make an informed decision regarding which method is appropriate for a given situation. A library of comparative studies, for example, is a resource that could aid the structural engineer in making such decisions. These studies can make evident the benefits and limitations inherent in a certain analytical method when applied to a given structural configuration, and thus can help the engineer select an appropriate analytical method. Moreover, these studies can provide insight into the level of analytical sophistication required to use a given analytical method. The FRSE Information Management System is designed to be populated by resources, such as comparative studies, which can directly aid the structural engineer in performing the functions of the FRSE process.

This chapter illustrates and discusses the use of three different methods for determining or predicting the response of individual structural members to the high temperature conditions experienced during a compartment fire. These methods are: laboratory fire tests, theoretically-based spreadsheet applications, and advanced finite element models. The response of a structural steel beam subjected to a standard fire time-temperature curve (ASTM E119 Standard Fire Test Method) [20], is the focus of this study. From this comparison, conclusions are drawn regarding the accuracy of the latter two methods in replicating the actual response observed in fire tests and the level of analytical sophistication required to obtain results that predict the actual structural response with reasonable accuracy.

7.1.1 Goals of the Study

The two primary goals of this study are to explore analytical methods of varying levels of sophistication and to gauge their predictions against data obtained in laboratory fire tests. The fire tests were not carried out specifically for this study, but instead were drawn from the work of Professor Richard Bletzacker of Ohio State University [21]. Although the tests were conducted more than 35 years ago, their documentation is extensive, making them excellent candidates for use in studying analytical methods. By comparing the structural response predicted by spreadsheet applications and finite element computer programs to the data obtained in the fire tests, one can begin to draw conclusions regarding the accuracy with which these numerical methods simulate the empirical tests.

As a third goal, the model study is also intended to elaborate on the informational needs of the FRSE process. To fully comprehend structural fire behavior and to be able to best utilize the fire-robust engineering process, similar activities must be carried out to cover any gaps in the range of informational needs. The informational gaps must be filled by research, some of which has already been performed by others and is available to the structural designer, and some of which is yet to be performed by present and future engineers. This leads to the ultimate goal of contributing to the design of truly fire-safe structures.

One approach to incorporating analysis tools of varying levels of complexity into the design environment may be to categorize these tools in relation to each other and their applicability to different structural or architectural configurations. To this end, the different methodologies discussed herein have been chosen as representative of three different levels of analysis. Extrapolation of results from established empirical fire tests, such as those carried out by Bletzacker, will be defined here as *Level I* analysis. In a Level I analysis, observations of structural behavior in laboratory tests or in service in an existing building are used to draw general conclusions regarding structural performance. Often, sufficient conclusions can be drawn from empirical approaches to deem a member or assembly's performance acceptable. However, especially in the design of new buildings, costly laboratory tests are not a realistic approach to determining the performance of numerous structural elements.

The next higher level of analytical complexity is represented by *Level II* analysis. Spreadsheet applications based on theoretical relationships and correlations fall under this category. Such applications can be used as first-order approaches for determining expected structural performance of members or assemblies. These approaches, once implemented in spreadsheet form, do not require large amounts of time to use, and can often give reasonable approximations of real structural response. Additionally, configuration-specific laboratory testing is a Level II analysis technique. In the general structural design environment, such tests are often prohibitively expensive.

Some structural configurations may be too complex for accurate analysis through Level II approaches. Also, situations arise in which a greater level of analytical detail and certainty than can be provided through Level II approaches are desired. In this case, a higher level of analytical complexity, *Level III*, may be required. Advanced numerical methods, such as finite element models, fall into this category. They require more time, effort, and expertise to use, but they are capable of analyzing complex geometries and providing high levels of detail in predicting structural performance.

7.1.2 Relevance of the Work

During the fire-robust structural engineering process, the engineer must make decisions regarding the level of analysis required by different members and assemblies. This chapter explores the use of methods representative of these different levels of analysis in an effort to guide the engineer in this decision process. This is accomplished by demonstrating the use of Level II and Level III analytical methods and comparing the results obtained through each to published laboratory test data (Level I information).

The conclusions that have been drawn based on the modeling activities undertaken here may be of great benefit to the teaching and practice of FRSE. With numerous tools available for the analysis of structural components exposed to fire, some guidance is needed to choose appropriate analysis methods for different configurations. The structural engineer does not generally have time to explore the use of two or three completely different methodologies to predict the response of a single member or assembly. While such an analysis regimen would tend to provide bounds for the behavior that could be expected in the field, the time required to carry out the various analyses would be prohibitive in the modern structural design environment. Therefore, this study is designed to provide some level of insight into the accuracy of various analytical methods such that the engineer can decide on appropriate tools without actually carrying out multiple analyses.

7.1.3 Scope of the Study

The study is limited to a single structural member type. Complete understanding of the analysis of various structural configurations will require focused studies of the analysis of individual types of members or assemblies (local structural response) and subsequent exploration of their interaction with one another (global structural response). This study looks at various methods of analyzing simply supported beams exposed to fire conditions. The results of this study and other similar studies of the behavior of other types of structural components may eventually lead to a library of studies that will serve as a resource for the teaching and practice of FRSE.

Additionally, the model study is limited to performance-based methodologies. Analysis techniques that can be used to predict the performance of members exposed to elevated temperature conditions are explored, while code specifications and prescriptive standards are not taken into account. The FRSE process is a performance-based technique, and this study is designed to benefit the users of this process.

Due to constraints on the availability of computer and software resources, analytical tools used herein are limited to two examples. Numerous finite element analysis programs are available in the engineering marketplace. This study utilizes the program LS-DYNA [22] as a representative finite element code. Results obtained using this program can be considered illustrative of finite element programs in general, as most are based on similar element formulations and equation-solving techniques.

The spreadsheet application utilized in this study is based on the methods of Pettersson and Magnusson [23]. They provide in-depth guidance for the analysis (using basic principles and correlations) of structural steel members exposed to fire. The techniques presented in this reference are considered representative of available basic techniques for the analysis of steel structural members exposed to fire conditions.

Consistent with the tests presented by Bletzacker {21}, the model studies are limited to the analysis of a structural steel beam. In addition, the assumed fire conditions are based on the ASTM E119 standard fire curve [20], since Bletzacker used the standard fire curve to control the furnace in his laboratory tests.

7.2 Beam Performance Determination Using Laboratory Fire Tests

All information provided in this section originates from Bletzacker's final report, dated September 1966 [21]. The fire test program involved a series of twelve tests on various configurations of protected steel beams. The research was designed to determine the effects of end restraint (support conditions) on the fire performance of floor and roof assemblies supported by structural steel beams. Various levels of restraint were used and the effects of these on time to failure of the assembly were determined. Bletzacker's report provides extensive data from the tests, including deflection, end rotation, strain, and time to failure measurements.

For the purposes of this thesis, one test will be chosen from the test program and the given configuration will be modeled using two different analytical methods. The performance predicted by the analytical tools will be compared to the actual performance observed in the fire tests.

Note that Bletzacker's work makes frequent reference to the ASTM E119 Standard Test Method, 1965 version. For the purposes of this thesis, the most recent version of this Standard, published in 2000, is used here. Comparison of the two versions shows that the goals and procedures of the Standard Test Method have not changed over the 35-year span, and key details such as the standard fire time-temperature curve have remained unchanged.

7.2.1 Goals of the Test Program

The test program was originally carried out with the purpose of determining the effects of end restraint applied to protected structural steel beams in the ASTM E119 Standard Fire Test. In some cases, the restraint conditions were also applied to the concrete slabs supported by the steel beams. Bletzacker theorized that different levels of end restraint could result in drastically different levels of performance under ASTM E119 conditions. Inconsistencies in fire resistive performance had been noted in comparisons of tests results of different, yet essentially identical assemblies [21]. While variations in materials, construction details, and assembly loading conditions were recognized as factors affecting fire performance, Bletzacker postulated that the end restraint generated by the support assembly used in the test had the greatest effect on fire endurance.

End restraint of assemblies in the ASTM E119 test is applied at the perimeter of the assembly being tested as a result of the framing of the support structure and the tolerances allowed in fitting assemblies into this support structure. According to the ASTM E119-00 Standard, Section 35.3, assemblies should be supported and restrained during a test in such a way that would be typical of actual building conditions during a fire. Bletzacker developed a test program to explore the significance of the level of end restraint actually achieved by the test assembly in the determination of a member or assembly's fire endurance.

7.2.2 Test Setup

This section describes the apparatus and test assembly used in one portion of Bletzacker's test program (Test B7). Refer to Bletzacker [21] for detailed descriptions of the different tests carried out in this program.

7.2.2.1 Apparatus

The test assembly described in the next section was mounted within a test furnace designed to conduct standard fire endurance tests, such as that described in ASTM E119 [20]. The furnace was constructed of masonry materials, and included a burner fed with an unspecified flammable gas. Gas flow to the burner was controlled in order to achieve temperatures corresponding to the desired time-temperature curve (see Figure 7.8).

A concrete-filled, structural steel restraining frame was mounted on top of the furnace enclosure. This restraining frame was designed to apply end restraint forces, as appropriate to any given test configuration. For fixed-end conditions, the steel frame was utilized as the primary restraint for the opposition of end rotation and axial thrust. To strengthen the frame, 1-3/8 in. diameter steel rods were installed between two sides of the frame and parallel to the test beam. These steel rods exerted restraining forces against a matched pair of heavy steel girders, which in turn transferred the restraining forces to the furnace frame. A section view of these furnace modifications is shown in Figure 7.1.

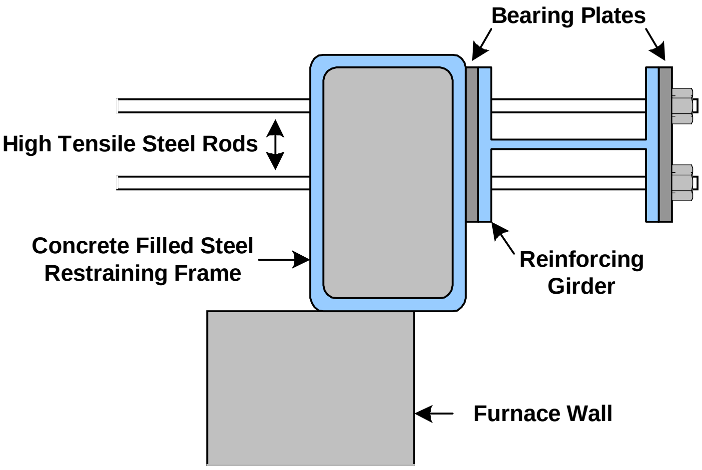


Figure 7.1. Furnace Modifications (Section View – Not to Scale)

7.2.2.2 Test Assembly

The beam-and-slab assembly used in the test is shown below in Figure 7.2

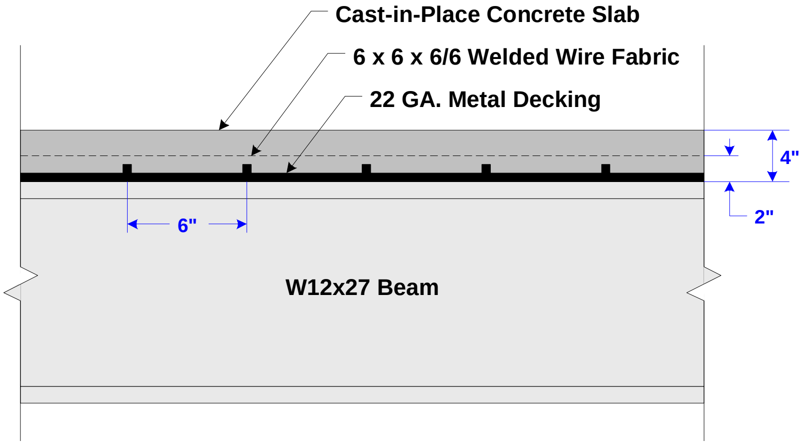


Figure 7.2. Test Assembly (Elevation View – Not to Scale)

For this test, the assembly was constructed as pseudo-composite [21]. Pseudo-composite construction refers to the tack welding of the metal decking supporting the concrete slab to the top flange of the supporting steel beam. This type of construction is representative of normal field practice, although it is typically considered to be non-composite from a design standpoint because true composite action is not guaranteed, i.e. there is relatively little resistance to slip between the concrete slab and the steel beam. Factors such as tack weld strength and consistency of weld quality determine the degree to which composite behavior is actually achieved in the field. A section of the test assembly is shown in Figure 7.3.

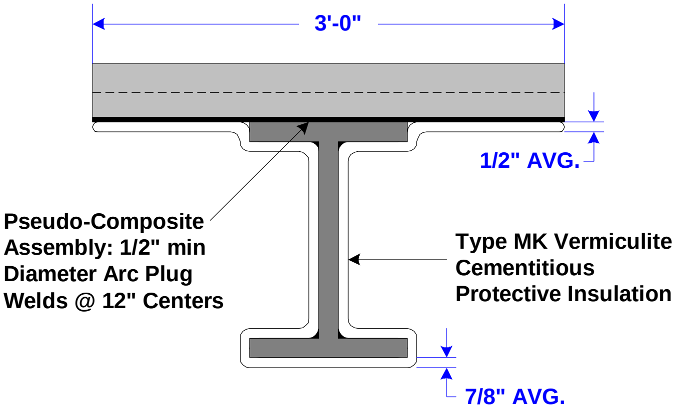


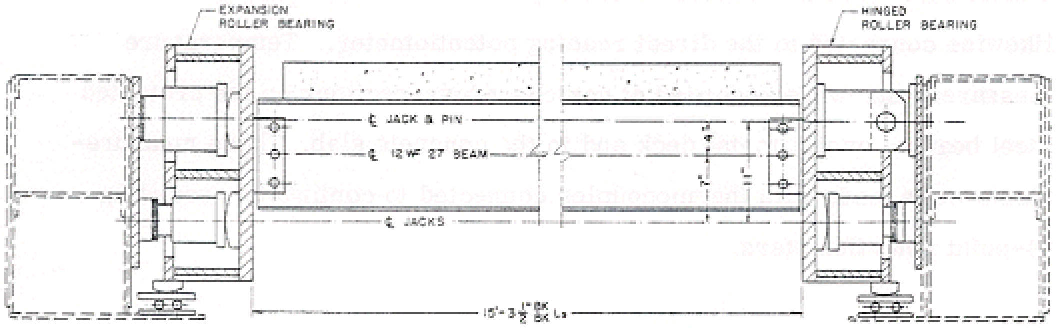
Figure 7.3. Test Assembly (Section View – Not to Scale)

7.2.2.3 Member Protection

The exposed steel surfaces of the test assembly, including the underside of the metal decking, were sprayed with a vermiculite cementitious mixture as a protective insulation. The protective material is known in the industry as Type MK fire insulation. According to the test report [21], insulation thickness on the underside of the metal decking averaged approximately 1/2" in. The insulation was applied in a slightly thicker layer over the steel beam, where it averaged 7/8 in. thick. According to Bletzacker, the insulation was applied according to the standards of practice provided by the Vermiculite Institute, and "the thickness of the insulation was chosen to provide simulated fire exposures in the range of 1-1/2 to 2-1/2 hours, and solely for the convenience of the test program" [21].

7.2.2.4 Beam Support and Restraint

Figure 7.4, taken from Bletzacker [21], shows the support assembly used in the laboratory test.



Bletzacker, 1966

Figure 7.4. Beam Support and End Restraint Assembly

The test assembly was supported within the furnace by a jacking frame constructed of heavy-gauge steel members. A set of three hydraulic rams was used to provide varying levels of end restraint. A matched pair of 100-ton hydraulic rams was mounted symmetrically 4 in. above the midheight of the beam at one end of the beam. A pair of heavy steel pins were mounted directly opposite the 100-ton jacks at the other end of the beam. Two matched pairs of 50-ton hydraulic rams were mounted 7 in. below the beam's midheight. This assembly allowed the control of end restraint against end rotation and expansion parallel to the axis of the beam. Changes in the hydraulic force required to prevent end rotation and elongation were monitored and used to calculate the axial thrust resulting from expansion of the beam during the test.

The beam was attached to the supports using AISC B-Series bolted clip angle connections. At each end, the steel beam was cut back ¼ in. from the back of the connection angles. This connection is shown in Figure 7.5.

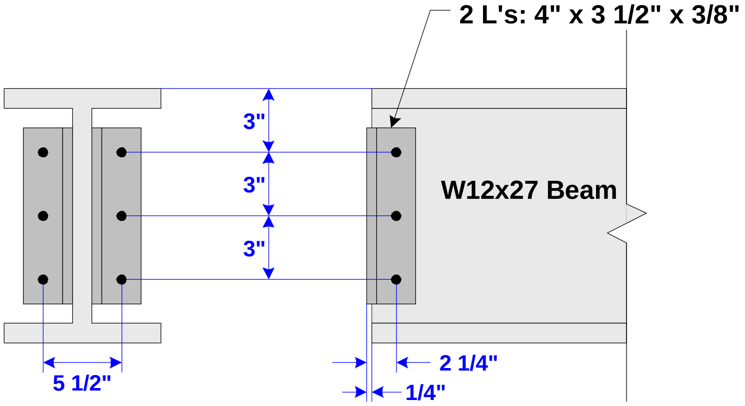


Figure 7.5. Beam Connection Details (Not to Scale)

7.2.2.5 Assembly Loading

In addition to the gravity loads associated with the test assembly and the axial forces applied to the beam ends in an effort to resist end rotation and elongation, a pair of concentrated loads was also applied to the slab. These superimposed loads were applied in order to load the steel beam to its theoretical bending capacity based on the provisions of allowable strength design [21]. For the pseudo-composite, restrained configuration, which is assumed to be non-composite in most design standards, the required vertical loads were calculated as 13,300 lbs (59.2 kN). These loads were applied using a pair of matched hydraulic rams mounted above the test assembly, as shown in Figure 7.6.

Calculation of the stresses within the steel beam resulting from the load configuration shown in Figure 7.6 reveal that the maximum stress occurs in the bottom flange, with a value of 24 ksi (167 MPa) [21]. Based on AISC specifications [10], the theoretical design allowable stress is given as $0.66F_y$, where F_y is the yield strength of the steel, in this case 36 ksi (250 MPa). Thus, the allowable design stress of the steel beam is 0.66 x 36 ksi, or 24 ksi (167 MPa), and the beam is loaded to its theoretical design stress capacity.

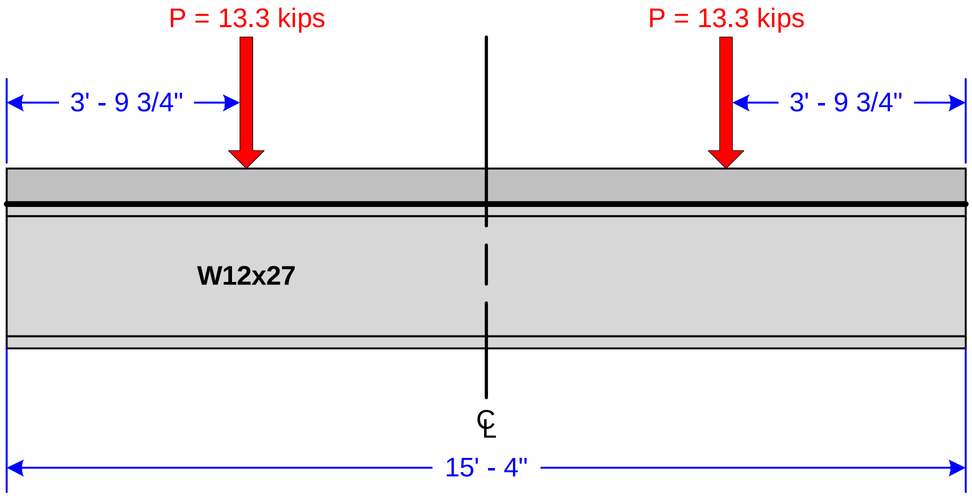


Figure 7.6. Assembly Loading in Laboratory Test (Not to Scale)

7.2.2.6 Instrumentation

Temperature conditions during the tests were measured using Chromel-Alumel wire thermocouples installed at various locations within the furnace and along the test assembly. Thermocouples located on the beam were installed at the mid-height of the protected beam's web for the purpose of measuring surface temperatures. Additional thermocouples were installed to monitor various critical points in the test apparatus, including the jacking frame and high-tension rods.

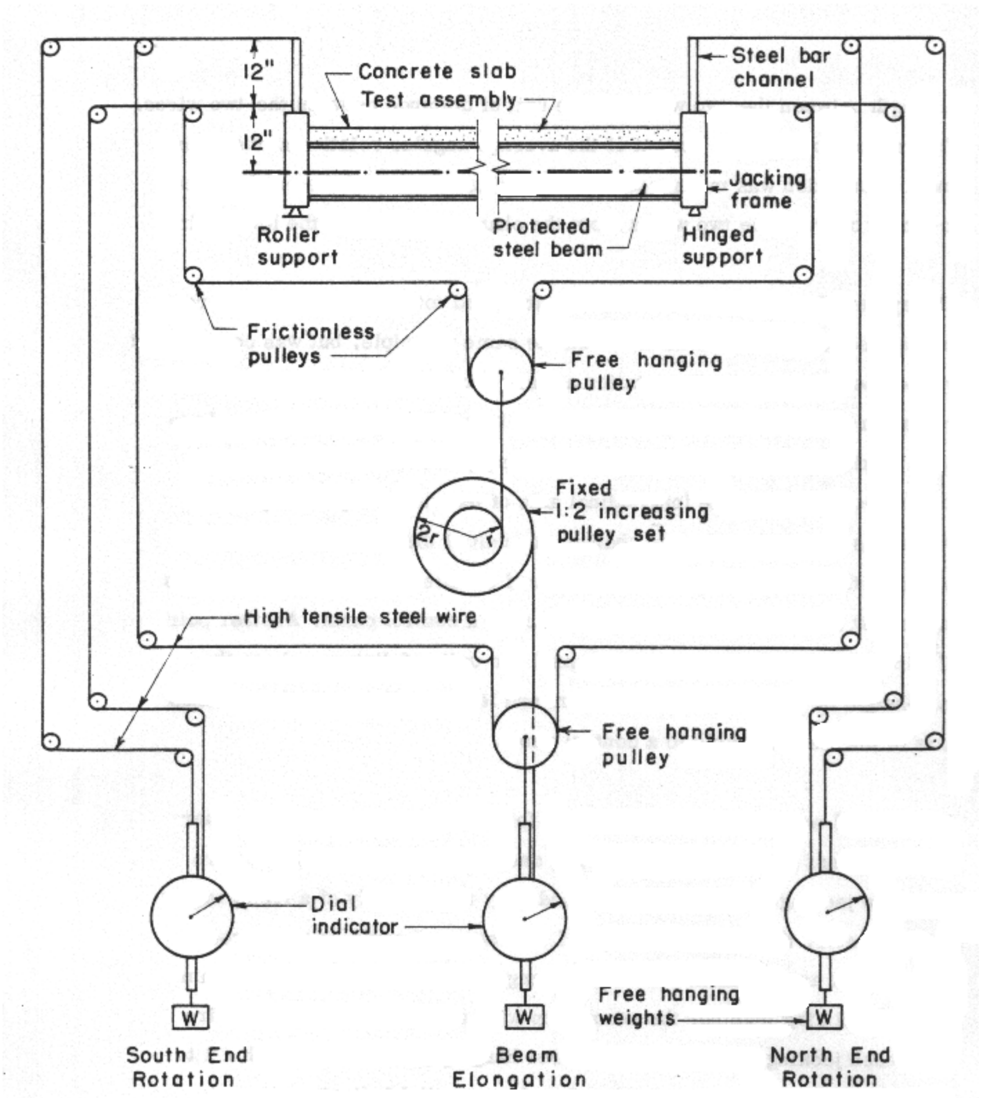
Deflection was measured during the test using a system of high tensile steel wires attached to the assembly at the quarter points (including the center). The wires were strung over low-friction pulleys connected to reducing wheel sets (10:1) attached to the roof structure of the laboratory. The wire attached to the smaller wheel of the reducing wheel set was in turn attached to a 0.001 in. graduated dial indicator and a free hanging weight to keep the wires in tension. A similar setup was utilized to monitor any movement of the laboratory roof support and corrections were made if roof movement was observed.

Measurements of end rotation and assembly elongation were accomplished using a system of wires, pulleys, and indicator dials similar to that used to measure deflection. Steel channels were welded to each end of the steel beam perpendicular to the longitudinal axis of the beam. The rotation and elongation instrumentation is show in Figure 7.7, taken from Bletzacker [21].

Restraining forces and moments were controlled by a series of hydraulic rams mounted in the test frame. These rams were calibrated before the test and operated using a hand pump. A master ram acting on a load cell was used to monitor the forces being applied.

The superimposed loads were applied using a pair of long-travel hydraulic rams operated in a similar manner to that of the end restraint rams. These, too, were monitored using a master ram acting on a load cell. The rams were calibrated prior to the test.

Strain at selected sections of the test assembly was measured using SR-4 electric resistance strain gauges adhered to the surface of the steel beam and the concrete slab [21].



Bletzacker, 1966

Figure 7.7. Rotation and Elongation Instrumentation

7.2.3 Test Procedure

7.2.3.1 The Fire

The burner installed within the test furnace was controlled according to the ASTM E119 *Standard Test Method for Fire Tests of Building Construction and Materials*. This standard defines a time-temperature curve for the testing of materials in laboratory furnaces. By defining a standard time-temperature curve, ASTM E119 theoretically allows the performance of various members or assemblies to be compared under the same fire exposure. The time-temperature relationships that define the standard fire curve are given below in Table 7.1 [20].

Table 7.1. ASTM Standard Fire Curve Key Points

Time (min)	Temperature (°C)
5	538
10	704
30	843
60	927
120	1010
240	1093
480	1260

The full standard time-temperature curve is shown below in Figure 7.8.

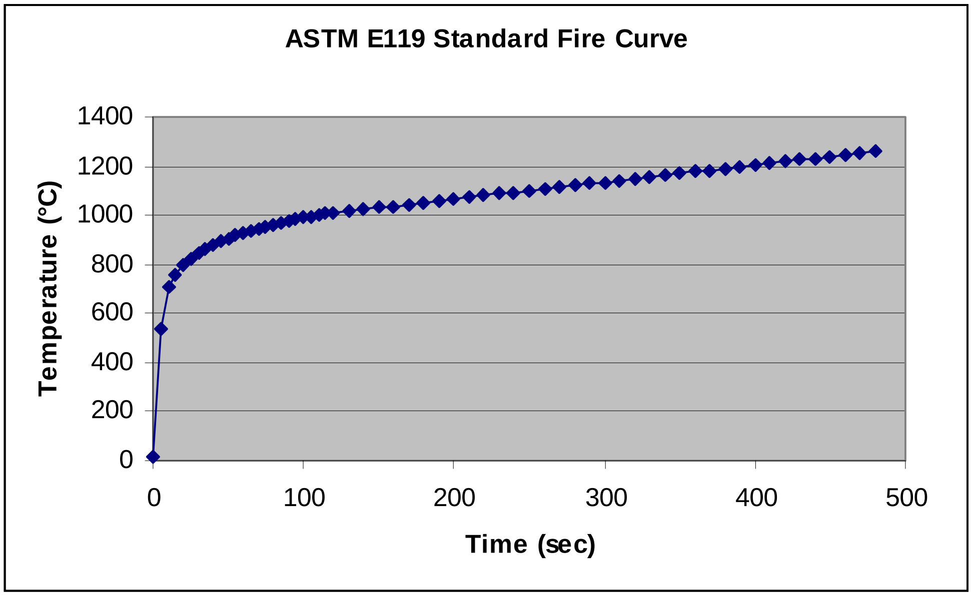


Figure 7.8. ASTM E119 Standard Fire Curve

The temperature inside the furnace was monitored using a series of thermocouples installed in stainless steel tubes.

7.2.3.2 Failure Definition

Failure of the test assembly was defined as the point at which the assembly could no longer support the superimposed design load, and thus collapsed. When this occurred, the time was recorded as the limit of fire endurance for the assembly. While temperature values were recorded on the top (unexposed) surface of the concrete slab, these were not taken into consideration in determining time to failure.

7.2.4 Results and Conclusions

The test program utilized by Bletzacker included twelve different tests. Comparison of the results of these tests led the test operators to come to several conclusions regarding the effects of end restraint and composite behavior on the fire endurance time of steel beam floor assemblies. Refer to Bletzacker's report [21] for a full review of these conclusions. For the purposes of this thesis, the data gained from Test B7, involving fixed end conditions, will be used to draw some basic conclusions regarding two different types of analytical methods. The pertinent data from Bletzacker [21] is presented here.

The maximum steel surface temperatures, observed at the center of the span of the beam, are shown in Figure 7.9.

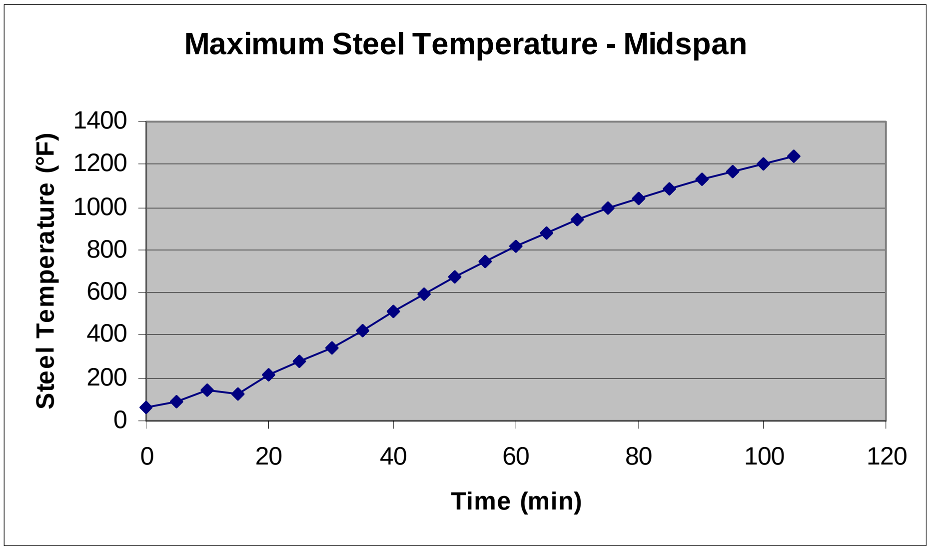


Figure 7.9. Midspan Steel Beam Temperatures

Deflections were measured at three locations along the span of the beam: the midpoint and the outer quarter points, where the concentrated loads were applied. The measured deflections are shown in Figure 7.10.

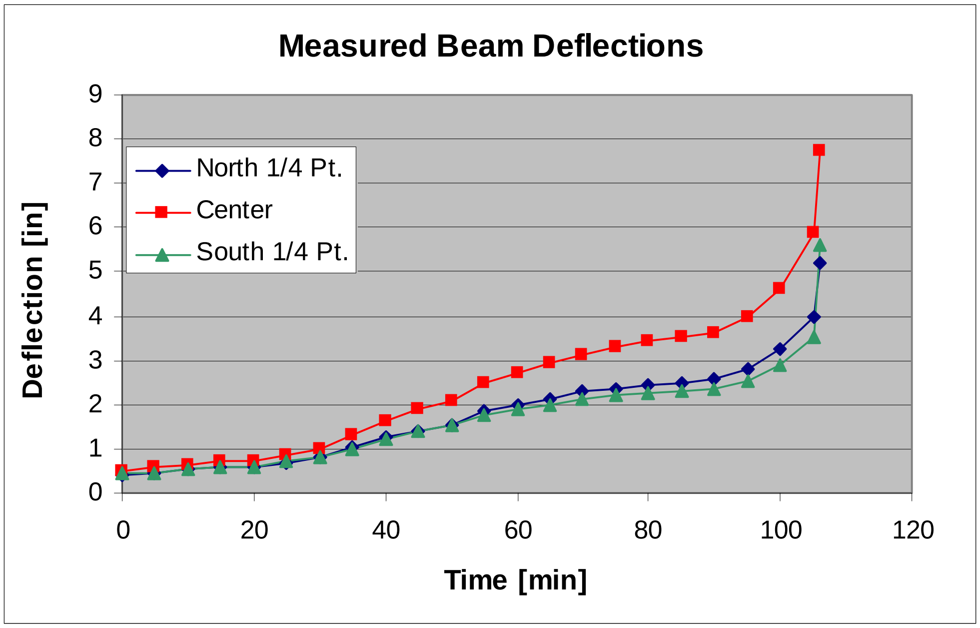


Figure 7.10. Recorded Beam Deflections

The recorded axial thrust observed during the test is shown below in Figure 7.11. Note that positive axial thrust indicates that, due to the applied level of end restraint, the beam was under compression during the duration of the test.

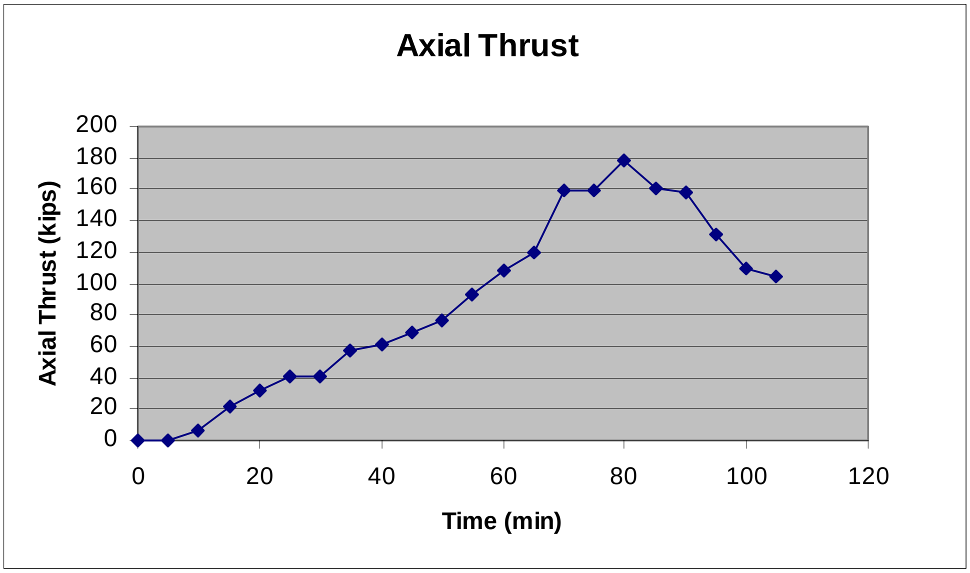


Figure 7.11. Recorded Axial Thrust

7.3 Beam Performance Determination Using Spreadsheet Applications

This section presents a simplified method of determining a steel beam's response to the time-temperature relationships for a given fire condition. The beam-and-slab assembly described in Section 7.2 has been modeled here using a lumped-parameter analytical method. This methodology can be implemented in a simple spreadsheet form, allowing ease of use in a design office. However, due to the simplified nature of this approach, certain aspects of structural member response to elevated temperatures may not be directly considered, and thus complex response mechanisms may be neglected. This section presents the results obtained through a lumped-parameter analysis approach in which the spray-protected steel beam described in the previous section has been theoretically exposed to the same elevated temperatures as in the laboratory tests. In the concluding section of this chapter, these results will be compared to the results of the laboratory fire tests in an effort to gauge the success with which the simplified spreadsheet approach calculates structural response to fire.

7.3.1 Analytical Method

This analysis uses a combination of methodologies to predict the performance of a structural member to elevated temperature conditions. First, a lumped-parameter method is used to predict the temperature of the steel member in relation to know temperature conditions within the fire compartment [23]. Then, the temperature predictions are used to determine changes to member capacity and deflected shape by applying known material property-temperature relationships. In this analysis, the development of plasticity in the beam is considered, with calculation of plastic moment capacity at key points (hinges) along the beam determining time to collapse. Appendix F includes a complete discussion of the analysis methodology used here.

7.3.2 Modeling of Test Beam

This section describes the input parameters used to model the protected steel beam using a lumped-parameter spreadsheet application.

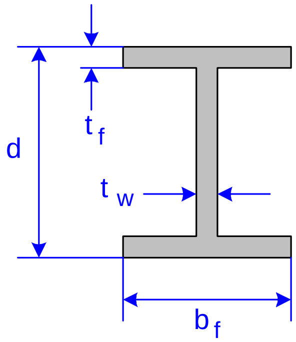
7.3.2.1 Beam Input Parameters

The steel beam used in this analysis was a W12x26 wide flange shape. According to AISC specifications [10], this standard shape has the following properties:

Table 7.2. Member Parameters for W12x26 Beam

Parameter	Value
Weight per unit Length	26 lb/ft
Moment of Inertia (X-X)	204 in^4
Elastic Section Modulus (X-X)	33.4 in^3
Plastic Section Modulus (X-X)	37.2 in^3

Additionally, the dimensional specifications of a W12x26 beam are as follows:



b_f = 6.49" (165 mm)
d = 12.22" (310 mm)
t_f = 0.38" (10 mm)
t_w = 0.23" (6 mm)

Figure 7.12. Dimensional Parameters of W12x26 Beam

Note that, as shown in Figure 7.2, the beam used by Bletzacker in the laboratory tests was a W12x27 shape. This is no longer a standard AISC wide flange beam shape, so a W12x26 section has been substituted in the analysis performed herein. The two designations have nearly identical cross-sectional dimensions [10,21].

7.3.2.2 Spray-On Protection Input Parameters

The test program being simulated here included the application of spray-on vermiculite-based insulation on the fire-exposed surfaces of the test assembly. Application thickness varied somewhat, but the average depth of the insulation layer over the steel beam was 7/8 in, as shown previously in Figure 7.3.

The lumped-parameter approach incorporates member protection materials by reducing the heat to which the steel is exposed based on the heat transfer properties of the protection. For sprayed-on vermiculite cementitious insulation, the following properties are used in the calculation.

Table 7.3. Spray-On Protection Properties

Parameter	**Value**
Thermal Conductivity	0.064 kcal/m C h [24]
Thickness	0.875 in. (22 mm)

Appendix F includes discussion of the heat transfer calculations used to take the protective layer into account.

7.3.2.3 Fire Input Parameters

The average gas temperatures surrounding the steel beam were assumed to follow the time-temperature curve presented in the ASTM E119 *Standard Test Method for Fire Tests of Building Construction and Materials*. The ASTM curve was utilized in the control of the furnace used in the laboratory tests discussed in Section 7.2, and thus must be used in the spreadsheet analysis for proper comparison of analysis results to the laboratory test results. The test burner was controlled by monitoring the gas temperature within the furnace assembly. Thus, it is reasonable to assume that the gas temperatures surrounding the steel beam were uniform and consistent with the ASTM curve. The ASTM standard time-temperature curve is shown below in Figure 7.13 [20].

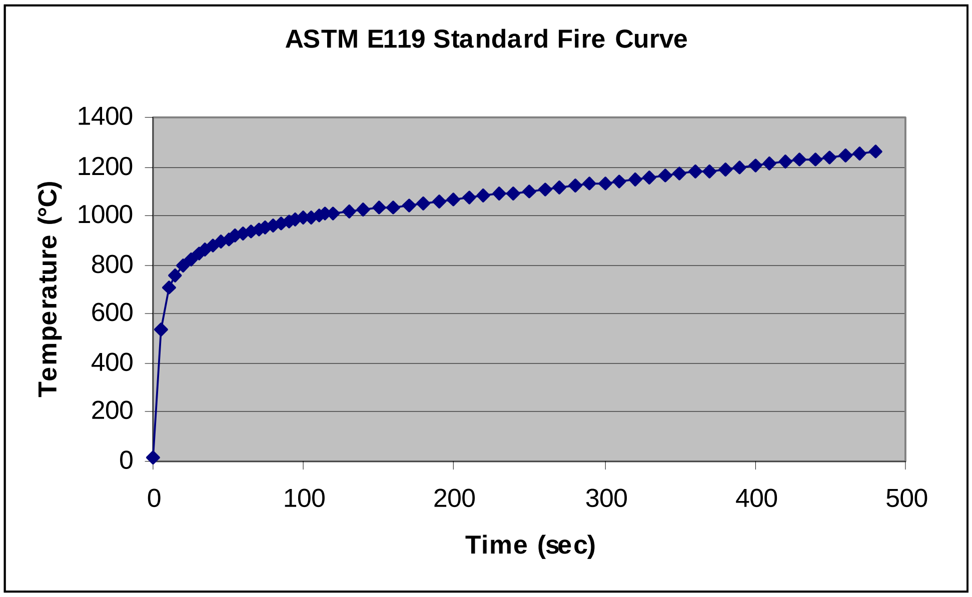


Figure 7.13. ASTM E119 Standard Fire Curve

Through application of the lumped-parameter method described in Appendix F, the steel temperature during the standard fire was calculated. The time-temperature curve for the steel beam is shown below in Figure 7.14.

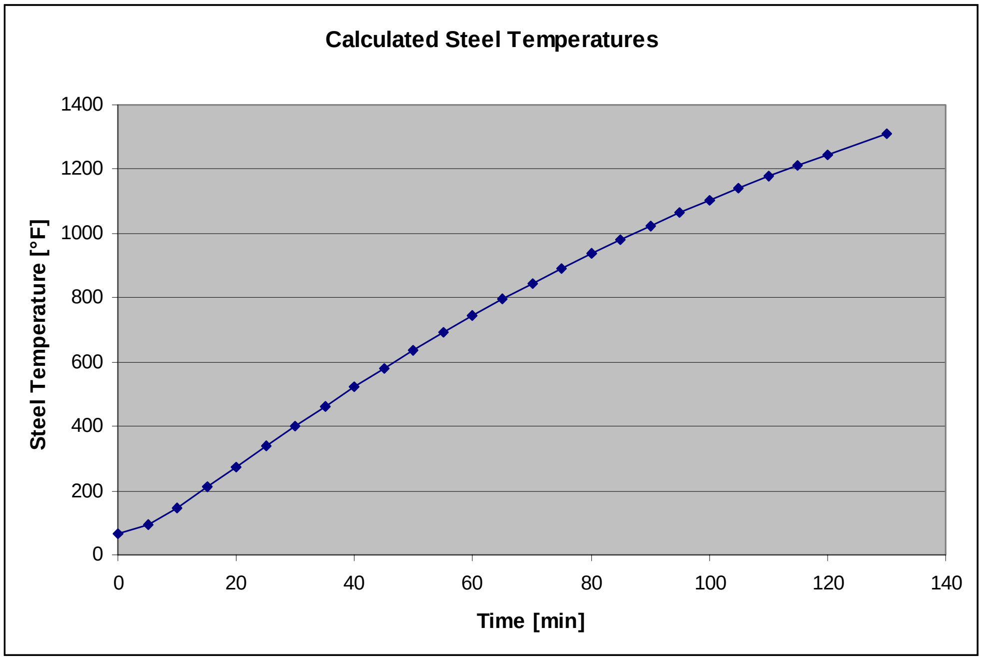


Figure 7.14. Steel Beam Time-Temperature Curve

7.3.2.4 Temperature-Dependent Properties

As a steel beam is subjected to thermal energy during a fire, its engineering properties change and correspondingly alter the performance (capacity, serviceability, etc.) of the beam. For the spreadsheet analysis carried out here, three properties were assumed to be temperature-dependent: the *yield strength (σ_y)*, the *modulus of elasticity (E),* and the *coefficient of thermal expansion (α)*. According to Milke [25], these parameters can be assumed to follow the following temperature-dependent relationships:

$$\sigma_{y\theta} = \sigma_{y0}\left(1 - 0.78\theta - 1.89\theta^4\right) \qquad \text{[Eq. 7.1]}$$

where,

$\sigma_{y\theta}$= yield strength at elevated temperature [ksi]
σ_y = yield strength at room temperature [ksi]
$\theta = (T - 68)/1800$, T in °F
T = steel temperature [°F]

$$E = E_0(1\text{-}2.04\theta^2) \qquad \text{[Eq. 7.2]}$$

where,

E = modulus of elasticity at elevated temperature [ksi]
E_0 = modulus of elasticity at room temperature [ksi]
$\theta = (T - 68)/1800$, T in °F
T = steel temperature [°F]

and,

$$\alpha = (6.1 + 0.0019T) \times 10^{-6} \qquad \text{[Eq. 7.3]}$$

where,

α = coefficient of thermal expansion [in/in°F]
T = steel temperature [°F]

It should be noted that the equations for the temperature dependency of σ_y and E are appropriate for θ values less than 0.63, and that of α is appropriate for θ values less than 0.68. These limits correspond to steel temperatures of 1200°F

(650°C) and 1300°F (700°C), respectively. As shown in Figure 7.9, failure was observed prior to when θ exceeded these limits.

7.3.2.5 Beam Loading Conditions

To simulate the loading conditions associated with the laboratory test case, two different types of loads were considered to be acting on the beam. The first is composed of the dead weight of the beam itself and the slab assembly supported by the beam. These loads were distributed over the length of the beam. As noted in Table 7.2, the beam's self weight is 26 lb/ft.

The slab installed in the test assembly described in Section 7.2 was 4 in. (100 mm) thick, 3 ft. (0.9 m) wide, and spanned the entire length of the beam. Assuming a concrete density of 150 lb/ft^3, the distributed load due to the concrete slab was about 150 lb/ft. The weight of the corrugated steel decking is considered to be insignificant in relation to the concrete weight, and thus can be neglected.

Figure 7.15 shows the loading condition for the analytical model of the steel beam.

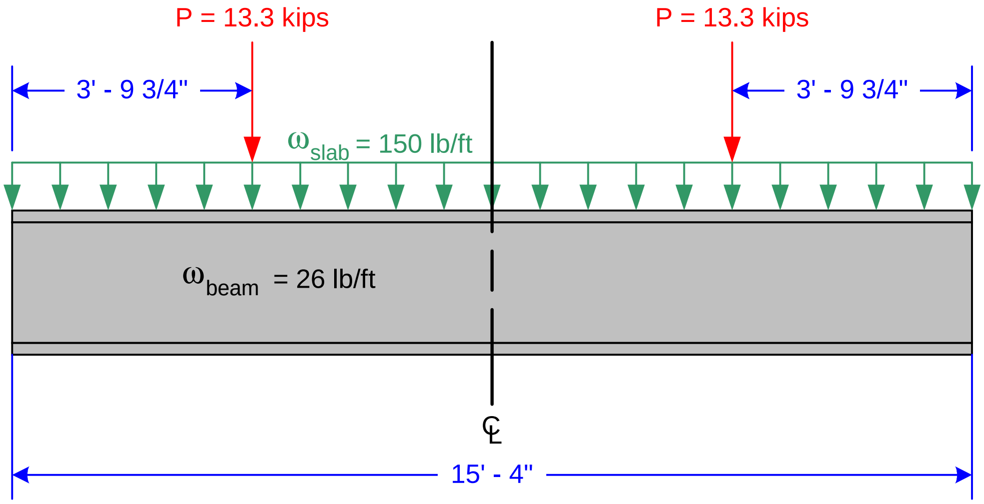


Figure 7.15. Beam Loading Conditions (Not to Scale)

7.3.2.6 Definition of Failure Conditions

Much like in the laboratory tests described previously, failure is predicted in the spreadsheet approach by determining when the beam can no longer support the loads imposed upon it. The beam is considered to fail when its theoretical capacity drops below the total load applied to it, including the effects of its self-weight, the weight of the concrete slab and metal deck, and the superimposed concentrated loads. As in the laboratory tests, deflection is not considered as a failure criterion for this analytical method.

7.3.3 Results and Conclusions

This section presents the results obtained from the spreadsheet-based analysis of the beam-and-slab assembly. Refer to Appendix F for a discussion of the equations used to calculate beam capacity and deflection.

Figure 7.16 shows the predicted change in beam capacity over time during the fire duration.

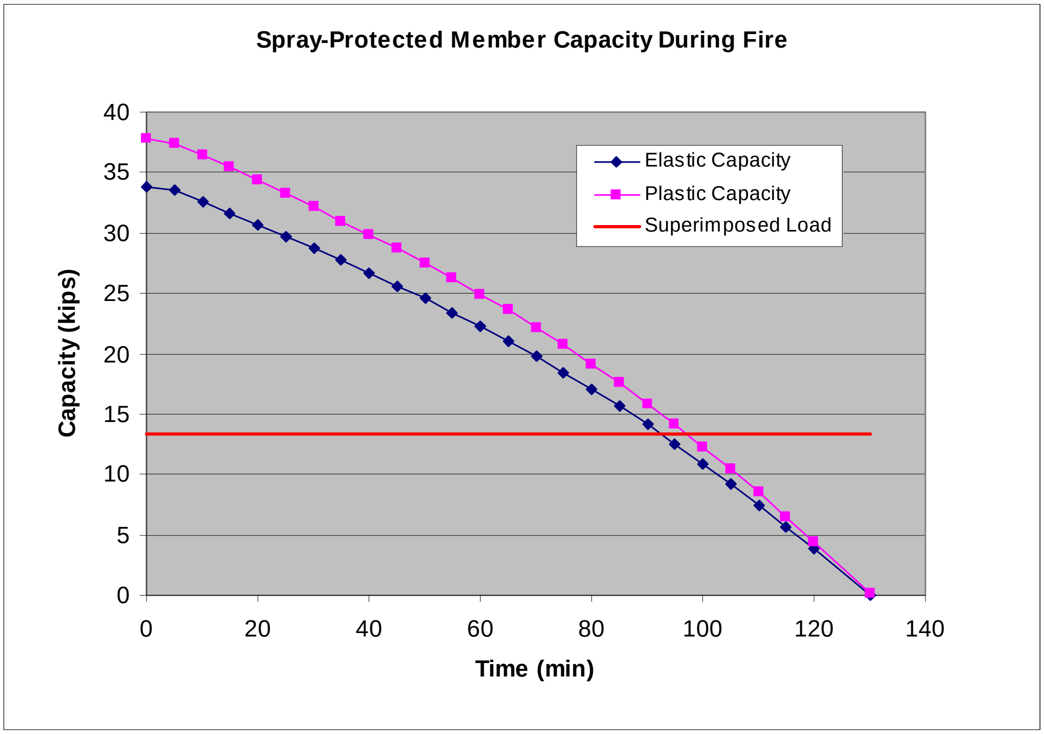


Figure 7.16.Calculated Member Capacity During Fire Exposure

Figure 7.17 gives a comparison of calculated versus observed time to failure. Failure was observed in the test at a time of 107 minutes. This analytical method predicted failure at 99 minutes. This small error, at approximately 6.5%, may be acceptable in many cases, especially given that it predicts failure slightly before it actually occurs. By underestimating the capacity of the beam, this method gives a conservative estimate of time to failure. This may be favorable in many situations, although the engineer may need to consider the possibility of overdesign and its impact on project cost.

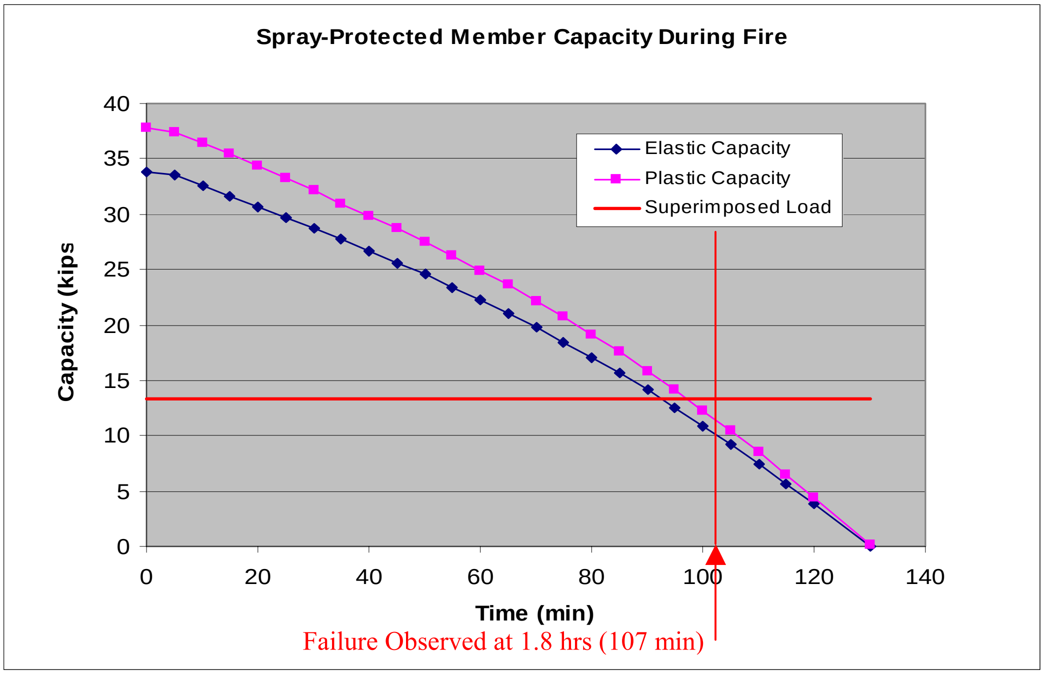


Figure 7.17.Comparison of Observed and Calculated Time to Failure

Figure 7.18 gives an indication of the deflection behavior of the beam as predicted through the use of the lumped-parameter method. Deflection values are shown from the start of the fire period until the failure point calculated based on beam load-carrying capacity.

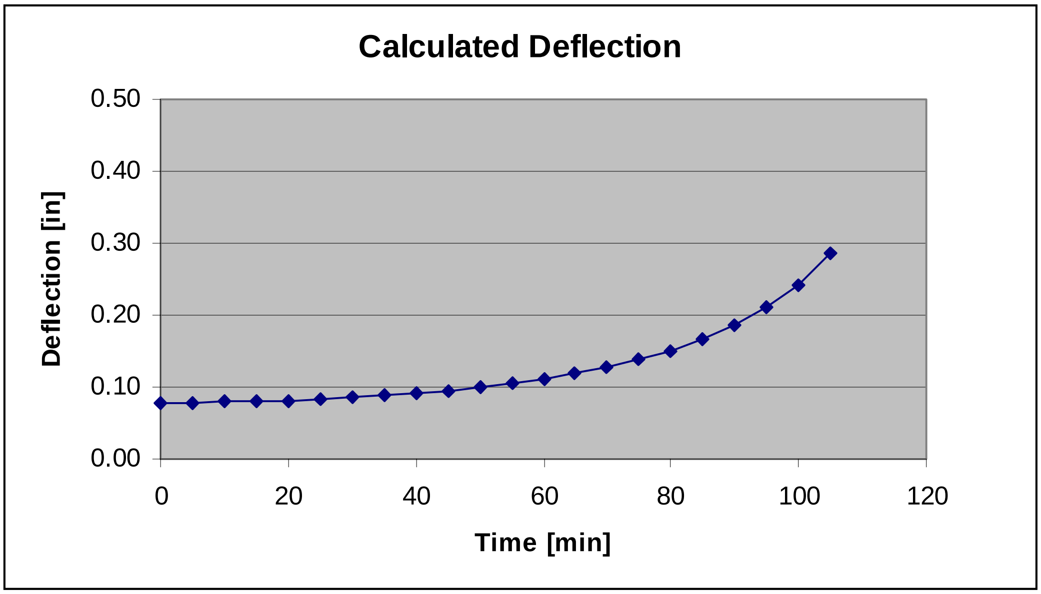


Figure 7.18.Calculated Deflection During Fire Exposure

As discussed in Appendix F, the deflection values shown in Figure 7.18 are based on superposition of midspan deflections for different elastic systems. Additional mechanisms may increase the level of deflection expected for the heated beam. At elevated temperatures, these mechanisms may have a significant effect on the deflection behavior of a beam.

The axial thrust resulting from the expansion of the beam can magnify the beam deflection, consistent with the behavior of beam-columns (p-Δ effect). This magnification, or p-Δ effect, can be taken into consideration during the calculation of the beam's deflection. First, the axial thrust must be calculated as [26]:

$$P = \alpha \Delta T A E \qquad \text{[Eq. 7.4]}$$

where,

P = axial thrust [lbs]
α = coefficient of thermal expansion [in/in°F]
ΔT = temperature change [°F]
A = beam cross-sectional area [in^2]
E = modulus of elasticity [ksi]

The axial thrust can then be used to calculate a magnification factor for deflection [10]:

$$B = \frac{1}{1 - {}^{P}\!/_{P_{CR}}} \qquad \text{[Eq. 7.5]}$$

where,

B = deflection magnification factor
P = axial thrust [lbs]
P_{CR} = Euler buckling load [lbs]

For fixed-end support conditions, the Euler buckling load is defined as [26]:

$$P_{CR} = \frac{\pi^2 EI}{(0.5L)^2} \qquad \text{[Eq. 7.6]}$$

where,

P_{CR} = Euler buckling load [lbs]
E = modulus of elasticity [ksi]
I = moment of inertia [in^4]

The deflection magnification factor, B, can be applied to the calculated deflection in order to take the effects of axial thrust into account.

Figure 7.19 shows the effect of this adjustment on the calculated beam deflection curve.

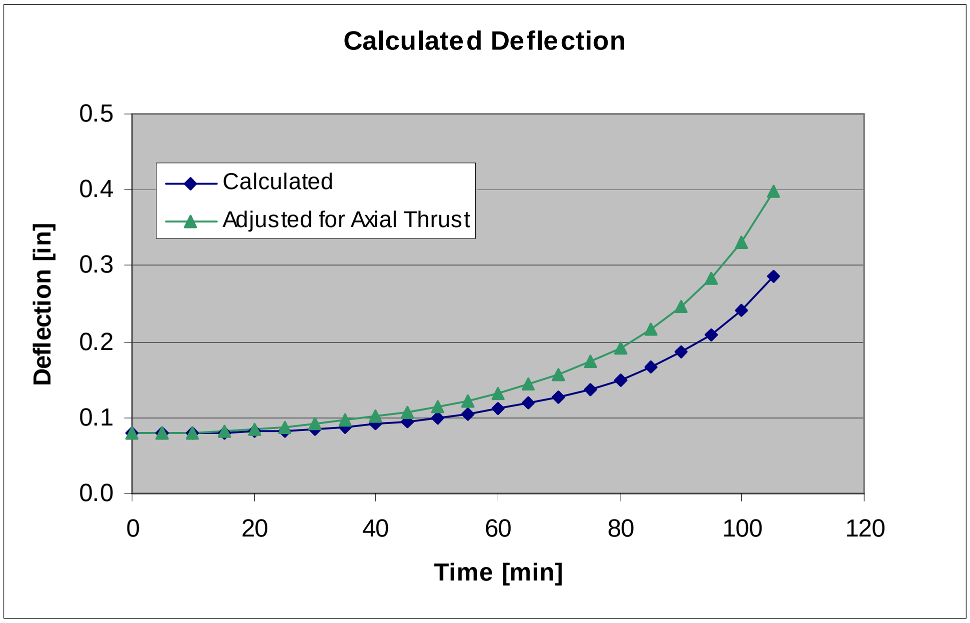


Figure 7.19.Calculated Deflection Refinements

As steel is heated, it expands. This expansion occurs at a rate that is dependent on temperature. Elevated temperatures cause expansion to occur at a greater rate than lower, normal operating temperatures. During a fire, this can cause the length of a given member to increase substantially. In the case discussed here, the ends of the beam are fully fixed against translation in all directions. This means that the ends of the beam cannot displace to accommodate thermal expansion. The expected result is an increase in the lateral deflection resulting from the loading conditions. This effect can be taken into account by assuming that the deflected shape of the beam follows an assumed curve and using geometric relationships and the predicted thermal expansion of the beam to determine the increase in deflection. However, if lateral beam buckling is considered in addition to the thrust effects discussed above, then the actual thrust force will be much less than the theoretical maximum value calculated using Equation 7.4. Because of this, consideration of the beam's expansion in the calculation of beam deflection is considered an alternate approach and has not been implemented here.

Figure 7.20 gives a comparison of observed and calculated deflection values. It is evident from this figure that the simplified approach does not accurately predict deflection values for this structural configuration.

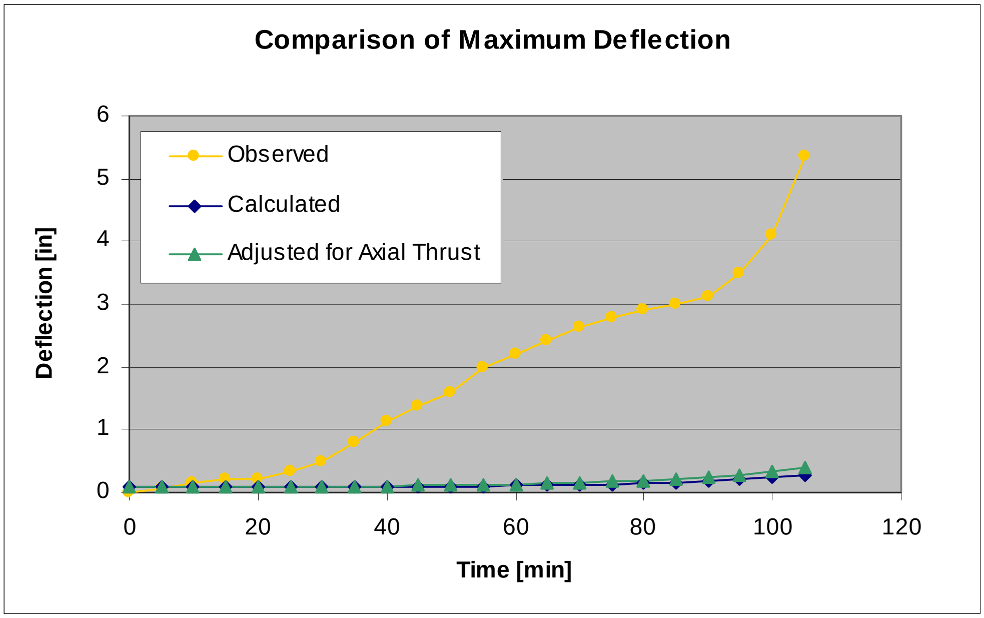


Figure 7.20.Comparison of Observed and Calculated Deflection

The lumped-parameter approach uses plastic theory in predicting time to failure. However, it does not include an in-depth plastic analysis for the purpose of calculating deflection. Since the deflection behavior of the fixed-end beam is characterized by large rotations subsequent to the development of plastic hinges, plastic analysis techniques are required to accurately predict the deflection of the beam

7.4 Beam Performance Determination Using Finite Element Methods

Unlike simplified correlations and equations based on the laws of physics, which can be relatively easily implemented in spreadsheet form and used to provide quick, first-cut estimates of structural member response to fire conditions, finite element methods are highly complex, but can be used to model sophisticated geometries and complicated linear and nonlinear structural behavior. For practical purposes, finite element methodologies are generally implemented in computer model form.

7.4.1 Analytical Method

Finite element methods utilize relatively simple linear or quadratic functions on small elements to describe local variations of different flow variables (mass, energy, etc.) [27]. In such an analysis, an attempt is made to find an exact solution satisfying the governing equation of flow. Because the functions used to describe the different flow variables are generally piecewise, exact solutions are not possible. To compensate for this, a residual is defined to measure errors between the expected exact solution and that obtained through calculation. Weighting functions are used to minimize these residuals, and a set of algebraic equations result that can be used to calculate the unknown coefficients in the governing equations. Thus, changes in flow can be traced for individual elements, and the interaction of these elements can be determined in order to predict the global behavior of a structural member or assembly.

It should be noted that the use of finite element methodologies, even when implemented in computer model form, requires thorough understanding of the physical phenomena predicted by such a model. While computer models greatly expedite the process of formulating and carrying out a finite element analysis, the user must be knowledgeable in the finite element methodology in order to make appropriate decisions regarding input parameters.

This section describes a finite element model developed using the software package LS-DYNA [28]. The model simulates the test procedure described in Section 7.2 with the goal of predicting results similar to those obtained during the laboratory test. The results obtained here will be compared to those obtained in Section 7.3 in order to make judgments regarding the degree of sophistication that may be necessary to accurately model the performance of structural elements in a fire environment.

7.4.2 Description of Computer Model (LS-DYNA)

LS-DYNA is a general-purpose finite-element analysis program first developed in 1976 at the Lawrence Livermore National Laboratory in California [22]. The program was under constant refinement over the course of the next ten years, with many additional features and capabilities being added. In 1988, Livermore Software Technology Corporation (LSTC) was founded to further develop the program for general use, with an emphasis on the ability to perform crashworthiness simulations (a task previously impractical with the original program). LS-DYNA has been utilized for many different applications, including the following:

- Automobile crash simulation
- Airbag design
- Automotive part manufacturing
- Metal forming
- Seismic engineering
- Fluid-structure interaction
- Biomedical design
- Behavior of box structures and cellular materials

As can be seen above, LS-DYNA is used extensively in the automobile design and testing industry, but its use has been extended to many other fields, including the design and analysis of buildings.

LS-DYNA utilizes first principles to perform analyses – constitutive relationships and laws of physics are used to predict the response of simulated elements to various conditions, be they loadings, environmental conditions, or other external or internal influences. For example, known relationships for material properties (including strength and elasticity), mechanics of materials, and the laws of motion would be used by the program to analyze a model of an automobile bumper impacting some sort of barrier. The simulation would predict how the bumper would be expected to deform, if it would fail and how, and what levels of stress are present throughout the bumper during the impact.

LS-DYNA analyzes structures (from individual parts, to systems of components assembled to make up a building, for example) by dividing each aspect of the structure into various elements. The first principles discussed above are applied to determine the reaction of each element to the given event, as well as the interactions between elements during the event. When observed together, all of these elements combine to predict the overall behavior of the structure during the event.

LS-DYNA includes a library of element types that provides the user with a variety of possibilities for modeling different structures. An element type must be chosen based on the specified event, the geometry of the structure, the desired output, and the desired analysis efficiency. Some common element types that are available in the current version of LS-DYNA are [28]:

- Membranes
- Shells (thin or thick)
- Bricks
- Beams
- Welds (layered spot, fillet, butt, or combination fillet and butt)
- Discrete springs and dampers
- Discrete lumped masses
- Plane stress or strain elements

There is also an option to develop and implement new element formulations, but this feature requires knowledge of and access to the source code. This is only necessary in specific, abnormal structures. Generally, the library of available elements provided with the program is sufficient for modeling most structures, and new element formulations are only necessary in specific abnormal structures.

LS-DYNA utilizes numerous material models, depending on the type of structure being modeled and the information input into the model. Some general material models available are [28]:

- Elastic materials (isotropic, orthotropic, anisotropic, temperature-dependent, etc.)
- Elasto-viscoplastic materials (temperature-dependent, viscous, creep, etc.)
- Foam materials
- Geological models (tensor, kinematic hardening, concrete*, soil)
- Composites (shells, solids, matrix, fiber, etc.)
- Glass
- Biomedical materials (heart tissue, lung tissue)
- Fluid analyses (liquids, metals, gases, chemical reactions, crushable materials)

*Note: thermal degradation of concrete is not currently considered in LS-DYNA [28].

In addition to modeling stress, strain, and deformation as a result of some sort of physical loading, LS-DYNA is also adaptable to modeling the effects of thermal loads. It can model both heat flow through a model, and temperature-dependent material properties. A user can input any temperature-dependent property history that may be appropriate for a given material, and LS-DYNA will take these into account in predicting the behavior of the structure. This capability can be very useful when modeling materials exposed to high temperatures, when various strength and elasticity/plasticity factors may change with temperature. As a result, the combined effects of small elastic deformations, large inelastic deformations, and thermal expansions can be accurately predicted.

Because of the finite element method's use of comparatively small individual elements to make up large models, it provides great ease in modeling both simple and complex structures. Uncommon member geometries and specific construction details can be easily modeled. The use of individual elements that interact with one another also allows mechanical and thermal analyses to be performed simultaneously and to interact with each other, a factor that is vital for modeling loaded structures exposed to varying temperature conditions.

7.4.3 Modeling of Test Beam

This section describes the model parameters used to describe the test assembly, loading conditions, and boundary conditions in the LS-DYNA finite element model. This model is designed to simulate the conditions of the laboratory fire test described in Section 7.2. Note that the complete LS-DNYA input files are provided in Appendix G.

7.4.3.1 Beam Input Parameters

The cross-sectional dimensions of the beam model developed using LS-DYNA are identical to those utilized by the spreadsheet analysis presented in Section 7.3. These are shown in Figure 7.12.

The steel beam was modeled as a series of 376 shell elements. Along the flanges, the element size measured 3.9 in (100 mm) long by 3.25 in (83 mm) wide. Within the web, the elements measured 3.9 in (100 mm) long and 2.9 in (74 mm) wide. The length and width of the shell elements were defined such that the aspect ratios of the shells were as close to 1 as possible as possible. This allows for more efficient modeling than if the aspect ratios were greater than 1. The shells comprising the flanges were defined as 0.38-in- (10-mm-) thick elements, and those comprising the web were defined to be 0.23 in (6 mm) in thickness. The simulation was set to follow Belytschko-Tsay element formulation methodologies, which are appropriate for two-dimensional thin shell elements [28]. While the flanges and web were modeled with just one node through their depth, two through-thickness integration points were specified for the individual shells. This allows the direct consideration of bending deformation of the shells. Figure 7.21 shows the element mesh used to represent the test beam.

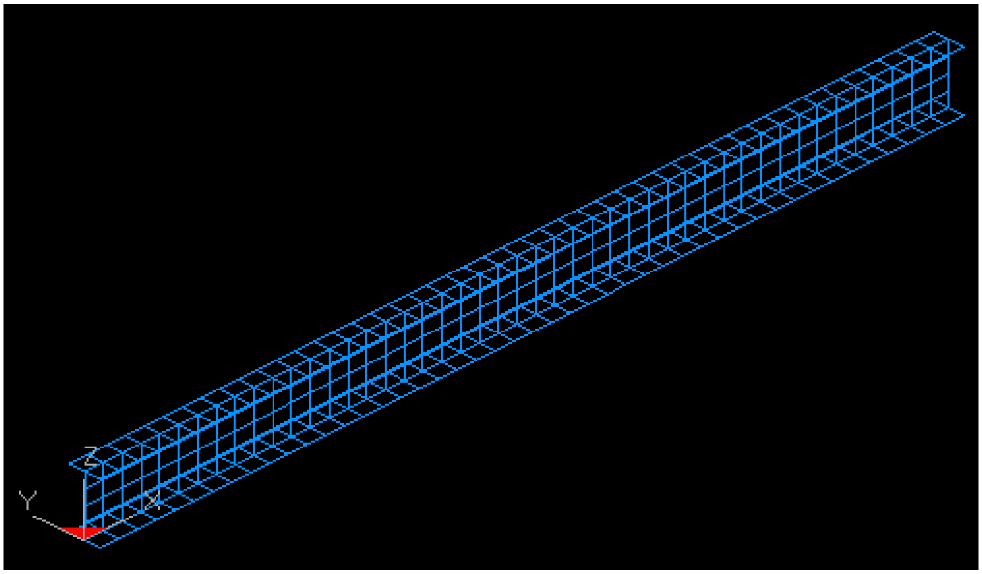


Figure 7.21. Beam Model Incorporating Shell Elements

LS-DYNA's *MAT_ELASTIC_PLASTIC_THERMAL material model was used to describe the constitutive properties of the steel beam. This model allows the specification of temperature-dependent material properties, and can be used to predict nonlinear plastic behavior. In addition to the temperature-dependent properties to be discussed in Section 7.4.2.5, the density of the material was set to 490 lb/ft³ (7,850 kg/m³) [26].

7.4.3.2 Concrete Slab Input Parameters

In the interest of conserving computational time, the 4 in (100 mm) concrete slab was omitted from the finite element model. The weight of the slab was represented by a 150 lb/ft (2.19 kN/m) distributed load acting along the full length of the beam. The conclusion to this section discusses the ramifications of the elimination of the slab from the model.

It is expected that the heat sink effect of the concrete slab is captured in the laboratory test data since steel surface temperatures were measured directly by thermocouples welded to the steel surface and placed under the insulation layer.

7.4.3.3 Spray-On Protection Input Parameters

Similar to the concrete slab, the spray-on protection was also eliminated from the finite-element model. The justification for this lies in the fact that the temperatures input into the LS-DYNA model were taken directly from the laboratory test report authored by Bletzacker [21]. These temperatures were measured using thermocouples welded to the steel beam, and were covered, along with the beam, by the spray-on protective layer. Thus, the temperature readings represent the steel surface temperature, which is the required input in the model. If the thermocouples had been exposed during the test, radiative heating would be a concern and the temperature measurements might not represent actual steel surface temperatures.

Inclusion of the spray-on protection in the LS-DYNA model would require accurate knowledge of the temperature conditions on the fire-exposed sides of the protective layer. Although the experiment was controlled such that ambient temperatures within the furnace followed the ASTM E119 time-temperature curve, direct application of the ASTM E-119 temperatures to the model, rather than the recorded steel surface temperature readings, would likely ignore the presence of differential heating conditions caused by any nonuniformities in test fire application and thermal gradients over the length and cross-section of the beam caused by heat sink effects afforded by the concrete slab.

7.4.3.4 Fire Input Parameters

The test fire was input indirectly by application of temperature measurements to the individual nodes comprising the beam model. Thermal loads were applied to 15 independent sections of the beam. The beam was divided into five sections lengthwise, and time-temperature curves for the upper flange, the lower flange and the web were input independently. The thermal loading regions are shown in Figure 7.22.

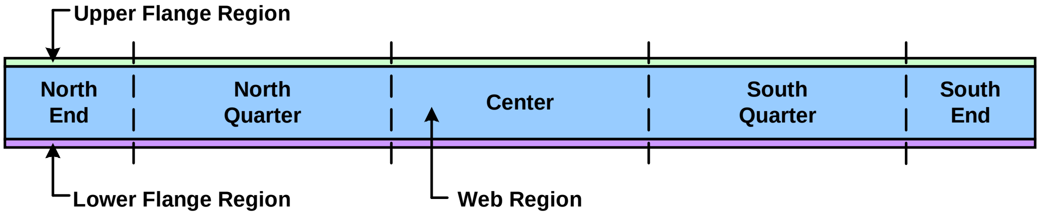


Figure 7.22. Thermal Loading Regions

A table of temperature measurements [21] that were used to define thermal loadings in this model is provided in Appendix H.

7.4.3.5 Temperature-Dependent Properties

The *MAT_ELASTIC_PLASTIC_THERMAL material model in LS-DYNA allows the specification of five different temperature-dependent properties. These are:

- Yield Strength,
- Modulus of Elasticity,
- Coefficient of Thermal Expansion,
- Poisson's Ratio, and
- Plastic Hardening Modulus.

The temperature dependency of the yield strength, modulus of elasticity, and coefficient of thermal expansion have been based on equations provided by Milke [25]. Refer to section 7.3.2.4 for a full description of these formulae.

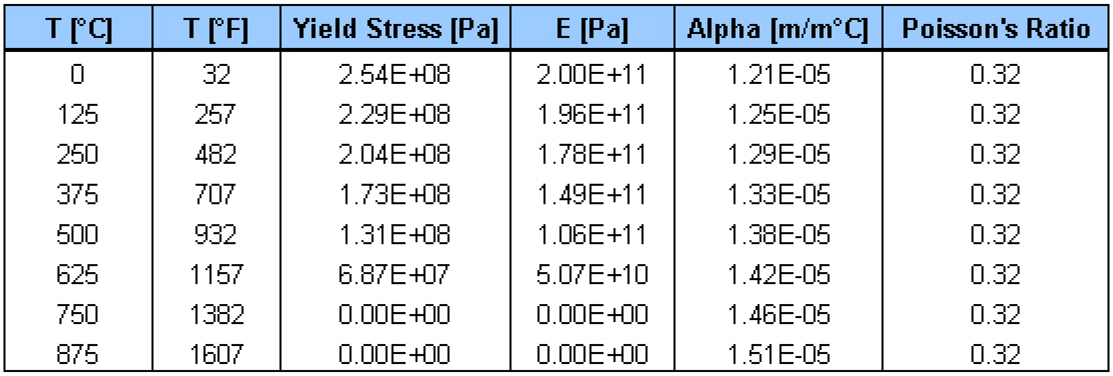
Reliable data could not be obtained regarding the temperature-dependence of Poisson's ratio. Poisson's ratio relates axial effects (tensile or compressive) to changes in the cross-section of deformable bodies [26]. For example, as a steel bar is stretched axially, its cross section will decrease in diameter. In the elastic regime, the ratio of longitudinal to lateral strain is essentially a constant, and is equal to Poisson's ratio. Beyond the elastic regime, Poisson's ratio does not necessarily describe a material's true behavior because of the nonlinear nature of plastic behavior.

Due to the lack of information available on the temperature-dependence of Poisson's ratio and the elastic-plastic behavior expected due to the support conditions of the beam and the heating conditions, Poisson's ratio was assumed to be constant.

Similar to Poisson's ratio, little data exists on the temperature-dependence of the plastic hardening modulus. Because of this, the LS-DYNA model was instructed to ignore the effects of temperature-based changes in the plastic hardening modulus.

Table 7.4 summarizes the temperature-dependent properties as input into the model.

Table 7.4. Temperature-Dependent Properties



T [°C]	T [°F]	Yield Stress [Pa]	E [Pa]	Alpha [m/m°C]	Poisson's Ratio
0	32	2.54E+08	2.00E+11	1.21E-05	0.32
125	257	2.29E+08	1.96E+11	1.25E-05	0.32
250	482	2.04E+08	1.78E+11	1.29E-05	0.32
375	707	1.73E+08	1.49E+11	1.33E-05	0.32
500	932	1.31E+08	1.06E+11	1.38E-05	0.32
625	1157	6.87E+07	5.07E+10	1.42E-05	0.32
750	1382	0.00E+00	0.00E+00	1.46E-05	0.32
875	1607	0.00E+00	0.00E+00	1.51E-05	0.32

Truly rigorous modeling of fire-exposed steel structural members may require exploration into the temperature dependence of such properties as Poisson's ratio and the plastic hardening modulus. This is reserved for possible future work.

7.4.3.6 Beam Loading Conditions

In addition to the distributed load imposed to represent the concrete slab (as discussed in Section 7.4.2.2), two superimposed point loads were applied at the outer quarter points of the beam as in the laboratory tests. Each load measures 13.3 kips (59.2 kN). The superimposed loads are shown in Figure 7.23.

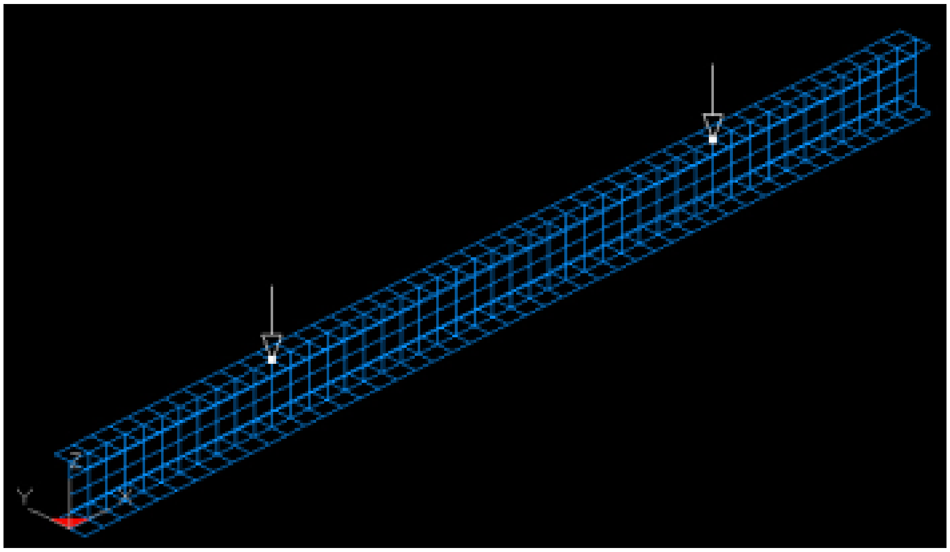


Figure 7.23. Superimposed Loading

7.4.3.7 Beam Restraint Conditions

In order to represent the laboratory tests described in Section 7.2, a good deal of consideration was given to the appropriate boundary conditions. According to Bletzacker's report [21], the test beam was kept under constant axial and rotational restraint for the duration of the test through the application of forces opposing thrust and rotation. The beam-to-support connection for the test assembly was shown previously in Figure 7.5; it consists of steel brackets attached to the beam by three high-strength bolts at each end. To replicate this condition in the LS-DYNA model, constraint was applied to nodes in the approximate locations of the support bolts. These nodes were constrained from translation and rotation in all directions, essentially fixing them in space. The beam end restraint is shown in Figure 7.24.

Additionally, the need for lateral bracing was made apparent by early test simulations. When the concrete slab was omitted, the beam was left fully unbraced along its entire length, and unexpected local buckling conditions resulted, including excessive deformation of the top flange. This is not representative of the laboratory test, in which the beam was spot-welded to the metal decking upon which the concrete slab was poured. These spot welds, along with the friction caused by the slab's weight, provide some degree of lateral bracing to the beam.

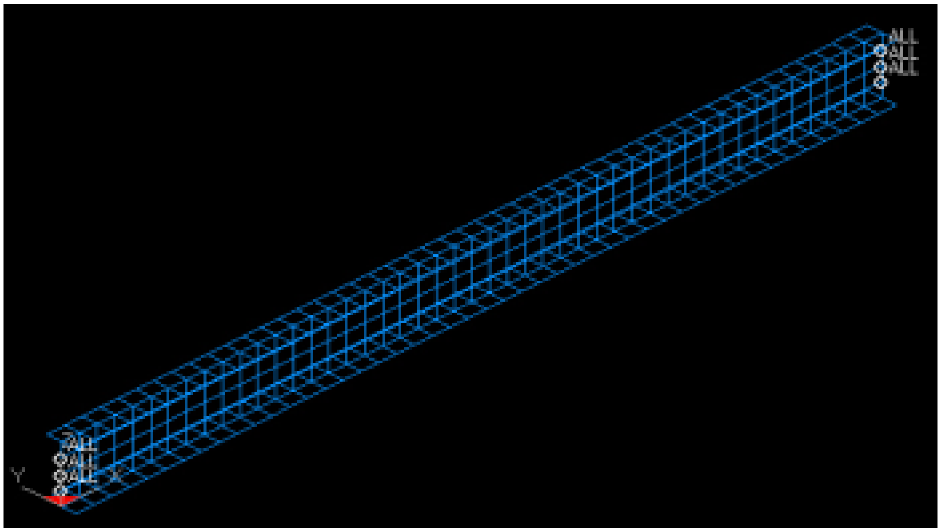


Figure 7.24. Beam End Restraint

An iterative process was used to determine appropriate levels of lateral restraint for bracing purposes. Ultimately, the application of lateral restraint (restraint against Y-translation only) at all $^1/_8$ points along the top flange of the beam model produced results that best matched the behavior observed during the laboratory tests. This bracing condition is shown in Figure 7.25. Note that the label "2" refers to translational restraint in the global Y direction.

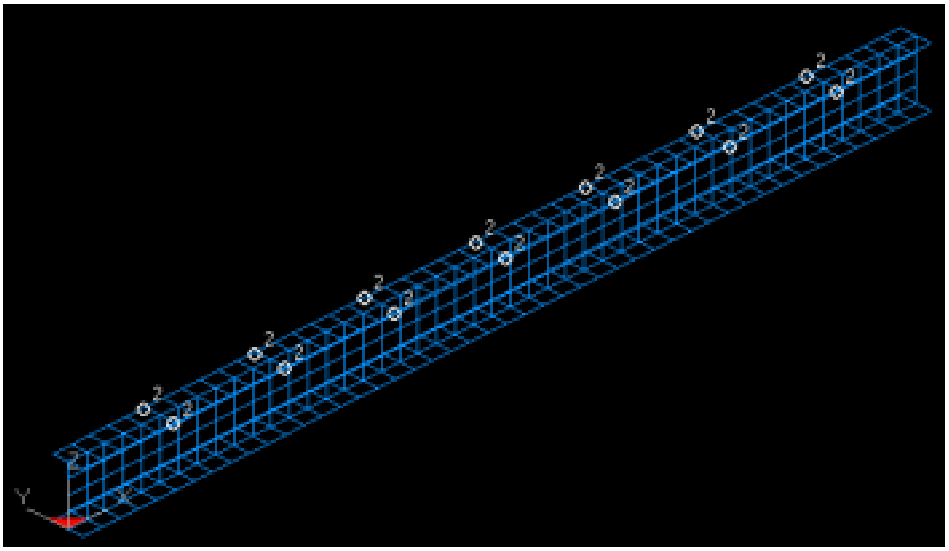


Figure 7.25. Lateral Bracing

7.4.3.8 Simulation Parameters

Various model inputs in addition to the physical parameters describing the beam, the boundary conditions, and the loading conditions must be defined. One series of these, which control a process known as dynamic relaxation, are important during the initial phases of the simulation. Dynamic relaxation techniques can be used to initialize the stress within the modeled structural member prior to the start of the simulation duration. Relaxation occurs when strain is suddenly applied to a viscoelastic material [29]. In order to simulate real building conditions, in which loads application to structural members is gradual in relation to a comparatively short fire (thermal loading) event, the stresses resulting from these loads must be brought to normal operating levels. The process of dynamic relaxation allows stress levels to be initialized at normal-temperature operating conditions prior to the application of thermal loads to the model.

The parameters that control the dynamic relaxation process within a LS-DYNA model include a convergence tolerance and a dynamic relaxation factor. These have been set to 0.001 and 0.995, respectively.

The total simulation time modeled here was 110 minutes. While it is possible to specify the time step that LS-DYNA uses, this simulation utilized LS-DYNA's ability to calculate an appropriate time step for a given simulation. This calculation bases the time step on the physical dimensions of the model elements. The time step size approximately corresponds to the time required for an acoustic wave to travel through an element along the shortest characteristic distance [28]. For the simulation described here, LS-DYNA calculated a time step of approximately 1.0×10^{-5} seconds.

7.4.3.9 Definition of Failure Conditions

As with the application of spreadsheet methods, and in the original laboratory tests [21], beam failure for the finite element analysis was defined as the point when the beam was no longer capable of supporting the imposed loads. As discussed previously, a collapse mechanism occurs when three plastic hinges develop within the beam, one at each end and the third within the span. Failure was assumed when each of these plastic hinges has formed. The formation of these plastic hinges was traced by monitoring the plastic strain within the beam. High levels of plastic strain (greater than 0.01 m/m or so) indicated transition to fully plastic behavior and the formation of plastic hinges.

7.4.4 Results and Conclusions

Analysis took place in two phases. The first phase involved loading the beam at normal temperature conditions and verifying the various model inputs. Figure 7.26 shows the deflected shape of the beam under the prescribed loading conditions at ambient temperatures. In this figure, deflection values are given in meters.

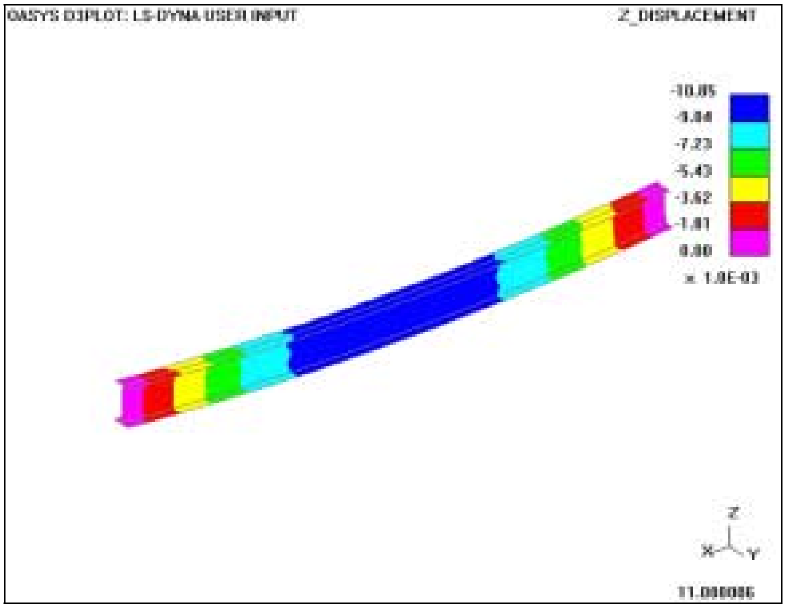


Figure 7.26. Displacement of Beam at Ambient Temperature Conditions

As can be seen in the figure above, the maximum deflection predicted by the model is approximately 0.011 m (0.40 in). This corresponds well with the predicted levels of deflection based on the given loading conditions and the use of elastic beam theory (as described in Appendix F). Similarly, the model predicted stress levels indicative of those expected in this beam. These are shown in Figure 7.27, in which stress values are given in units of Pa. Note that the yield strength of the steel beam is $250\text{x}10^6$ Pa (36 ksi), and that the maximum stresses expected in the beam based on flexural capacity formulas in $168\text{x}10^6$ Pa (24 ksi). This level of stress occurs in the bottom flange of the LS-DYNA beam model.

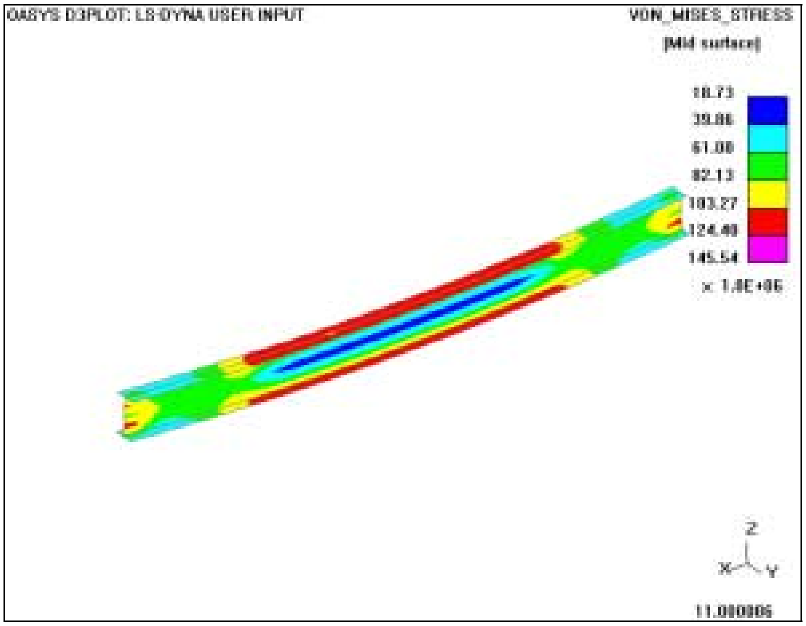
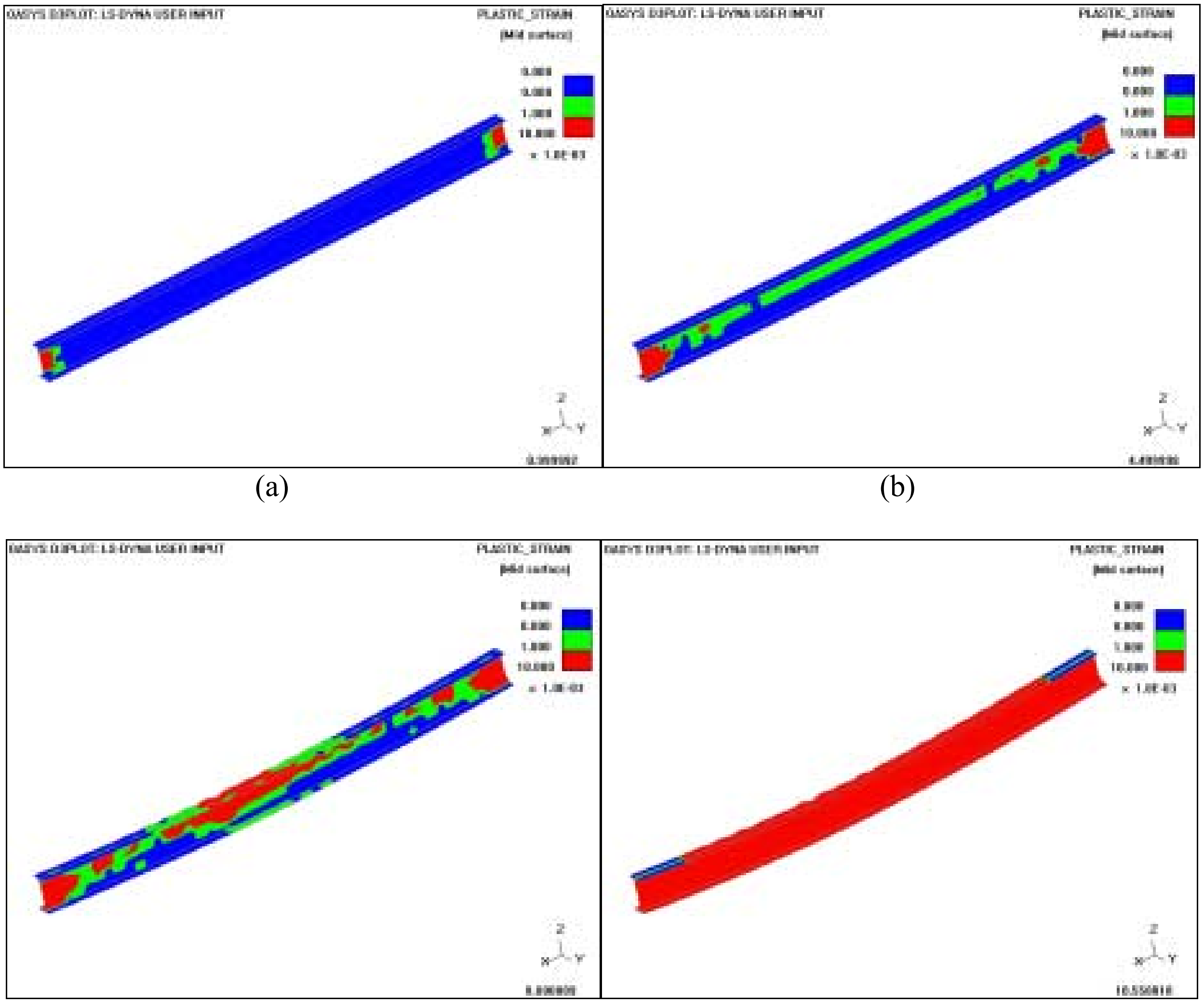


Figure 7.27. Member Stress at Ambient Temperature Conditions

The second phase of the analysis involved application of thermal loads as discussed earlier in Section 7.4.3.4.

During the heating of the steel beam, the development of plasticity was monitored by observing the plastic strain of different areas of the beam. Failure of the beam resulted after four distinct stages of plasticity development. Figures 7.28(a-d) show the sequential development of plasticity in the beam.



(a) (b)

(c) (d)

Figure 7.28.a-d Development of Plasticity in Model Beam

In (a), plasticity first began to develop at the beam's supports at approximately 20 minutes. Next, in (b), yielding began to occur in the upper portions of the web after 45 minutes. This behavior was due to the high thermal gradients experienced across the height of the web and between the two flanges. The bottom flange was exposed to higher temperatures, and thus expanded at a greater rate than the top flange. Additionally, the superimposed bending and axial compression conditions due to the beam's restraint against thermal expansion cause stresses in the web. In (c), yielding has begun to move to the bottom flange near the center of the span. However, the fixed ends continue to resist moment and prevent higher levels of yielding near the center of the beam's span. Lastly, at 105 minutes and 30 seconds, development of plastic hinges at the support points is completed, and all moments are transferred to the center of the beam. Plasticity develops almost instantaneously at this point, and the critical third plastic hinge forms, leading to collapse at this time. In comparison, the laboratory test predicted similar failure at 107 minutes [21].

Observation of the nodal displacement along the length of the beam (x direction) near the bolted supports in the beam's web can lend some insight into the development of plastic hinges at the supports. As the beam heats up and begins to deform, the nodes in the web near the supports undergo displacements. Prior to the formation of the plastic hinges at the supports, these nodes displace in the same direction (towards the supports) along the length of the beam due to thermal expansion. However, as plastic hinges begin to form, upper nodes within the web displace in the opposite direction to the lower nodes, a condition indicative of end rotation. Figure 7.29 shows approximate nodal movements subsequent to the formation of a plastic hinge at the support. The deformed orientation is exaggerated in this figure.

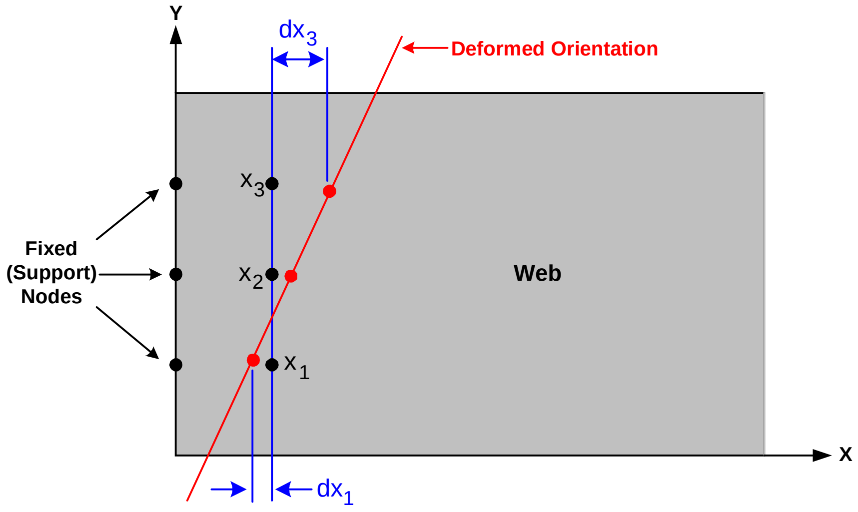


Figure 7.29. Approximate Nodal X-Displacements

Figure 7.30 tracks the x-displacements of nodes x_1 and x_2 in the previous figure. Note that a rather abrupt change in displacement direction occurs at approximately 65 minutes. This indicates that the fixed supports are no longer able to prevent end rotation due to the plasticity of the web at the connection.

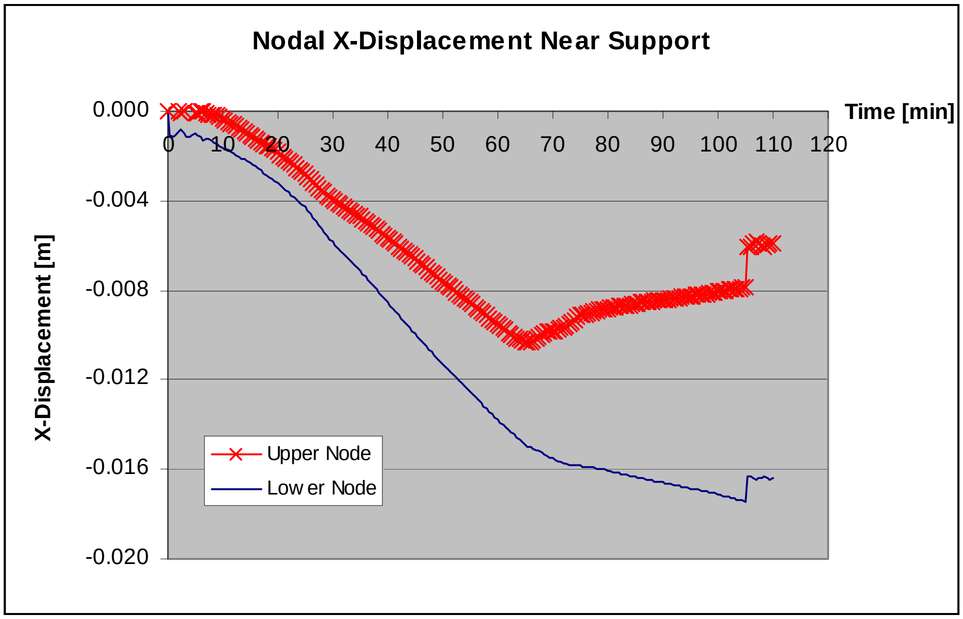


Figure 7.30.Nodal X-Displacement Comparison

Next, deflection will be considered. Figure 7.31 shows the deflection of the beam just before failure. Units in this figure are meters.

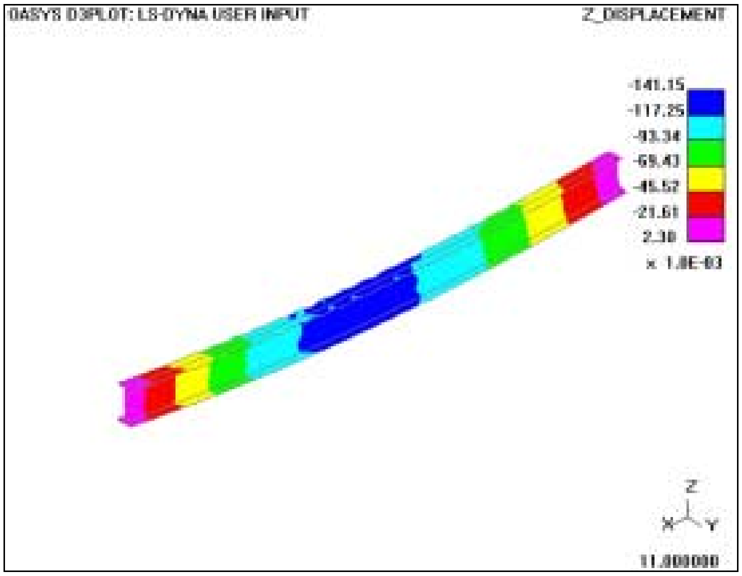


Figure 7.31.Beam Deflection at Elevated Temperatures (105 minutes)

The calculated maximum deflection just before failure is approximately 5.5 in (141 mm). This corresponds nicely with the value of maximum deflection just prior to failure in the laboratory test, which was recorded as 5.86 in (149 mm). Figure 7.32 compares the calculated maximum deflection of the beam with that observed during the test.

Note that, at approximately 65 minutes, a significant increase in the rate of deflection is observed. This is due to the formation of plastic hinges at the supports, as predicted by Figure 7.30. The laboratory test data (“observed” curve) suggests that plastic hinges began to form slightly earlier than LS-DYNA predicted, creating a deviation between observed and predicted deflection values between 50 and 65 minutes from the start of the test.

The results presented here indicate a high level of correspondence between the observed structural behavior of the test assembly and the calculated response predicted by LS-DYNA analysis.

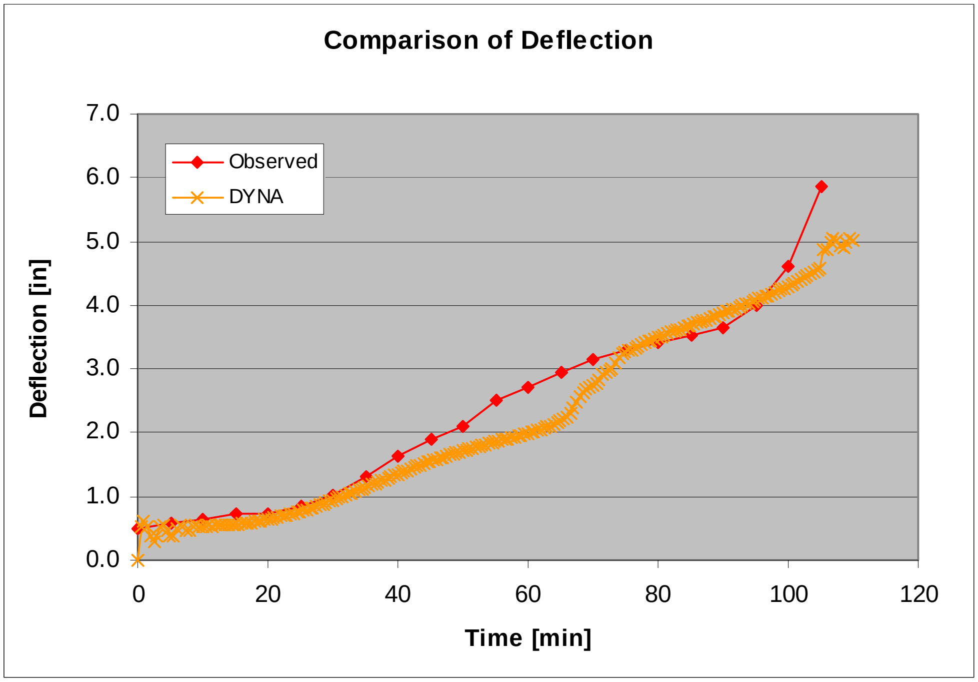


Figure 7.32.Comparison of Calculated Deflection to Observed Deflection

7.5 General Conclusions

This section compares the results of the two different analytical approaches utilized here to each other and to the data obtained during the laboratory fire test.

7.5.1 Comparison of Results Obtained from Different Methods

Table 7.5 compares the time to failure observed in each analytical method.

Table 7.5. Comparison of Time to Failure Predictions

Analysis Level	Predicted or Observed Time to Failure
Laboratory Tests (Level I)	107 minutes
Spreadsheet Applications (Level II)	100 minutes
Finite Element Analysis (Level III)	105 minutes, 30 seconds

Both analysis techniques predicted the time to failure of the beam well. The spreadsheet approach, with a deviation of 6.5% from laboratory results, was slightly less accurate than the finite element method, although both predicted failure times that could be considered conservative from a design point of view. A 6.5% underestimate of time to failure will not likely result in significant overdesign of the structural member, a condition that could raise cost issues. However, it does point out the need for experience and reasonable engineering judgment in using available analytical tools.

Deflection results did not compare as favorably as failure time estimates did. While the finite element method predicted deflection behavior that tracked well with that observed during the laboratory test, the simplified spreadsheet approach greatly under-predicted deflection values. Figure 7.33 compares these results.

The results of these comparisons indicate that deflection behavior is not predicted well through the use of simplified approaches based solely on expected changes to material properties at elevated temperatures. Such approaches overlook complex nonlinear behavior that contributes to member deformation.

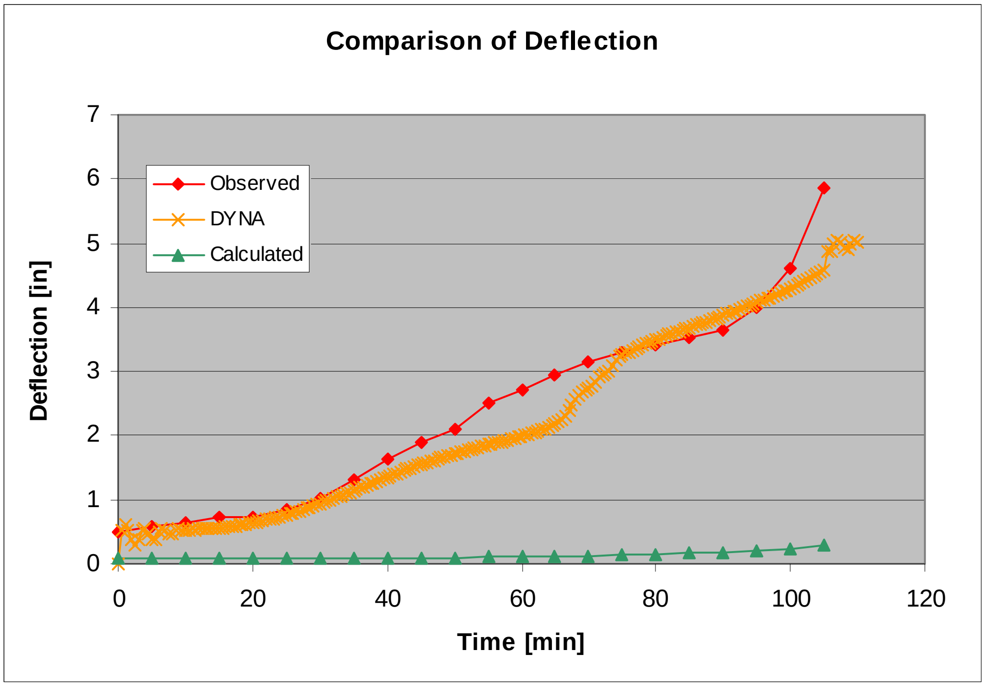


Figure 7.33. Deflection Comparison

7.5.2 Observed Benefits and Limitations

As has been previously discussed, spreadsheet applications and finite element methods appear to perform favorably in predicting time to failure. However, several limitations are associated with each analytical method.

Spreadsheet applications are very efficient. Once a basic spreadsheet template is established, a large number of instances of a given type of structural member can be analyzed in a relatively brief time period. This can be key in a design office where efficient tools used in a repetitive manner help to contribute to the rapidity of the design process. However, spreadsheet applications do not track member deformation well. If serviceability is a concern, spreadsheet applications based on correlations and basic physical laws may not provide accurate views of deformation behavior.

Finite element methodologies are much more rigorous for the analysis of structural components than spreadsheet applications. Also, they can be applied to assemblies, frames, and entire structures, while spreadsheet applications generally cannot. However, the appropriate use of finite element programs requires extensive knowledge of finite element methodologies and data appropriate to the behavior of materials under load and at elevated temperatures. The results of such a program can be no more accurate than the input. This places a burden on the engineer to use reliable sources for input parameters, to justify any decisions made during model formulation, and to use reasonable engineering judgment in evaluating results.

In the modern design office, time is an important commodity. Spreadsheet applications, subsequent to the initial development of spreadsheet templates, can take very little time and effort to use. On the other hand, finite element models can take extensive amounts of time to prepare, their analysis may take significant computer processing time, and the post-processing of results requires more time and effort than with simplified approaches. Because of these time requirements, finite element methods are generally only used in critical situations. It is left to the engineer to determine which situations must be considered critical.

Both analytical methods discussed here depend on the availability of temperature-dependent property data for the material being modeled. While sources of this data do exist, the completeness and accuracy of these sources may require verification by the engineer.

7.5.3 Foreseen Impact on Structural Fire Analysis

While a primary concern within the structural design office is the efficient and timely development of structural drawings and specifications such that time requirements of nonstructural elements of the building design and construction process are not negatively impacted, this work has shown that simplified analytical tools, while efficient, are not always appropriate for every situation. A simplified approach, as evidenced by the spreadsheet methodology implemented here, can perform well in meeting certain objectives, such as reasonably accurate definition of time to failure. However, the limitations of such a methodology must be understood and taken into account, and its application must be appropriately controlled.

This is not to say that detailed finite element analyses are necessary for all components of a structural system in order to determine true structural fire performance. Such an approach is highly impractical. It is left to the engineer to make judgments regarding specific structural configurations and to decide upon appropriate levels of analytical sophistication. For example, a certain connection may be view as critical to the stability of a given structural frame. The engineer may find it necessary to perform a finite element analysis on this portion of the structure in exclusion of the rest of the frame. The engineer may then be able to quantify the structural performance (to an acceptable degree) of the remainder of the frame using simplified approaches. In other cases, such as highly complicated structural configurations or buildings with occupancies considered critical, a comprehensive finite element analysis may be considered worthwhile.

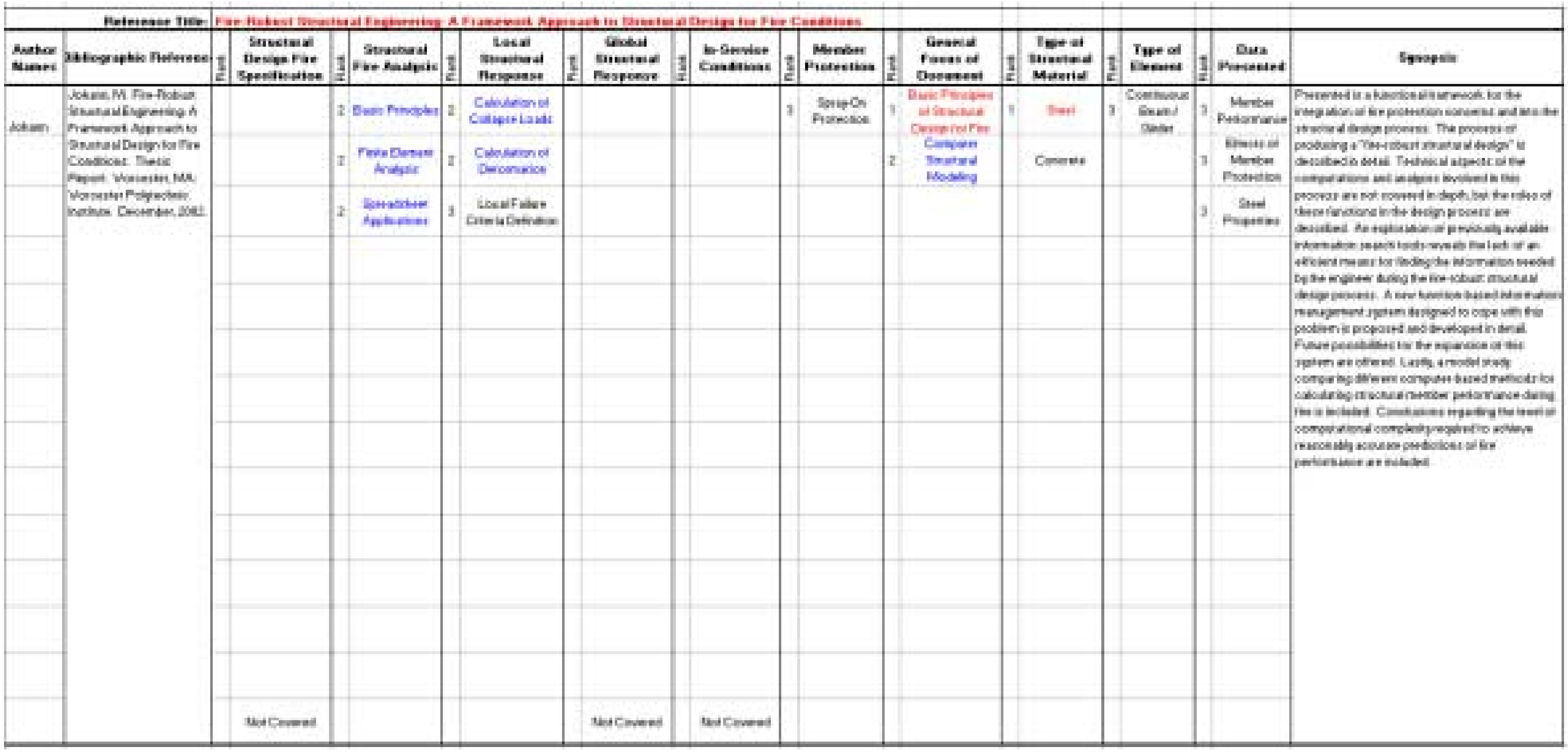
Studies such as this are useful in guiding the structural engineer in making appropriate decisions regarding analytical tools. The FRSE information management system is designed to provide engineers with sources of guidance for the various functions integral to fire-robust structural engineering. By populating the IMS with resources developed with the guidance of structural engineers in mind, the correct and appropriate practice of FRSE can be made possible.

7.5.4 Model Study Inclusion in the FRSE IMS

The model study was designed as an example of a type of resource that could be included in the FRSE IMS to guide the structural engineer in making decisions regarding the application of different analytical methods. To demonstrate how the model study could be included in the IMS, the record input for this thesis is included in Figure 7.34. The record entry covers the entirety of this thesis, but also points out the specific information provided by the model study. Topics listed in red are considered to be the primary foci of the document. Descriptors listed in blue are also considered to be important topics that are well covered in the document but receive less emphasis that primary topics. Topics listed in black are ancillary information that may be useful to the engineer but are not the foci of the document itself. This color-coding system allows the primary contributions of the study to be emphasized through its record entry.

7.5.5 Possible Future Work

This thesis includes two separate sections dealing with possible future work. Here, foreseen avenues of future research regarding the topic of this model study are discussed. Chapter 8 includes a discussion of future work related to the development and implementation of the FRSE process and the FRSE IMS.



Reference Title: Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions

Author Names	Bibliographic Reference	Rank	Structural Design Fire Specification	Rank	Structural Fire Analysis	Rank	Local Structural Response	Rank	Global Structural Response	Rank	In-Service Conditions	Rank	Member Protection	Rank	General Focus of Document	Rank	Type of Structural Material	Rank	Type of Element	Rank	Data Presented	Synopsis
Jokinen	Jokinen, M. Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions. Thesis Report. Worcester, MA: Worcester Polytechnic Institute. December, 2002.			2	Basic Principles	2	Calculation of Collapse Loads					3	Spray-On Protection	1	Basic Principles of Structural Design for Fire	1	Steel	3	Continuous Beam / Girder	3	Member Performance	Presented is a functional framework for the integration of fire protection concerns and into the structural design process. The process of producing a "fire-robust structural design" is described in detail. Technical aspects of the computations and analyses involved in this process are not covered in depth, but the roles of these functions in the design process are described. An exploration of previously available information search tools reveals the lack of an efficient means for finding the information needed by the engineer during the fire-robust structural design process. A new function-based information management system designed to cope with this problem is proposed and developed in detail. Future possibilities for the expansion of this system are offered. Lastly, a model study comparing different computer-based methods for calculating structural member performance during fire is included. Conclusions regarding the level of computational complexity required to achieve reasonably accurate predictions of fire performance are included.
				2	Finite Element Analysis	2	Calculation of Deformations							2	Computer Structural Modeling		Concrete			3	Effects of Member Protection	
				2	Spreadsheet Applications	3	Local Failure Criteria Definition													3	Steel Properties	
			Not Covered						Not Covered		Not Covered											

Figure 7.34.Record Entry for Thesis

Clearly, the model study presented here and the conclusions drawn herein cannot be considered a comprehensive and final overview of the topic of structural fire performance analysis methodologies. Also, it cannot be considered the final word on the analysis of spray-protected, fully fixed steel beam floor systems. This work has focused on a single laboratory test, and thus its conclusions are generally limited to this specific situation. However, it has shown the type of investigation necessary to draw useful conclusions about two different analysis methods, and thus it can be considered a template for the further exploration of this and other structural configurations.

It should be noted that the specific effects of the concrete slab were neglected in each analysis, excepting the imposition of distributed loads to represent the slab's self weight. The slab, in fact, may have several effects on the thermal and structural performance of the given assembly. These include heat sink effects that may serve to slow the heating of the steel beam, as well as the load-carrying capacity and deflection resistance afforded by the concrete itself. In regard to the former effect, the thermocouples that were used to record steel surface temperatures were tack welded to the beam, and were placed under the spray-on protection layer. This would tend to indicate that any heat sink effects attributed to the concrete would have been taken into account in the steel surface temperature readings.

In regard to the effect of the slab capacity, during the laboratory test, the slab was not reinforced with the intention of using it to carry load. Also, it was not constructed with shear studs necessary for composite action with the steel beam. For these reasons, it has been assumed here that the strength of the slab did not significantly contribute to the load-carrying capacity of the assembly. The favorable correspondence of the predicted failure times to that observed in the laboratory indicates that this assumption was most likely correct. However, situations may arise where the contributions of the concrete slab may be important. Further research into the effects of a concrete slab on the fire performance of a steel beam floor assembly is necessary to determine the true contributions of the slab to the system.

Several concerns have already been addressed in attempting to increase the accuracy of the deflection predictions made using the simplified spreadsheet approach. The effects of axial thrust and thermal expansion have been explored, but were not sufficient to explain the deviation between observed and calculated values. Extended research may be necessary to determine appropriate simplified methods for the prediction of deflection and the consideration of the complex plastic behavior (plastic hinge development and rotation of beam segments) governing such deflection.

It has been mentioned previously that the engineer must determine which situations should be considered critical and require in-depth, complex analysis, such as that achieved through finite element methodologies. Comprehensive guidance in making such decisions could be vital to the successful implementation of FRSE techniques, and thus should be the topic of significant future work.

Because each of the analytical approaches discussed here requires data on the temperature dependency of material properties, sources for appropriate values for these properties are required. Some data currently exists, especially regarding temperature effects on the yield strength, modulus of elasticity, and coefficient of thermal expansion of steel. However, in some cases other properties may be considered important to the structural performance of a given member or assembly. These may include Poisson's ratio and the plastic hardening modulus, which were discussed in Chapter 7.4 but were kept constant in the analysis. Future research into the temperature dependency of such parameters could be very beneficial.

8 OVERALL CONCLUSIONS

Due largely to the lack of a shared perspective, the structural engineer and the fire protection engineer have traditionally worked separately. However, they do share a common goal: to contribute to the design of safe buildings. The process of designing safe structures can only be optimized if the knowledge of these two disciplines is efficiently linked. To form this link, it may be necessary to move beyond the specification of hourly fire ratings for general classes of structural components and more towards the idea that fire causes specific structural stresses and strains that can be analyzed. The fire-robust structural engineering process presented in this work represents the integration of the analysis of fire-related stresses and strains into the traditional structural design process. By describing the FRSE process as a functional framework for engineering design and analysis, and by identifying a clear means of guiding the structural engineer in the practice of FRSE, this thesis has intended to provide a foundation for the growth and widespread implementation of performance-based structural fire protection.

8.1 Benefits of Fire-Robust Structural Engineering

The design and construction of buildings for robustness to extreme loading and environmental conditions created by earthquakes, windstorms, fires, and explosions has become an important aspect of the building industry over the past several decades. In the case of earthquakes and windstorms, modern building code provisions and engineering standards for structural design and disaster mitigation reflect the practical compilation and synthesis of findings from both field experience and scientific research efforts. In contrast, despite significant advances in the understanding of structural behavior under fire conditions over the last two decades, relatively few structural engineers are familiar with analytical techniques and scientific findings that the fire research community has developed to support the practice of structural design for fire safety. Consequently, structural design has continued to rely upon somewhat archaic methods of addressing structural fire safety.

The framework presented in this thesis has been developed in recognition of the need to integrate the findings from the fire research community into the practice of structural engineering. The fire-robust structural engineering process defines the functions necessary to develop a fire-robust design, and identifies sources of analytical and informational needs that the engineer must consider to execute such a design. Furthermore, it sets forth a formal definition of performance-based structural design. For such an approach to be widely accepted by engineers and regulatory bodies, it must be well defined, tested, and verified. This thesis has begun by defining the process. Future implementation of the process will depend on further development of the understanding of structural response to fire, as well as a consensus regarding the process itself. If this can be accomplished, the potential to improve the fire safety of new buildings is great.

8.2 Benefits of the FRSE Information Management System

The FRSE information management system is designed to be a comprehensive source for the information required by a structural engineer in carrying out fire-robust structural engineering tasks. Additionally, the structure of the system is such that the functions necessary to the design and analysis of structures for performance under fire conditions and their relationships within the overall FRSE process are identified. In this way, the system can act as an educational tool, and can help ensure that the structural engineer gives consideration to all functions needed to result in a fire-robust structure.

The FRSE IMS incorporates a record format that helps identify the potential benefits contained within resources. By doing so, the system can help engineers identify appropriate resources quickly, and can help eliminate wasted time and effort in exploring false informational leads possible with general search mechanisms and databases.

8.3 Anticipated Future of the IMS

The information management system version developed in this thesis is not ready for commercial application to structural design. This initial design was intended simply to demonstrate the proposed system architecture and the functionality afforded by the design. It is expected that future versions will expand upon the prototype version established herein.

The prototype version of the IMS is implemented using a spreadsheet program. The reasoning behind this has been discussed in Chapter 5. However, this format does not lend itself well to multiple users or availability on the Internet, where the greatest number of engineers could benefit from its use. Full-scale implementation of the system will require software development based on a more appropriate platform – one that is designed for multi-user object-oriented database functionality.

Additionally, initial full-scale implementation of the IMS in a public form will require a great amount of effort to categorize and input existing references based on the proposed record format. While this record format is partially based on traditional record format styles, the ranking scheme and summary components require the extra effort in resource compilation. The author submission form presented in Appendix D may serve to alleviate the burden of record compilation for recent documents, but many resources will still require external record compilation.

Based on observation of other publicly available database systems, maintenance of such a system may be as great a concern as original full-scale implementation. Research is constantly under way in the various aspects of structural design and analysis for fire conditions, and thus new resources are produced frequently. The IMS will be most effective if kept current, so efforts to update the database on a regular basis should be maintained.

Public implementation of the FRSE IMS will likely require committee or industry support for monetary, skills, and labor needs. Such support would also serve to regulate the implementation process and help ensure that the system design that is made available to the public is as beneficial as possible. Given a source of support for the implementation and maintenance of a full version of the information management system, it is foreseen that the system could be available to assist structural engineers with designing fire-robust structures within three to five years of the publication of this thesis.

8.4 Possible Future Work

The efforts of this thesis have made evident a series of tasks that are viewed as potentially beneficial but have been left for future work. These are discussed briefly here as a guide to others interested in furthering the work of this report. Also, these help to define the possible future path of FRSE process development. Please see the concluding section of Chapter 7 for future work relating directly to the model study.

- The FRSE process, as described in Chapter 3, includes many functions that are not fully understood. While the existing body of knowledge of structural fire protection is significant, many areas of research must be developed further before all aspects of structural performance under fire conditions can be fully understood. Each of these topics will not be specifically enumerated in here, but in general they include analysis methods, regulatory approaches to performance-based engineering, knowledge of material properties at elevated temperatures, understanding of complex structural behavior of individual members, connections, assemblies, frames, and entire structures, and improved design techniques.

- Many tools and techniques are available to accomplish different tasks. An example of this is evident in the model study carried out for this thesis, in which different analytical approaches were compared. In order to provide the structural engineer with guidance in choosing appropriate techniques for performing the functions of the FRSE process, additional studies are required. The model study provided in Chapter 7 presents a framework for carrying out such a study in a way that can help the engineer decide amongst competing methodologies. Such studies can be included in the Information Management System designed herein and can thus be made available to the practitioners of FRSE.

- In addition to guidance in deciding which tools are appropriate for given functions, engineers generally require assistance in using these tools. For example, the finite element analysis carried out for the model study required approximately three weeks of time to complete. It is estimated that 50% of this time was devoted to researching appropriate techniques and making decisions based on this research.

- Implementation of the FRSE information management system will require significant additional work. This work has been discussed in the previous subsection. It is considered critical to the widespread acceptance of the FRSE process since this process requires dissemination of knowledge to all structural engineers using FRSE.

REFERENCES

1. *SFPE Engineering Guide to Performance-Based Fire Protection, Analysis, and Design of Buildings*. Quincy, MA: National Fire Protection Association, 2000.

2. Burritt, B. "Functional Highway Design." *Civil Engineering*. Volume 65, Number 4, 1995.

3. Greene, J. et al. *Chemical Function Queries for 3-D Database Search*. Sunnyvale, CA: Molecular Simulations, Inc., 1994.

4. Lide, D. R., Ed. *Handbook of Chemistry and Physics*. Boston, MA: CRC Press, 1990.

5. McCormac, Jack C. *Structural Steel Design: LRFD Method. Second Edition*. New York: HarperCollins Publishers, 1995.

6. Peacock, R. et al. *CFAST, the Consolidated Model of Fire Growth and Smoke Transport*. Gaithersberg, MD: National Institute of Standards and Technology, 1995

7. Walton, W. D. *ASET-B: A Room Fire Program for Personal Computers.* Gaithersberg, MD: National Bureau of Standards, 1985.

8. McGrattan et al. *Fire Dynamics Simulator (Version 2) – User's Guide*. Gaithersberg, MD: National Institute of Standards and Technology, 2001.

9. Fitzgerald, R. W. *The Anatomy of Building Firesafety, Volume 1: A Way of Thinking. Draft 5.* Worcester, MA: Worcester Polytechnic Institute, 2001.

10. *Manual of Steel Construction: Load and Resistance Factor Design, Second Edition.* Chicago: American Institute of Steel Construction, 1998.

11. Buchanan, Andrew H. *Structural Design for Fire Safety*. Chinchester, England: John Wiley & Sons, 2001.

12. Engineering Village 2 Website: www.ei.org/eicorp/eicorp?menu=engineeringvillage2menu&display=engineeringvillage2

13. Silberschatz, A., Korth, H., and Sudarshan, S. *Database System Concepts, Fourth Edition.* New York: McGraw-Hill, 2002

14. *ANSI/NISO Z39.50-1995: Application Service Definition and Protocol Specification*. Bethesda, MD: National Information Standards Office, 1995.

15. Correspondence with Van Fleet, X., Manager of Information Products, American Society of Civil Engineers. July, 2002.

16. Correspondence with James, C., Earthquake Engineering Librarian, NISEE Information Systems Manager, Earthquake Engineering Research Center. July, 2002.

17. Jason, Nora H. *FIREDOC: An Automated Bibliographic Database.* Boston, MA: Society of Fire Protection Engineers, 1986.

18. Jason, Nora H. *FIREDOC User's Manual, Second Edition.* Gaithersburg, MD: U.S. Department of Commerce, National Institute of Standards and Technology, Building and Fire Research Laboratory, 1991.

19. Sriram, D., Logcher, R., and Fukuda, S., eds. "Computer-Aided Cooperative Product Development." *Proceedings of the MIT-JSME Workshop, Cambridge, MA, 1989.* Germany: Springer-Verlag, 1991.

20. *ASTM E119-00: Standard Test Methods for Fire Tests of Building Construction and Materials*, *2000 Revision*. West Conshohocken, PA: American Society for Testing and Materials, 2000.

21. Bletzacker, Richard W. *Effect of Structural Restraint on the Fire Resistance of Protected Steel Beam Floor and Roof Assemblies.* Columbus, OH: Ohio State University, Building Research Laboratory, 1966.

22. LS-DYNA Website: www.lstc.com

23. Pettersson, O., Magnusson, S., and Thor, J. *Fire Engineering Design of Steel Structures.* Lund, Sweden: Lund Institute of Technology, Division of Structural Mechanics and Concrete Construction, 1976.

24. Mills, A. F. *Heat and Mass Transfer*. Chicago: Richard D. Irwin, Inc., 1995.

25. Milke, J. "Analytical Methods for Determining Fire Resistance of Steel Members". *SFPE Handbook of Fire Protection Engineering, Second Edition*. Quincy, MA: National Fire Protection Association, 1995.

26. Hibbeler, R. C. *Mechanics of Materials, Third Edition.* New Jersey: Prentice Hall, 1997.

27. Versteeg, H. K and Malalasekera, W. *An Introduction to Computational Fluid Dynamics: The Finite Volume Method.* Harlow, England: Pearson Education Limited, 1995.

28. *LS-DYNA Keyword User's Manual, Volume 1.* Livermore, CA: Livermore Software Technology Corporation, 2001.

29. Spyrakos, C. and Raftoyiannis, J. *Linear and Nonlinear Finite Element Analysis in Engineering Practice*. Pittsburgh, PA: Algor, Inc., 1997.

30. Nelson, H. E. and Custer, R. L. P. "Applying Models to Fire Protection Engineering Problems and Fire Investigations." *NFPA Fire Protection Handbook, Eighteenth Edition*. Quincy, MA: National Fire Protection Association, 2000.

31. Breyer, Donald B., Kenneth J. Fridley, Kelly E. Cobeen. *Design of Wood Structures: ASD*, *Fourth Edition*. New York: McGraw-Hill, 1999.

32. Kirby, B. R. and Preston, R. R. "High Temperature Properties of Hot-Rolled Steels for Use in Fire Engineering Design Studies." *Fire Safety Journal*. Volume 13, 1988.

33. Thomasson, B. *High Performance Concrete: Design Guidelines, Report*. Sweden: Lund University, 1998.

34. White, R. H. "Analytical Methods for Determining Fire Resistance of Timber Members." *SFPE Handbook of Fire Protection Engineering, Second Edition*. Quincy, MA: National Fire Protection Association, 1995.

35. Hibbeler, R. C. *Structural Analysis, Fourth Edition*. New Jersey: Prentice Hall, 1999.

APPENDIX A. GLOSSARY OF TERMS USED IN FRSE

As-Built Condition	The structural and architectural configuration in place at the time of occupancy of a building. This may or may not differ from the configuration specified in the design process.
Basic Principles	Theoretical relationships used to describe the physical and chemical processes occurring during a fire. These relationships are based on the laws of thermodynamics and physics rather than experimental observations or data.
Boundary Thermal Properties	Surface characteristics used to define the boundaries of a fire compartment for the purpose of predicting fire behavior. These details may include heat transfer parameters and combustibility characteristics used to determine the impact of the compartment bounding materials on the behavior of a fire within the room.
Building Standards	Accepted methods of achieving a given level of structural performance or safety. Building codes and regulations often refer to standards for guidance in achieving required levels of structural performance.
Code-Defined Loads	Gravity loading conditions (dead, live, snow loads, etc.) prescribed by applicable building codes or standards used to define required levels of load-carrying capacity of structures in normal temperature conditions.
Compartment Fire Tests	Scale or full-size fire simulations carried out to observe various aspects of fire behavior in a given compartment orientation. The results of such tests are often extrapolated in the prediction of fire conditions in compartments within planned or existing buildings.

Computational Fluid Dynamics Programs	Computer models that divide a space or compartment into a series of comparatively small elements (called *cells*) and analyze a fire's effects on these cells and the cells' interactions with each other (in terms of mass and energy flow). CFD models are expensive in terms of the effort and computer power required to run them, but they are useful in situations where space or fuel configuration is irregular, turbulence is a critical element, or fine detail is required [30].
Concept	An initial building perception that may include ideas on the basic architectural configuration, the usage, and the layout of a proposed building.
Consideration of Seismic Loads	A portion of the structural design process that takes into account the forces imposed upon a structure by an earthquake or similar seismic event. These considerations may include inertia forces, damping forces, elastic forces, and an equivalent forcing function [31].
Consideration of Wind Loads	A portion of the structural design process that involves the impact of the lateral forces developed as wind contacts the vertical surfaces of a building.
Define Model Room	The process of describing all aspects of the compartment for which a design fire is to be specified. Details may include dimensions, surface materials, ventilation conditions, fuel package descriptions, and possible ignition sources.
Describe In-Service Condition	The process of identifying the configuration of a building during a given point in its service life. This configuration may differ from that specified in the design of the building or that resulting from the construction process.

Describe Performance	The process of identifying the adequacy of a given structural configuration in relation to performance criteria set forth by the building's stakeholders.
Design for Fire Impact	Determination of a structural system's expected response to the high temperature conditions experienced during a fire event and evaluation of that response through comparison to performance criteria defined by the building's stakeholders in an effort to ensure acceptable performance during a real fire event.
Design for Gravity Loads	Structural design process that assumes a normal temperature operating environment and code-specified gravity and occupancy loading conditions. This process generally takes into account dead, live, and snow loads to determine suitable dimensions for structural members, connections, and details based on the predicted strength and serviceability performance of these elements under the given loading conditions.
Excessive Deformation	The state of bending or otherwise changing the shape of a structural member beyond a defined limit point. Such a limit point may be defined in terms such as building serviceability or capacity requirements.
Failure (Performance) Criteria	Limiting values of structural response modes with which the adequacy and performance of trial structural designs is judged [1].
Failure Rates	Statistical data that can be used in the prediction of the frequency of the failure of systems or components to perform as originally designed.
Finalized Design	A structural design that adequately meets all performance criteria, both in terms of normal temperature operation and response to fire conditions, for which final drawings and specifications are issued for construction.

Finite Element Analysis	Analysis methods, generally implemented in computer form, that can be used to predict mechanical events by representing solid materials by a mesh of small geometric elements (bricks, shells, etc.). Physical principles are used to determine the reaction of these elements under defined forces and the different cells' interaction with each other. Use of such methods can result in highly accurate prediction of complex mechanical behavior.
First Principle Computer Models	Computer models that automate the use of theoretical first principle relationships for the prediction of fire behavior within compartments.
First Principle Equations	Relationships based on accepted scientific principles (conservation equations, energy and mass transfer equations, etc.) that can be used to predict fire behavior within buildings.
Fuel Load	The material available within a given compartment to support the combustion process. Factors affecting the fuel load of a compartment include material type, amount, and configuration.
Global Structural Response	The response of a structural system as a whole to a fire event. This includes the interaction of all members included within a given structural configuration and the distribution of loads amongst these members.
Impact of Pre-Fire Event	Changes to the structural configuration resulting from non-fire events, including earthquakes, floods, blasts, and other accidental or intentional acts, as well as deterioration of structural or protective materials and accidental removal of protective coverings.
Initial Architectural Design	The spatial and visual configuration of a building specified during the development phases of the building design.

Initial Structural Design	A building's structural configuration based upon a structural design process that assumes normal temperature conditions and building code-based design considerations.
Inspection	The process of physically examining a structure to identify the current architectural and structural conditions.
Investigate Collapse Loads	The process of determining the ultimate load-carrying capacity of individual structural elements or assemblies in order to predict loading conditions that would cause collapse. Collapse loads are generally compared to actual loading conditions to determine the adequacy of a structural design.
Investigate Deformation	The process of determining the level of bending or other changes to original member shape caused by loading conditions imposed on that member.
Investigate Other Failure Modes	The process of exploring specific local mechanisms (other than deformation and collapse due to excessive load) that may cause a member to fail based on defined failure criteria. This generally includes consideration of response mechanisms that are specific to particular structural materials or types of elements.
Load Redistribution	A global structural response mechanism that involves the transfer of applied loads from member to member within a structural system. This often occurs when a member or members fail(s) and the loads applied to the structure must follow new load paths to be supported. A lack of available sufficient alternate load paths may lead to collapse.

Material Properties	Combustion and heat transfer parameters that can be used to predict the ignition and burning characteristics of various materials within a fire compartment. These are critical for predicting ignition, fire growth, flame spread, and fire size.
Modifications or Protection for Fire	Alterations to a building's original structural configuration that may change the fire performance of the structure. Such changes may include the addition or removal of protective materials, or any changes to structural members resulting from non-fire events (accidental or intentional) or general deterioration during occupancy.
Normal Structural Design	The structural configuration resulting from a traditional structural design process assuming normal temperature conditions.
Original Structural Design	The structural configuration specified during a building's design process, be it through traditional, normal temperature design, or through fire-robust design or some other specialized design process.
Performance and Risk Economics	Considerations or metrics used in the process of deciding on appropriate performance criteria or in judging the predicted performance of a structure in relation to such performance criteria. Performance and Risk Economics can include consideration of structural performance, serviceability and safety, as well as constructability and cost.
Post-Fire Condition	The structural configuration of a building subsequent to a fire event, with consideration of any damage to, weakening of, or removal/collapse of any structural elements.

Progressive Collapse	A global structural response mechanism that involves the gradual or sudden failure of structural member(s) and the transfer of the loads they previously supported to other members that are not able to support the imposed loads, and therefore collapse as well.
Protection Re-Design	Reconsideration of the protective measures prescribed for a given structural member or system for which inadequate performance has been predicted in an effort to improve that member or system's fire performance.
Regulations	Building standards that are enforceable by law and are designed to prescribe design and construction requirements for different types of occupancies.
Room Size	The geometric dimensions (length, width, and height) of the fire compartment in question.
Safety Factors	Adjustments made to compensate for uncertainty in the methods, calculations, and assumptions employed in the development of structural designs [1].
Select Fire Scenarios	The process of deciding upon appropriate sets of conditions to describe the worst-case situation(s) of fire development and spread of combustion products through a given building.
Spreadsheet Applications	Computer implementation of basic concepts and correlation equations for the purpose of predicting structural response to fire conditions.
Statistics	Data drawn from a review of historical events that can often be extrapolated for the prediction of future events. Such data may include frequencies of events, severities of different types of events, etc.

Structural Design Fire	A set of conditions that describes the development of a fire and the conditions created by the fire within the fire compartment. In this case, design fires are limited to those that have some impact of the structural system of a building.
Structural Fire Analysis	The process of determining the impact of the conditions generated by a fire within a building on the structural systems of that building and the response of the building to those conditions.
Variability	A measure of the range over which a given parameter's value may fall. Consideration of variability is important in fire protection due to the highly complicated, parameter-sensitive nature of fire behavior.
Ventilation	The availability of air (oxygen) in a given fire compartment for the support of combustion within that compartment. A lack or surplus of oxygen can affect fire growth and must be considered in the prediction of fire behavior within a compartment. Sources of ventilation can be in place before a fire (open doors, windows) or can be created by the fire (window breakage, barrier failure).

APPENDIX B. OVERVIEW OF MATERIAL RESPONSE TO FIRE

This appendix provides a general overview of the ways in which different structural materials respond to elevated temperature conditions during a fire.

B.1. Response of Steel Members to Fire

When a steel member is exposed to fire conditions, and its temperature is increased, several specific changes occur. At elevated temperatures, the strength of steel and its stiffness both decrease. This can lead to deformations greater than those experienced at normal temperatures, and possibly to failure of a member or structural system. The response of a steel member to fire conditions depends on two major considerations:

- the fire to which the member is exposed, and
- the loading conditions experienced by the member during exposure.

The response of a steel structural member to a given fire depends on the severity of the fire, as well as the way the fire grows (fire growth curve) and the heat transfer mechanisms occurring between the fire and the member. Additionally, the portion of the member that is exposed to the fire's heat controls the level to which the fire affects the member. Lastly, any applied protection, be it sprayed-on coatings, slab or board insulation, or shielding, will decrease the heat transfer to the member and thus lessen the fire's impact on that member.

As a steel member is heated, its strength decreases. Figure B.1 shows how steel strength is affected by an increase in temperature [11].

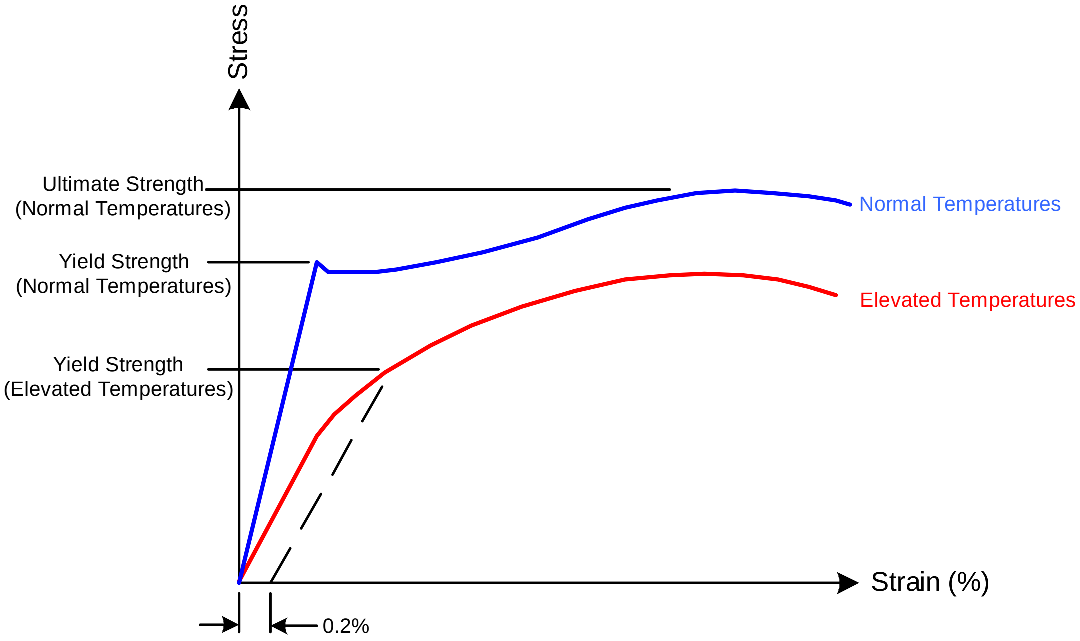


Figure B.1 Effect of Increased Temperatures on Steel Strength

As can be seen in Figure B.1, at normal temperatures, a well-defined yield strength exists. This yield strength value is generally used for design purposes. However, at elevated temperatures, the yield point becomes less well defined. In this case, a yield point must be defined in terms of an allowable level of strain. In the figure above, the dashed line is drawn parallel to the linear elastic portion of the elevated temperature strength curve with its origin at a defined acceptable level of strain. The point at which this line intersects the strength curve corresponds to the yield strength of the material at elevated temperatures. Recommendations for an acceptable level of strain range from 0.2% to 1% [32].

Unprotected steel structural members tend to perform rather poorly under fire exposure when compared with concrete or timber members. This is because, for normal temperature conditions, relatively thin steel members can be used to support large loads. Thin steel members have small thermal mass values when compared to larger concrete or timber members. Coupled with the fact that steel has a high thermal conductivity when compared to other structural materials, this results in rapid heating of the cross section of a steel member. Consequences of this may include rapid loss of strength and excessive deformation and expansion. The effects of high temperatures on structural steel can be greatly reduced by protecting the members using some sort of applied fire protection.

B.2. Response of Concrete Members to Fire

Concrete is a notoriously good performer during fires. It is a noncombustible substance, and has a low thermal conductivity. Thus, concrete members do not heat rapidly across their cross sections. Also, water, which is a main component in a concrete mixture, causes an endothermic reaction when a concrete member is heated. This reaction tends to control the rate of temperature rise of the concrete.

Even though concrete has a high level of inherent fire resistance, it is rarely used in construction by itself. Because it is only effective in compression, concrete must be reinforced with other materials, such as steel bars or mesh. Often, the ultimate performance of concrete members in a fire depends on the performance of their reinforcement. The concrete acts as an insulator for the reinforcement, but because the reinforcing steel generally consists of numerous steel members with small cross sections, large increases in temperature may not be required to fail them. Concrete members that are exposed to some degree of tensile loading generally fail in this mode, and the failure is generally a result of loss of reinforcement.

In situations where tensile failure of reinforcing material is not the primary failure mechanism, such as in pure axial compression, the strength of the concrete determines fire performance. For design purposes, a simplified approach to concrete's loss of strength at elevated temperatures is adopted. Generally, all portions of a concrete member seen to be at or under 500°C (932°F) are assumed to exhibit full strength. Areas above 500°C area assumed to have zero strength, and are ignored during capacity calculations [33].

Concrete can also experience a phenomenon known as spalling. Spalling is not well understood at this point, but it is generally assumed to be dependent on the type of aggregate used in the concrete mixture, the occurrence of thermal stresses at the corners of members, or the loss of water from the cement paste. When spalling occurs, the protective layer of concrete covering reinforcing materials can be lost, thus exposing the reinforcement to high temperatures and possibly causing failure at an earlier time that would be expected if the concrete stayed intact. Studies have shown that high moisture content, rapid heating rates, highly slender members, and large material stresses can all result in spalling [11].

B.3. Response of Timber Members to Fire

Timber structures fall into two general categories:

- Heavy timber construction (beams and columns > 150 mm minimum nominal dimension, decks > 50 mm nominal thickness) [31], and
- Light timber construction.

Many years of experience in the construction industry has shown that heavy timber construction performs very well in a fire. Initially, the outside surface of an exposed heavy timber member may ignite and burn rapidly. As this layer burns, it creates a layer of char surrounding the unburned wood below it. The char layer helps insulate the unburned wood, and results in a decrease in the burning rate REF. Some heat does penetrate the char layer, however. This heat can result in evaporation of moisture from near the surface of the unburned portion of the timber. Some of this moisture can serve to increase the moisture content of the unburned wood further in towards the center of the member, thus increasing its level of protection.

For design, charred portions of a timber member are considered to have zero strength. Correlations exist to predict the charring rate of different wood species [34]. These correlations can be used to predict the depth of the char layer over the course of a fire, and the resulting loss of section can be take into account during calculations of performance.

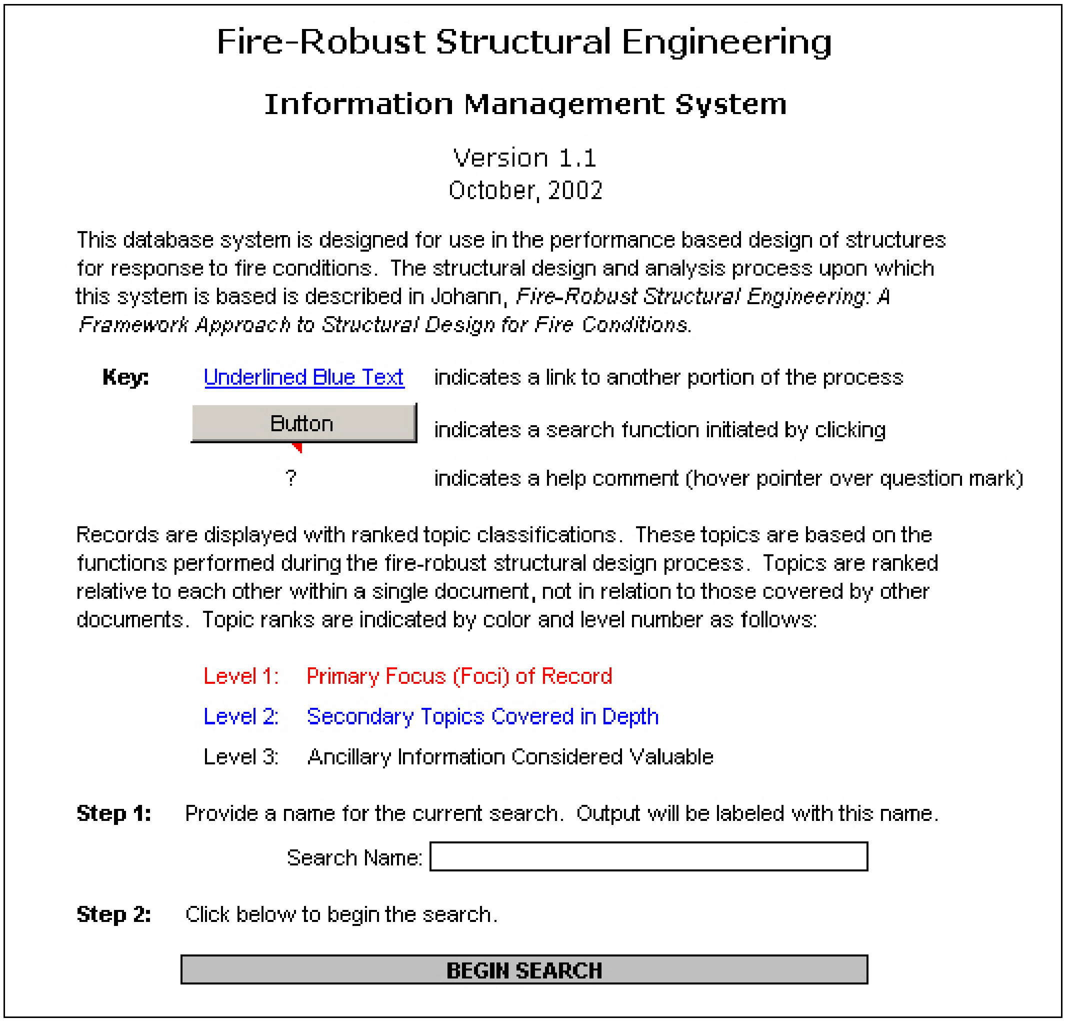
Light timber construction has very little inherent fire resistance. This is because light timber members may be very small in cross section, and thus small to moderate char layer depths can result in proportionally significant loss of section. Also, a small cross section will allow heat to travel throughout the thickness of a member much more rapidly than in a larger member. Because of these observations, the fire performance of light timber construction is generally dependent on protective materials. Common protective materials for light timber construction include:

- Gypsum board (drywall);
- Plywood, particle board, or other wood-based panel materials;
- Cement-based panels; and
- Calcium silicate board.

When a light timber member is protected by one of the methods discussed above, the result is a reduction of heat transfer to the member and a shielding of the sides of the member from the fire. Charring may take place only on the side of the member in contact with the protective material. Thus, member section is not lost as rapidly as without the protection.

The success of a light timber assembly depends largely on the quality of the construction. If the protective layer of gypsum, plywood, or the like is penetrated, burned away, or otherwise lost, and light timber members are exposed directly to fire, failure conditions can develop rapidly. Because of this, light timber construction is often designed, specified, and tested as an entire assembly, including wood members, joinery details, and protective materials.

APPENDIX C. IMS SCREENSHOTS



Fire-Robust Structural Engineering

Information Management System

Version 1.1
October, 2002

This database system is designed for use in the performance based design of structures for response to fire conditions. The structural design and analysis process upon which this system is based is described in Johann, *Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions.*

Key:

Underlined Blue Text	indicates a link to another portion of the process
Button	indicates a search function initiated by clicking
?	indicates a help comment (hover pointer over question mark)

Records are displayed with ranked topic classifications. These topics are based on the functions performed during the fire-robust structural design process. Topics are ranked relative to each other within a single document, not in relation to those covered by other documents. Topic ranks are indicated by color and level number as follows:

Level 1:	Primary Focus (Foci) of Record
Level 2:	Secondary Topics Covered in Depth
Level 3:	Ancillary Information Considered Valuable

Step 1: Provide a name for the current search. Output will be labeled with this name.

Search Name:

Step 2: Click below to begin the search.

CHART 1: THE FIRE-ROBUST STRUCTURAL DESIGN PROCESS

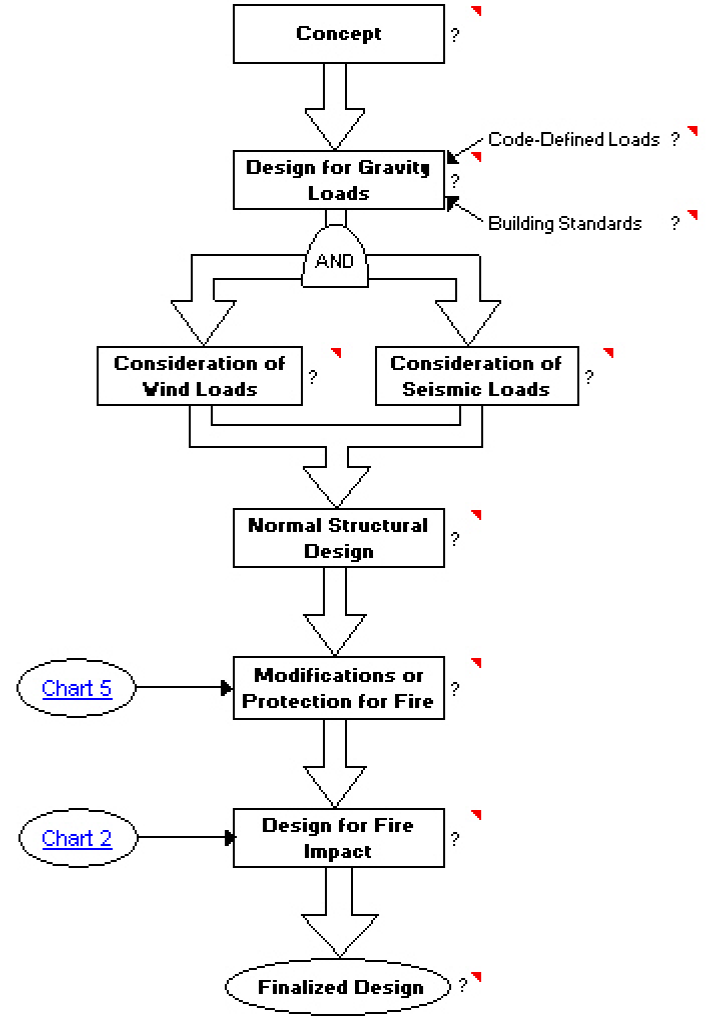


CHART 2: THE STRUCTURAL FIRE ANALYSIS PROCESS

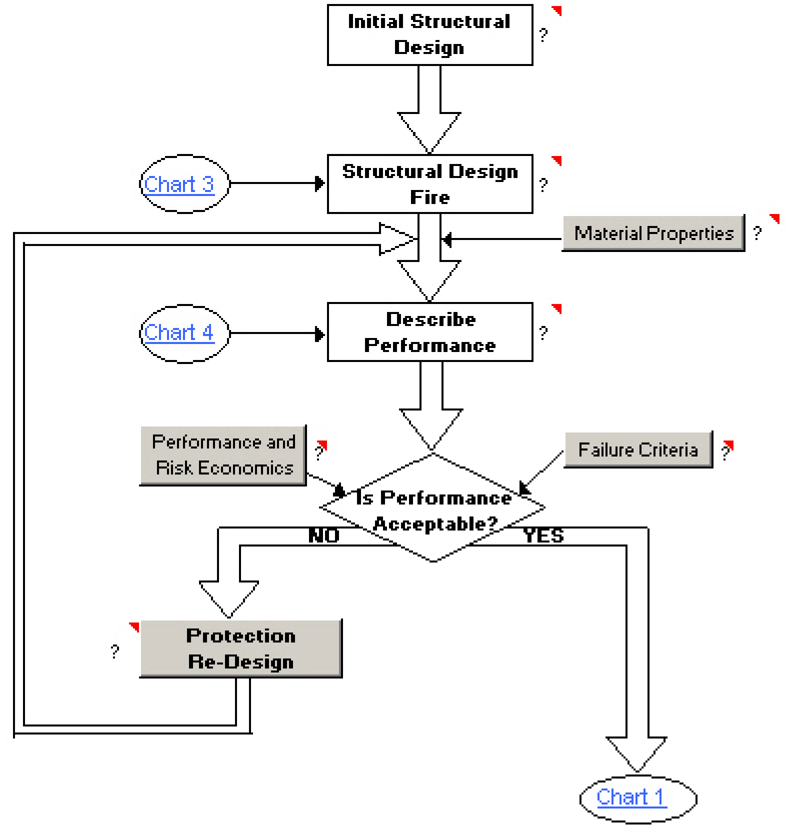


CHART 3: THE STRUCTURAL DESIGN FIRE QUANTIFICATION PROCESS

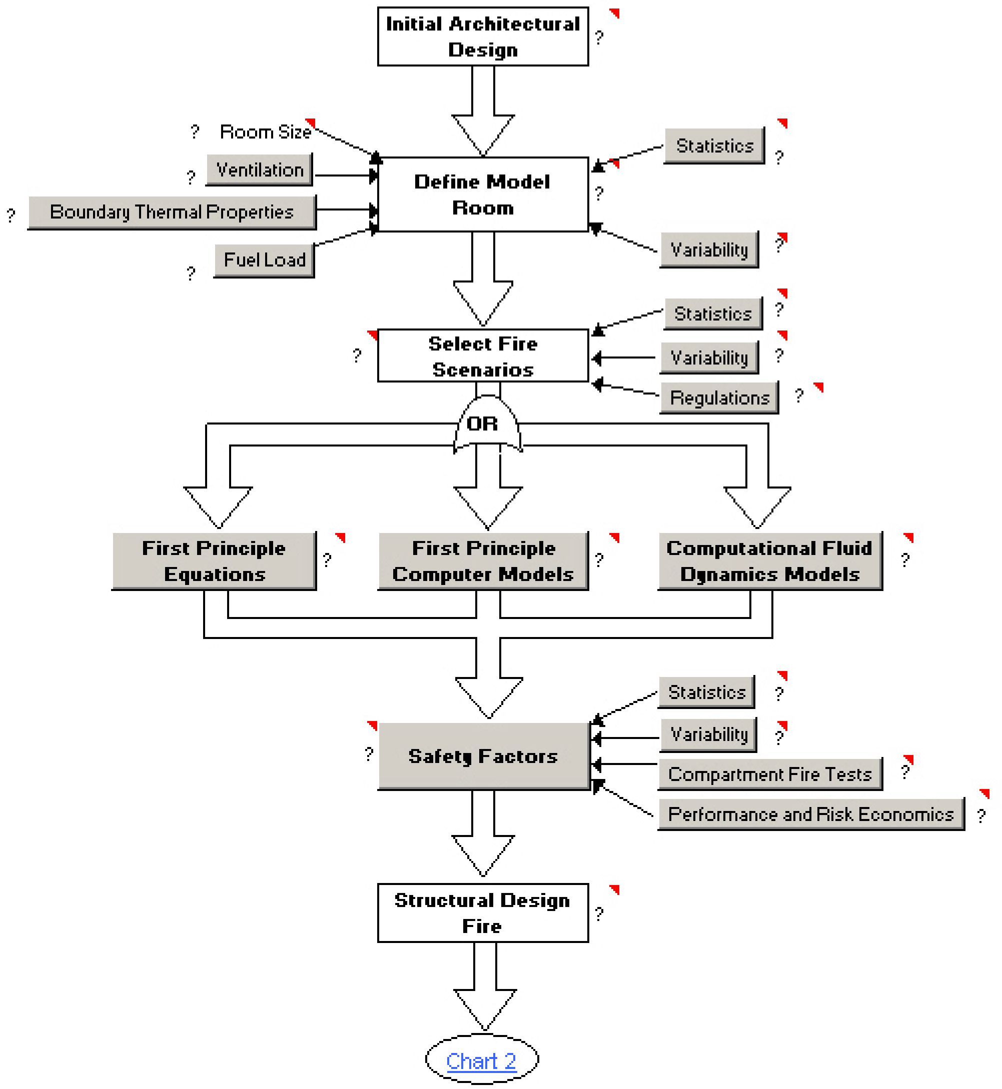


CHART 4: IDENTIFICATION OF STRUCTURAL FIRE PERFORMANCE

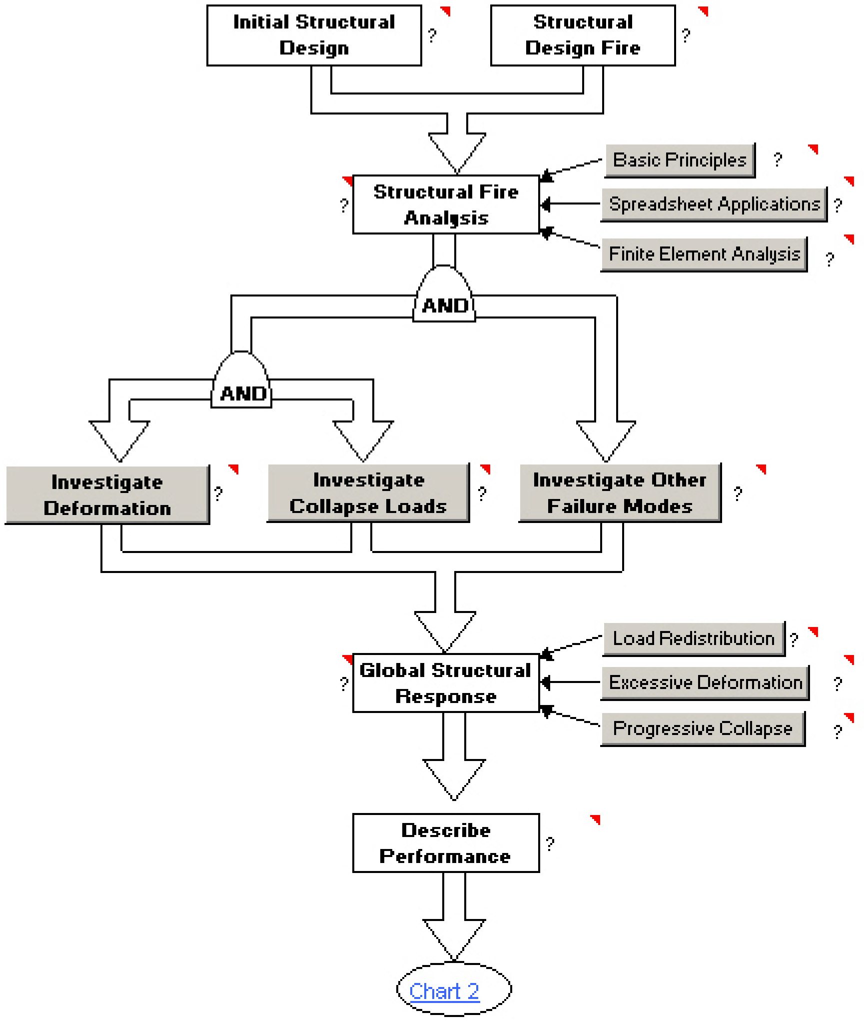
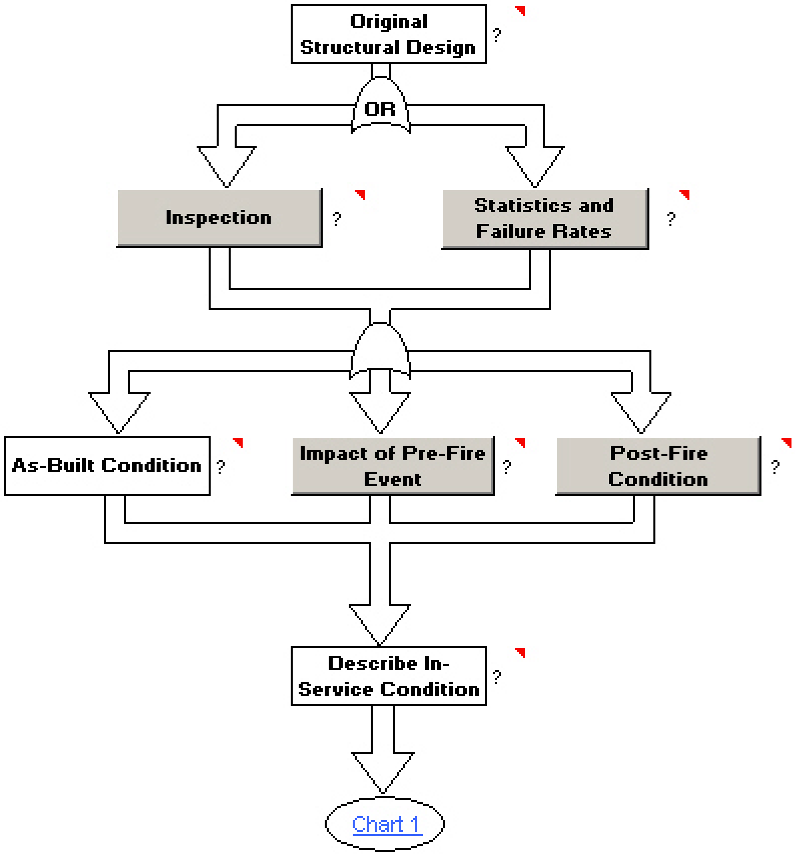


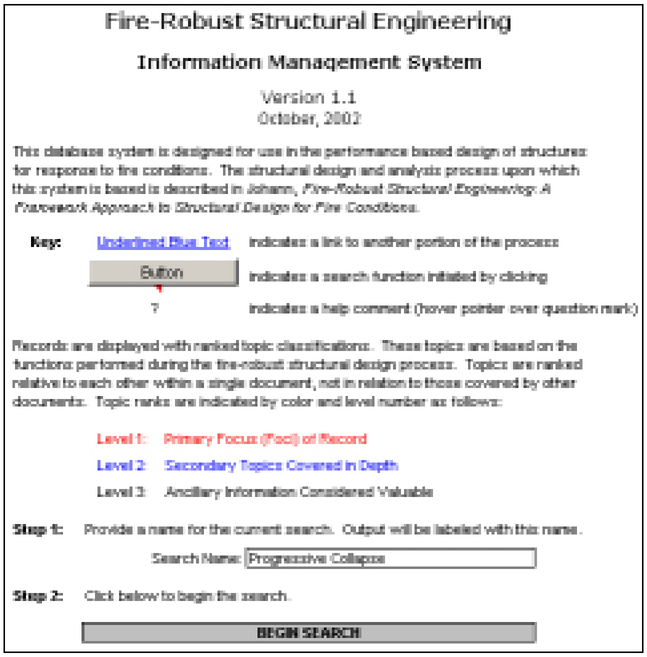
CHART 5: IDENTIFICATION OF IN-SERVICE STRUCTURAL CONDITIONS



APPENDIX D. IMS SEARCH EXAMPLES

This appendix includes examples of different queries that can be performed using the FRSE IMS. As discussed in Chapter 5, the system includes four orders of query complexity. Examples from different query orders are included here.

To begin any search, the engineer first enters a title for the search (see Figure D.1). This allows the results of the search to be labeled for differentiation from those of other queries.



Fire-Robust Structural Engineering

Information Management System

Version 1.1
October, 2002

This database system is designed for use in the performance based design of structures for response to fire conditions. The structural design and analysis process upon which this system is based is described in Johann, *Fire-Robust Structural Engineering: A Framework Approach to Structural Design for Fire Conditions.*

Key: Underlined Blue Text indicates a link to another portion of the process
Button indicates a search function initiated by clicking
? indicates a help comment (hover pointer over question mark)

Records are displayed with ranked topic classifications. These topics are based on the functions performed during the fire-robust structural design process. Topics are ranked relative to each other within a single document, not in relation to those covered by other documents. Topic ranks are indicated by color and level number as follows:

Level 1: Primary Focus (Foci) of Record
Level 2: Secondary Topics Covered in Depth
Level 3: Ancillary Information Considered Valuable

Step 1: Provide a name for the current search. Output will be labeled with this name.

Search Name: Progressive Collapse

Step 2: Click below to begin the search.

Figure D.1. Title Specification

A First Order search is the simplest type of query. As an example, consider a situation in which an engineer is looking for resources discussing the topic of progressive collapse of structural systems. This is a global response mechanism, and is included in Chart 4 of the FRSE process. The engineer can either follow the process through the first and second charts, or can jump directly to Chart 4 (Identification of Structural Performance). Then, the engineer must click on the “Progressive Collapse” button (see Figure D.2). This initiates the query, and all records in the database relating to this topic are displayed. Figure D.3 shows an example record from this list of results.

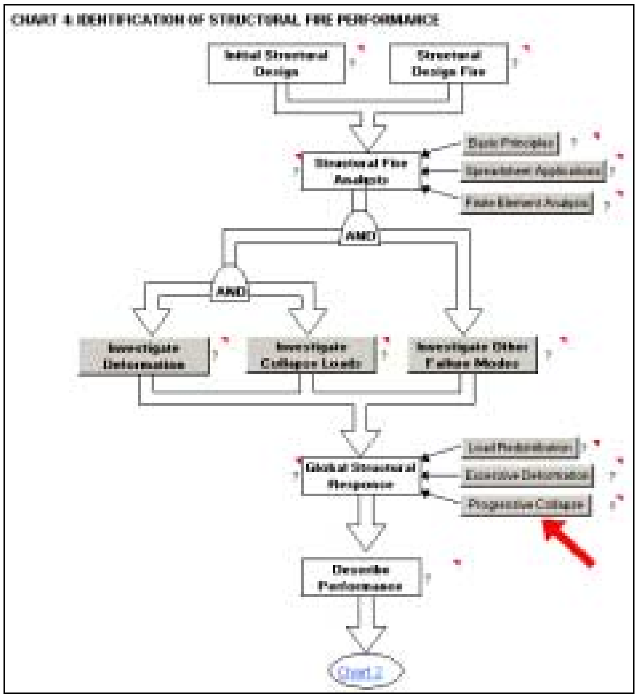


Figure D.2. Function Choice: Progressive Collapse

Figure D.3. Search Results: Progressive Collapse

The next example involves a Second Order search. This query is slightly more complicated than a Level 1 search. Suppose an engineer is interested in finding information regarding the definition of failure criteria for global response mechanisms. This topic is covered in Chart 2 (Structural Fire Analysis) of the FRSE process. The engineer must navigate through the system to this chart, and then must click the button marked “Failure Criteria” (Figure D.4).

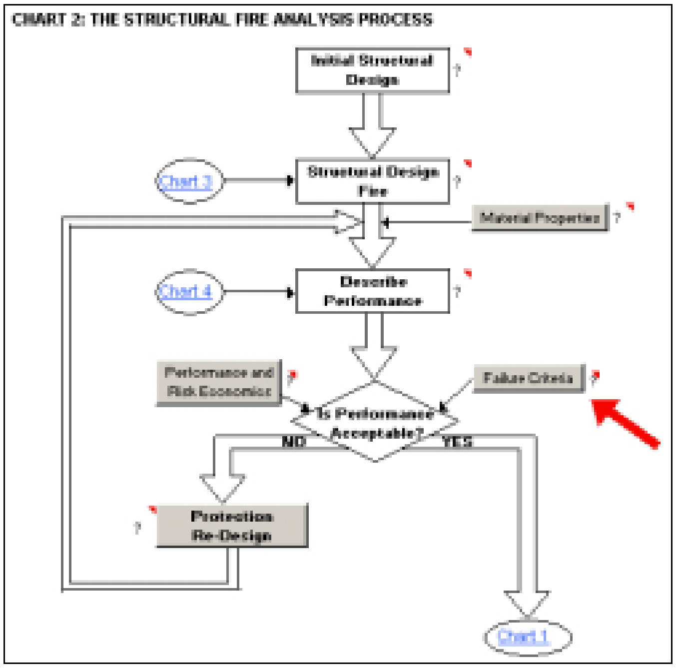


Figure D.4. Function Choice: Failure Criteria

At this point, the engineer is given the option of finding resources for local or global failure criteria definition. In this case, the engineer chooses "Global Failure Criteria" by clicking the corresponding radio button, as shown in Figure D.5.


Failure Criteria

Choose from the following types of failure criteria:

○ Local Failure Criteria

● Global Failure Criteria

Figure D.5. Failure Criteria Type Choice

At this point, the search is initiated, and all records included in the database dealing with the definition of global failure criteria are displayed. Figure D.6 gives an example record from this list. Note that Order 3 queries are performed in a similar manner to Order 2 queries, and thus an example of an Order 3 query is not included here.

Figure D.6. Search Results: Global Failure Criteria

As an example of the use of the FRSE IMS for an Order 4 search, assume a structural engineer is involved in designing a structural system, and requires information on the failure modes that must be considered in the analysis of steel columns exposed to elevated temperatures. The analysis of structural members during the FRSE process is included in Chart 4 (Identification of Structural Performance). Once Chart 4 is activated, the engineer can search for information regarding various types of failure modes. For the purposes of this example, assume that the engineer is interested in exploring column buckling. Chart 4 indicates that this topic occurs under the function "Investigate Other Failure Modes." Thus, the engineer clicks on this button (see Figure D.7).

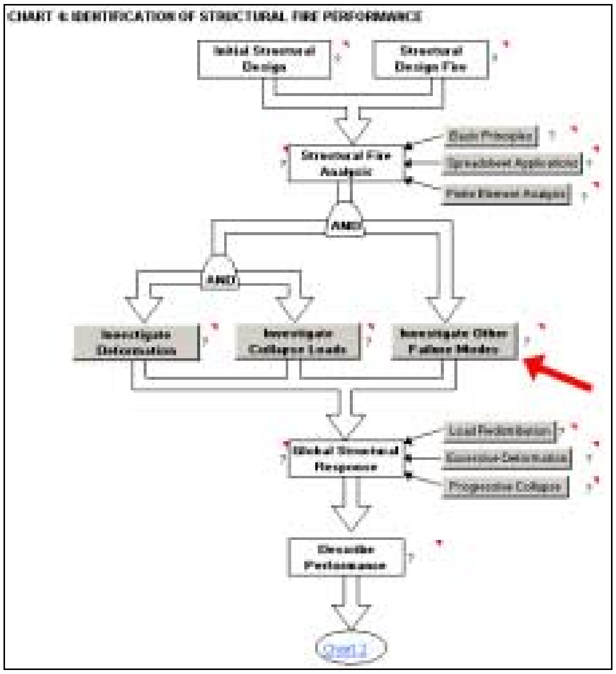
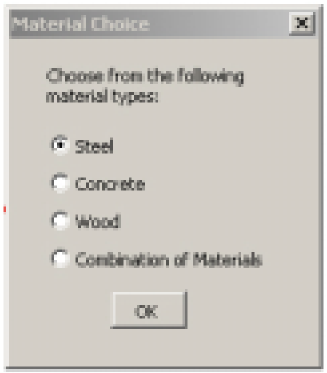


Figure D.7. Function Choice: Investigate Other Failure Modes

Next, the engineer is given a choice of materials, as shown in Figure D.8. The topic of interest is steel, and thus the engineer clicks the corresponding radio button and then clicks "OK" to continue.

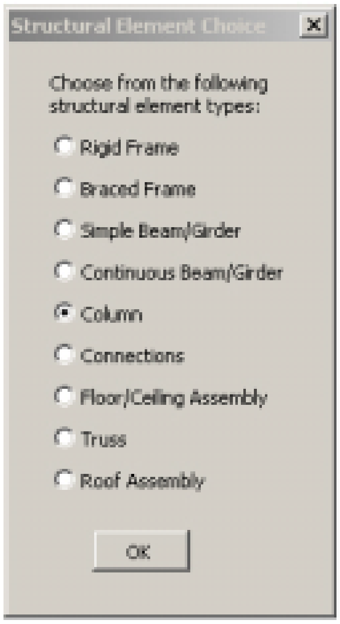


Choose from the following material types:

● Steel
○ Concrete
○ Wood
○ Combination of Materials

Figure D.8. Material Choice

The engineer is now presented with a choice of member types. Here, "Column" is chosen, and "OK" is clicked to continue (see Figure D.9).



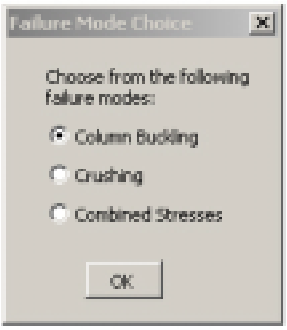
Structural Element Choice

Choose from the following structural element types:

- ○ Rigid Frame
- ○ Braced Frame
- ○ Simple Beam/Girder
- ○ Continuous Beam/Girder
- ● Column
- ○ Connections
- ○ Floor/Ceiling Assembly
- ○ Truss
- ○ Roof Assembly

Figure D.9. Member Type Choice

Lastly, the engineer must choose from a list of possible failure modes, as shown in Figure D.10. This list is dependent on the type of material and member chosen. The choices displayed in this case should be considered when analyzing a steel column. The engineer is interested in column buckling, and thus chooses the corresponding radio button, and the clicks “OK” to continue.



Failure Mode Choice

Choose from the following failure modes:

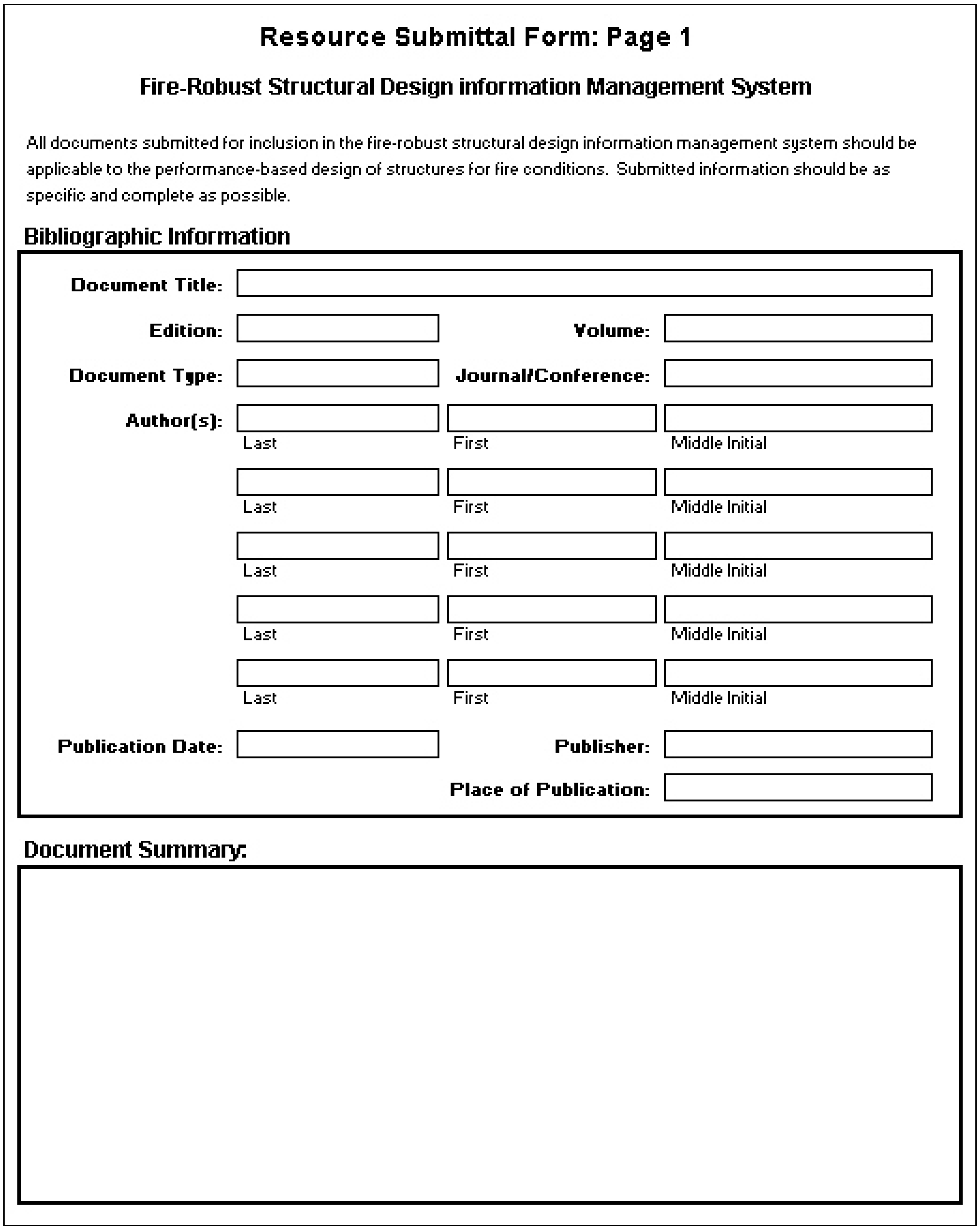
- ● Column Buckling
- ○ Crushing
- ○ Combined Stresses

Figure D.10. Failure Mode Choice

At this point, the query is initiated, and all resources providing information on the buckling of steel columns are presented, as shown in Figure D.11.

Figure D.11. Search Results Report

APPENDIX E. AUTHOR SUBMISSION FORM



Resource Submittal Form: Page 1

Fire-Robust Structural Design information Management System

All documents submitted for inclusion in the fire-robust structural design information management system should be applicable to the performance-based design of structures for fire conditions. Submitted information should be as specific and complete as possible.

Bibliographic Information

Document Title:

Edition: **Volume:**

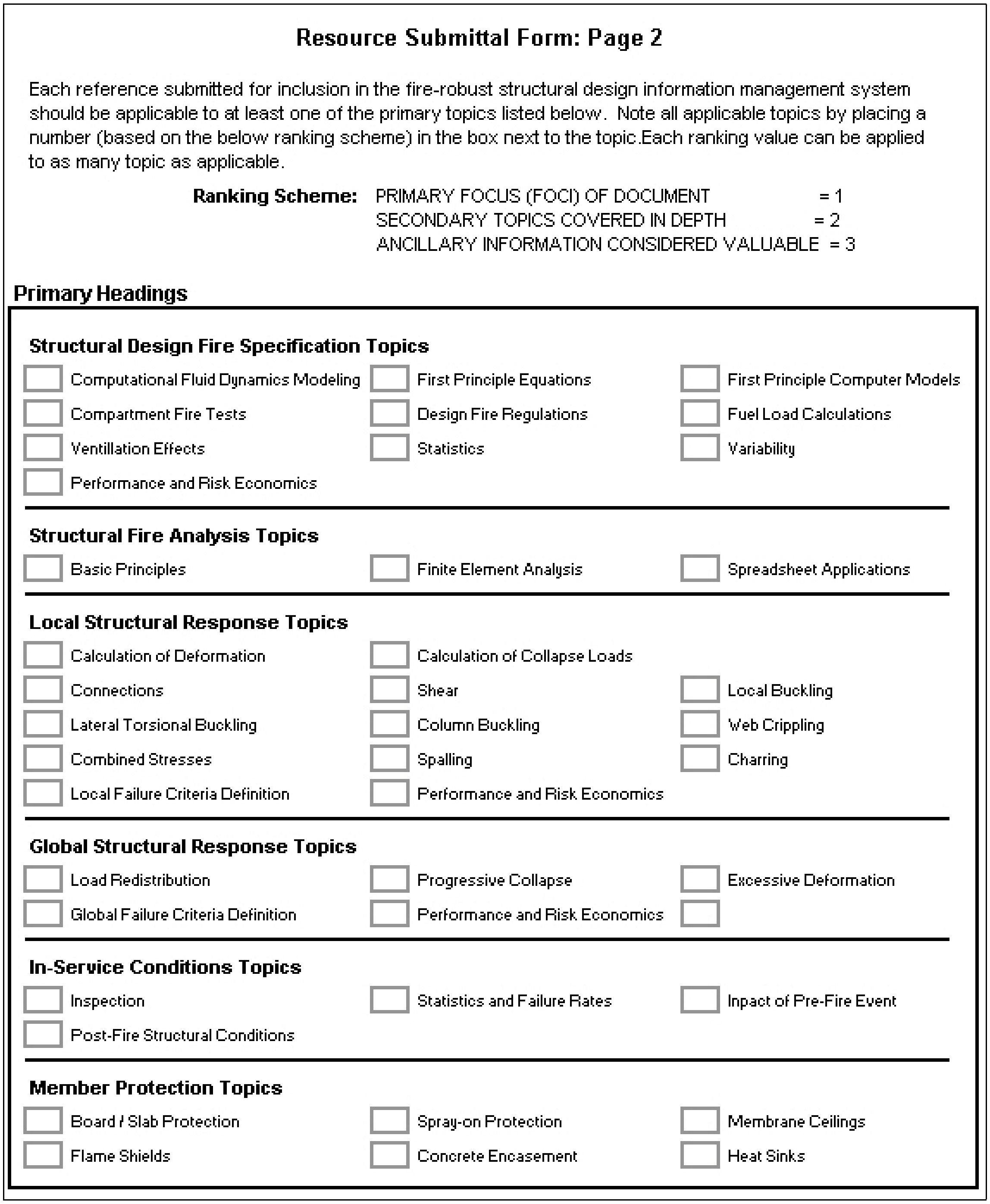
Document Type: **Journal/Conference:**

Author(s):
Last First Middle Initial
Last First Middle Initial
Last First Middle Initial
Last First Middle Initial
Last First Middle Initial

Publication Date: **Publisher:**

Place of Publication:

Document Summary:



Resource Submittal Form: Page 2

Each reference submitted for inclusion in the fire-robust structural design information management system should be applicable to at least one of the primary topics listed below. Note all applicable topics by placing a number (based on the below ranking scheme) in the box next to the topic.Each ranking value can be applied to as many topic as applicable.

Ranking Scheme: PRIMARY FOCUS (FOCI) OF DOCUMENT = 1
SECONDARY TOPICS COVERED IN DEPTH = 2
ANCILLARY INFORMATION CONSIDERED VALUABLE = 3

Primary Headings

Structural Design Fire Specification Topics

☐ Computational Fluid Dynamics Modeling
☐ Compartment Fire Tests
☐ Ventillation Effects
☐ Performance and Risk Economics
☐ First Principle Equations
☐ Design Fire Regulations
☐ Statistics
☐ First Principle Computer Models
☐ Fuel Load Calculations
☐ Variability

Structural Fire Analysis Topics

☐ Basic Principles
☐ Finite Element Analysis
☐ Spreadsheet Applications

Local Structural Response Topics

☐ Calculation of Deformation
☐ Connections
☐ Lateral Torsional Buckling
☐ Combined Stresses
☐ Local Failure Criteria Definition
☐ Calculation of Collapse Loads
☐ Shear
☐ Column Buckling
☐ Spalling
☐ Performance and Risk Economics
☐ Local Buckling
☐ Web Crippling
☐ Charring

Global Structural Response Topics

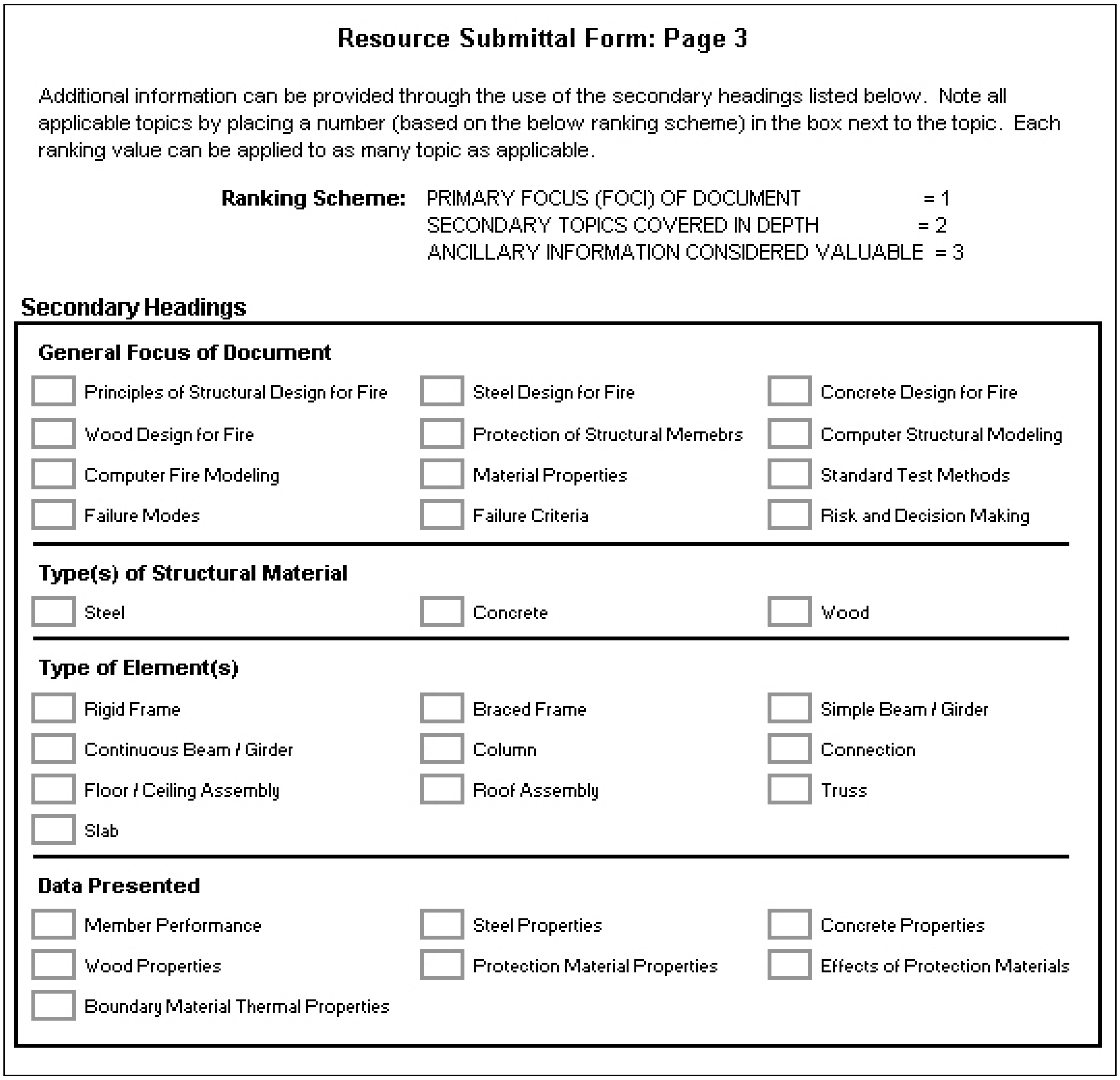
☐ Load Redistribution
☐ Global Failure Criteria Definition
☐ Progressive Collapse
☐ Performance and Risk Economics
☐ Excessive Deformation
☐

In-Service Conditions Topics

☐ Inspection
☐ Post-Fire Structural Conditions
☐ Statistics and Failure Rates
☐ Inpact of Pre-Fire Event

Member Protection Topics

☐ Board / Slab Protection
☐ Flame Shields
☐ Spray-on Protection
☐ Concrete Encasement
☐ Membrane Ceilings
☐ Heat Sinks



Resource Submittal Form: Page 3

Additional information can be provided through the use of the secondary headings listed below. Note all applicable topics by placing a number (based on the below ranking scheme) in the box next to the topic. Each ranking value can be applied to as many topic as applicable.

Ranking Scheme:
PRIMARY FOCUS (FOCI) OF DOCUMENT = 1
SECONDARY TOPICS COVERED IN DEPTH = 2
ANCILLARY INFORMATION CONSIDERED VALUABLE = 3

Secondary Headings

General Focus of Document

☐ Principles of Structural Design for Fire
☐ Wood Design for Fire
☐ Computer Fire Modeling
☐ Failure Modes
☐ Steel Design for Fire
☐ Protection of Structural Memebrs
☐ Material Properties
☐ Failure Criteria
☐ Concrete Design for Fire
☐ Computer Structural Modeling
☐ Standard Test Methods
☐ Risk and Decision Making

Type(s) of Structural Material

☐ Steel
☐ Concrete
☐ Wood

Type of Element(s)

☐ Rigid Frame
☐ Continuous Beam / Girder
☐ Floor / Ceiling Assembly
☐ Slab
☐ Braced Frame
☐ Column
☐ Roof Assembly
☐ Simple Beam / Girder
☐ Connection
☐ Truss

Data Presented

☐ Member Performance
☐ Wood Properties
☐ Boundary Material Thermal Properties
☐ Steel Properties
☐ Protection Material Properties
☐ Concrete Properties
☐ Effects of Protection Materials

APPENDIX F. SPREADSHEET ANALYSIS METHODOLOGY

The spreadsheet analysis presented in Section 7.3 is based on procedures set forth in Pettersson and Magnusson, *Fire Engineering Design of Steel Structures* [23]. This resource provides methodologies for the determination of the temperature of a protected member's cross-section as a function of time during an elevated temperature event (a fire). Given such calculations, the engineer can utilize correlations for temperature-dependent material properties to predict a member's response to the elevated temperature conditions. The calculation procedure presented herein is readily implemented in spreadsheet form.

F.1. Calculation of Protected Beam Temperature

In a lumped parameter analysis, it is assumed that the entire cross section of the steel member in question is at the same temperature at any point in time.

The first step in calculating the capacity of a protected steel member is to calculate the temperature of the steel at the various time steps over the duration of the given fire. The change in steel temperature over a given time step is:

$$\Delta T_S = \left[\frac{\lambda_i}{d_i c_p \gamma}\right]\left(\frac{A_i}{V_S}\right)\left(T_g - T_S\right)\Delta t \qquad \text{[Eq. F.1]}$$

where,

ΔT_S = change in steel temperature during the given time step [°C]
λ_i = thermal conductivity of the insulation [kcal/m °C hr]
d_i = insulation thickness [m]
c_p = specific heat of steel (0.13 kcal/kg °C)
γ = density of steel (7850 kg/m³)
A_i/V_S= ratio of inner surface area of insulation to volume of steel [m^{-1}]
T_g = gas temperature [°K]
T_S = temperature at previous time step [°K]
Δt = time step (hrs)

In this analysis, the time step is based on the ASTM standard fire time-temperature curve, for which temperature data is given in 5-minute increments. Increasing the time step may result in more precise definition of a failure point, but a 5-minute time step is expected to provide reasonable results.

The ratio A_i/V_S depends on the type of protection. The protection used in this analysis is a sprayed-on coating.

Figure F.1 shows the sprayed-on configuration on a beam or girder with a concrete slab above.

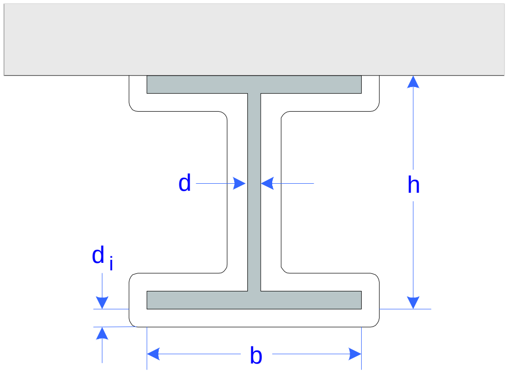


Figure F.1. Spray-Protected Beam or Girder

For sprayed-on protection on a beam or girder, the following formula is used:

$$A_i/V_S = (2h + 3b - 2d) / A_m \qquad \text{[Eq. F.2]}$$

where,

h = overall height of the member [in]
d = flange thickness [in]
b = overall width of the member [in]
A_m = cross-sectional area of the member [in^2]

F.2. Calculation of Beam Capacity

As a steel member is heated during a fire, various physical properties of the material change. This is the basis for the spreadsheet approach to the calculation of a beam's capacity at elevated temperatures. The temperature dependent properties of steel members are defined by the following equations [25]:

$$\sigma_{y\theta} = \sigma_{y0}\left(1 - 0.78\theta - 1.89\theta^4\right) \quad \theta < 0.63 \qquad \text{[Eq. F.3]}$$

where,

$\sigma_{y\theta}$= yield strength at elevated temperature [ksi]
σ_y = yield strength at room temperature [ksi]
$\theta = (T - 68)/1800$, T in [°F]
T = steel temperature [°F]

Also,

$$E = E_0(1-2.04\theta^2) \quad \theta < 0.63 \qquad \text{[Eq. F.4]}$$

where,

E = modulus of elasticity at elevated temperature [ksi]
E_0 = modulus of elasticity at room temperature [ksi]
$\theta = (T - 68)/1800$, T in °F
T = steel temperature [°F]

and,

$$\alpha = (6.1 + 0.0019T) \times 10^{-6} \quad \theta < 0.68 \qquad \text{[Eq. F.5]}$$

where,

α = coefficient of thermal expansion [in/in°F]
T = steel temperature [°F]

Using the equations presented above and the steel temperatures calculated using the lumped parameter approach, one can determine the capacity of a beam versus time during a fire event.

The beam discussed in Section 7.2 was loaded at its outer quarter points during the fire tests. With the assumption of fixed-end restraint, failure occurs in two phases. During the first phase, maximum elastic bending moments occur at the ends of the beam, as shown in Figure F.2. The first phase will progress until these fixed-end moments exceed the plastic moment capacity of the beam (refer to Equation F.8) and plastic hinges form. For phase two, the loads act on a different elastic system than in phase one. The beam essentially behaves as a simply-supported beam, redistributing the maximum moments to the center of the span (see Figure F.3). Ultimate failure occurs when this new maximum moment at the center of the beam's span also exceeds the plastic moment capacity. This results in instability due to the occurrence of three collinear hinges.

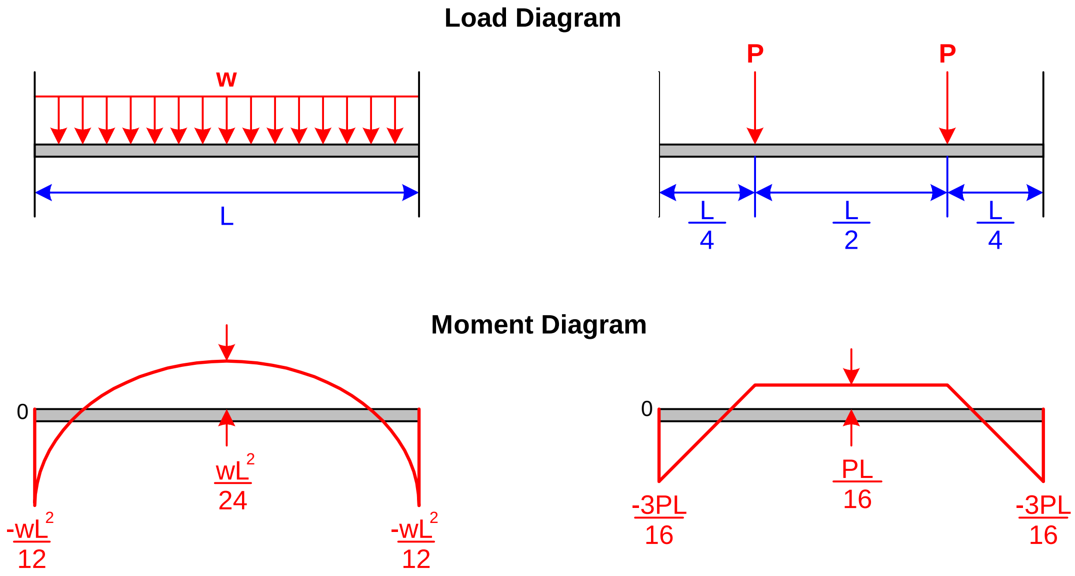


Figure F.2. Loading and Moment Diagrams for Fixed End Condition

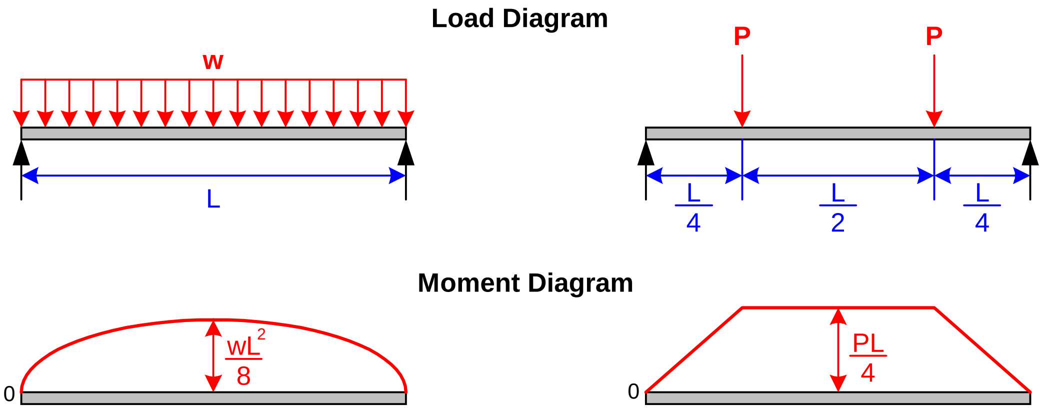


Figure F.3. Loading and Moment Diagrams for Simply Supported Condition

The load capacity of a beam with ends fixed and loads applied to the outer quarter points under normal temperature operating conditions is given by:

$$P_1 = \frac{16\left(M_{\max} - M_{dead,1}\right)}{3L} \qquad \text{[Eq. F.6]}$$

where,

P_1 = superimposed load capacity for phase one [kips]
M_{max} = moment capacity of beam section [kip-in]
$M_{dead,1}$ = moment caused by beam self weight, deck and slab for phase one [kip-in]
L = beam length [in]

The moment resulting from the dead load of the assembly (the beam's self weight, the metal decking, and the concrete slab) is considered separately from the superimposed point loads because it is treated as a distributed load over the length of the beam. The dead load of the assembly is always present, and thus always subtracts from the overall capacity in order to calculate the reserve strength available to support the superimposed load. The fixed-end moment due to a uniform distributed load is given by:

$$M_{dead,1} = \frac{\omega_1 L^2}{12} \qquad \text{[Eq. F.7]}$$

where,

$M_{dead,1}$ = moment caused by beam self weight, deck and slab for phase one [kip-in]
ω_1 = intensity of the uniformly distributed dead load for phase one [kips/in]
L = beam length [in]

The available moment capacity is defined in the elastic regime as:

$$M_{max,\ elastic} = S_x\sigma_y \qquad \text{[Eq. F.8]}$$

where,

$M_{max,\ elastic}$ = elastic moment capacity [kips-in]
S_x = elastic section modulus [in^3]
σ_y = yield strength [ksi]

In the plastic regime, S_x is replaced by Z_x, the plastic section modulus [in^3], resulting in the following equation:

$$M_{max,\ plastic} = Z_x\sigma_y \quad \text{[Eq. F.9]}$$

where,

$M_{max,\ plastic}$ = plastic moment capacity [kips-in]
Z_x = plastic section modulus [in^3]
σ_y = yield strength [ksi]

The ultimate capacity of a steel beam is determined by the plastic moment capacity.

A beam's capacity over the duration of a fire event is calculated by including the temperature-dependent nature of the yield strength of steel. If σ_y is replaced by $\sigma_y(T)$ in Equation F.9, it can be used to predict the plastic load capacity of the beam section as a function of time during the fire's duration.

Substituting Equations F.7 and F.9 into Equation F.6 gives an expression for the superimposed load, P_1, when the plastic hinges form at the fixed-end supports (end of phase one). At this point, the remaining beam capacity (in terms of superimposed loads at the outer quarter points) becomes:

$$P_2 = \frac{4\left(M_{\max} - M_{dead,2}\right)}{L} \quad \text{[Eq. F.10]}$$

where,

P_2 = superimposed load capacity for phase two [kips]
M_{max} = moment capacity of beam section [kip-in]
$M_{dead,2}$ = moment caused by beam self weight, deck and slab for phase two [kip-in]
L = beam length [in]

After plastic hinges have formed at the ends of the beam, the redistributed maximum bending moment due to the dead loads, M_{dead}, is found as:

$$M_{dead,2} = \frac{\omega_2 L^2}{8} \quad \text{[Eq. F.11]}$$

where,

$M_{dead,2}$ = moment caused by beam self weight, deck and slab for phase two [kip-in]
ω_2 = intensity of uniformly distributed dead load for phase two [kips/in]
L = beam length [in]

As before, M_{max} is replaced with Equation F.9 to determine the plastic capacity of the beam. The total beam capacity for the superimposed loading is given by the sum of the capacities for phase one and phase two: $P_{total} = P_1 + P_2$. Superposition of the capacity values for phase one and phase two results in the determination of the ultimate capacity of the beam. The results of these calculations for the model study are shown in Figure F.4.

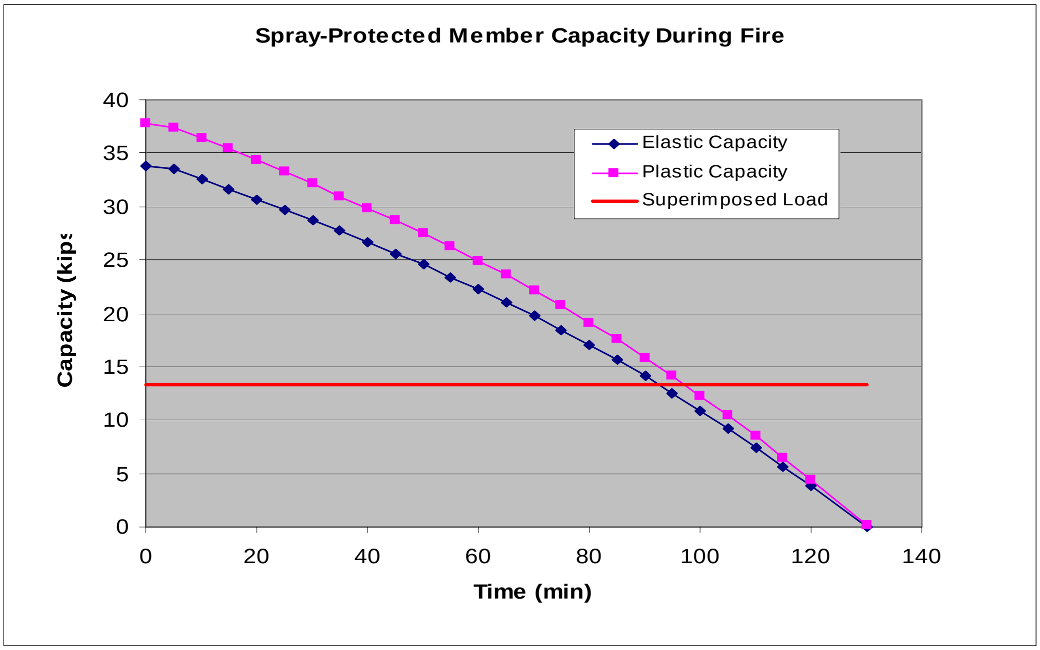


Figure F.4. Calculated Member Capacity During Fire Exposure

Because the failure mechanism of the fixed-end steel beam analyzed here involves the development of plastic hinges at the ends of the beam, and the along the span, the ultimate beam capacity is determined by calculating the plastic capacity.

F.3. Calculation of Beam Deflection

Much like the collapse mechanisms discussed above, beam deflection occurs in two phases. The first is based on the behavior of the fully fixed configuration. Once plastic hinges have formed at the ends of the beam, the deflection behavior is assumed to be consistent with that for a simply supported configuration.

The total deflection of the one-span beam with fully restrained ends being considered here is the sum of the deflections resulting from the uniformly distributed dead loads (beam self weight + slab weight) and the superimposed concentrated loads.

The deflection due to the uniformly distributed beam and slab weight is found as:

$$\Delta_{\text{dead},1} = \frac{\omega_1 L^4}{384EI} \qquad \text{[Eq. F.12]}$$

where,

$\Delta_{\text{dead},1}$ = maximum deflection due to dead loads for phase one [in]
ω_1 = intensity of uniformly distributed dead load for phase one [kips/in]
L = total length of beam [in]
E = modulus of elasticity [ksi]
I = moment of inertia of beam section [in^4]

The deflection due to the superimposed concentrated loads, which are equal and applied at the outer quarter points of the beam, can be calculated using conjugate beam theory [35]. This deflection is found as:

$$\Delta_{\text{superimposed},1} = \frac{P_1 L^3}{192EI} \qquad \text{[Eq. F.13]}$$

where,

$\Delta_{\text{superimposed},1}$ = maximum deflection due to superimposed loads for phase one [in]
P_1 = superimposed concentrated load for phase one [kips/in]
L = total length of beam [in]
E = modulus of elasticity [ksi]
I = moment of inertia of beam section [in^4]

Note that the maximum deflection in each case occurs at the midpoint of the beam due to the symmetry of the loading conditions. The value of P_1 is given by Equation F.6.

As mentioned previously, the modulus of elasticity is a temperature-dependent property. Substituting E(T) for E in the above equations, the deflection of the heated beam can be calculated for phase one throughout the duration of the fire.

Beyond the point where end moments first exceed the plastic moment capacity of the beam, the beam acts as though it were simply supported. In this case, deflection due to the beam's self weight and the weight of the slab is found as:

$$\Delta_{\text{dead},2} = \frac{5\omega_2 L^4}{384EI} \qquad \text{[Eq. F.13]}$$

where,

$\Delta_{\text{dead},2}$ = maximum deflection due to dead loads for phase two [in]
ω_2 = intensity of the uniformly distributed dead load for phase two [kips/in]
L = total length of beam [in]
E = modulus of elasticity [ksi]
I = moment of inertia of beam section [in^4]

Similarly, the equation of the deflection due to the superimposed point loads changes when simply supported behavior is achieved. This deflection becomes [10]:

$$\Delta_{\text{superimposed},2} = \frac{2P_2 L^3}{69EI} \qquad \text{[Eq. F.14]}$$

where,

$\Delta_{\text{superimposed},2}$ = maximum deflection due to superimposed loads for phase two [in]
P_2 = superimposed point load for phase two [kips/in]
L = total length of beam [in]
E = modulus of elasticity [ksi]
I = moment of inertia [in^4]

It is evident from comparison of the equations for phase one and phase two that the rate of deflection per unit load increases by a factor of about 5 after the formation of the initial plastic hinges at the ends of the beam.

Superposition of the calculated deflection values for phase one and phase two results in an estimate of deflection levels during the fire duration. Figure F.5 shows the results of these deflection calculations for the model study.

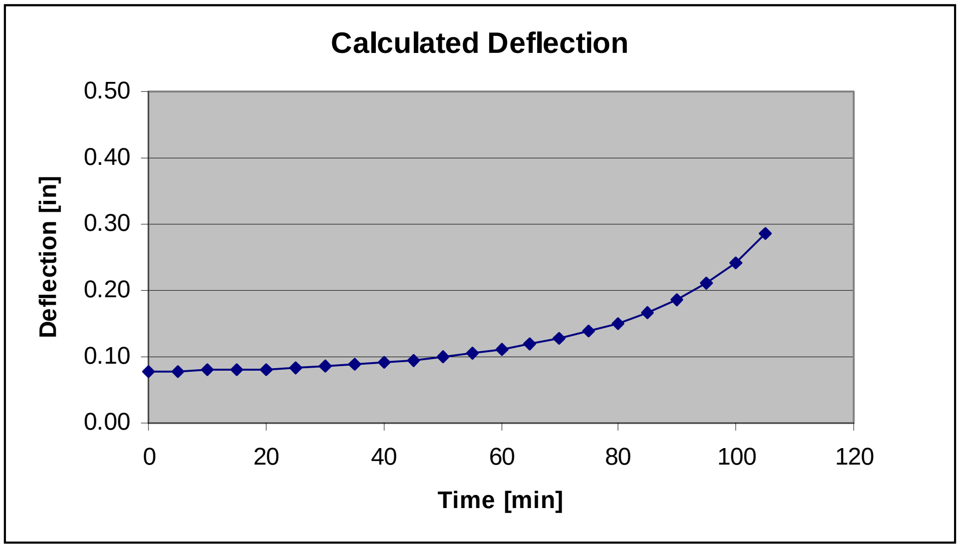


Figure F.5. Calculated Deflection During Fire Exposure

APPENDIX G. LS-DYNA INPUT FILE

G.1. Ambient Temperature Analysis

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AMBIENT TEMPERATURE ANALYSIS
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*CONTROL_ENERGY
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*CONTROL_OUTPUT
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         0
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*DATABASE_SPCFORC
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*DATABASE_BINARY_D3DRLF
         5
*DATABASE_BINARY_D3PLOT
    5.0E-2         0         0         0
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    5.0E-3         0
*DATABASE_BINARY_XTFILE
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      0.32      0.32      0.32      0.32      0.32      0.32      0.32      0.32
   1.21E-5   1.25E-5   1.29E-5   1.33E-5   1.38E-5   1.42E-5   1.46E-5   1.51E-5
    2.54E8    2.29E8    2.04E8    1.73E8    1.31E8    6.87E8       0.1       0.1
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Web
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Bottom Flange
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$ ==========
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423	-11.198650	86.557426	12.145120	0	0
424	-11.198650	86.557426	12.220310	0	0
425	-11.400740	86.557426	12.069940	0	0
426	-11.400740	86.557426	12.145120	0	0
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430	-11.299700	86.557426	12.220310	0	0
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$ ELEMENT cards
$ =============
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*ELEMENT_SHELL
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     373       1     325     324     100      99
     374       1     324     323     101     100
     375       1     323     322     102     101
     376       1     322     321     103     102
     377       1     321     320     104     103
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443	1	20	19	300	301
444	1	19	18	299	300
445	1	18	17	298	299

446	1	17	16	297	298
447	1	16	15	296	297
448	1	15	14	295	296
449	1	14	13	294	295
450	1	13	12	293	294
451	1	12	11	292	293
452	1	11	10	291	292
453	1	10	9	290	291
454	1	9	8	289	290
455	1	8	7	288	289
456	1	7	6	287	288
457	1	6	5	286	287
458	1	5	4	285	286
459	1	4	3	284	285
460	1	3	2	283	284
461	2	329	328	397	330
462	2	328	327	394	397
463	2	327	326	400	394
464	2	326	325	403	400
465	2	325	324	391	403
466	2	324	323	409	391
467	2	323	322	412	409
468	2	322	321	406	412
469	2	321	320	415	406
470	2	320	319	418	415
471	2	319	318	388	418
472	2	318	317	427	388
473	2	317	316	430	427
474	2	316	315	424	430
475	2	315	314	433	424
476	2	314	313	436	433
477	2	313	312	421	436
478	2	312	311	442	421
479	2	311	310	445	442
480	2	310	309	439	445
481	2	309	308	448	439
482	2	308	307	451	448
483	2	307	306	385	451
484	2	306	305	463	385
485	2	305	304	460	463
486	2	304	303	466	460
487	2	303	302	469	466
488	2	302	301	457	469
489	2	301	300	475	457
490	2	300	299	478	475
491	2	299	298	472	478
492	2	298	297	481	472
493	2	297	296	484	481
494	2	296	295	454	484
495	2	295	294	493	454
496	2	294	293	496	493
497	2	293	292	490	496
498	2	292	291	499	490
499	2	291	290	502	499
500	2	290	289	487	502
501	2	289	288	508	487
502	2	288	287	511	508
503	2	287	286	505	511
504	2	286	285	514	505
505	2	285	284	517	514
506	2	284	283	382	517
507	2	330	397	395	331
508	2	397	394	393	395
509	2	394	400	399	393
510	2	400	403	401	399
511	2	403	391	390	401
512	2	391	409	408	390

513	2	409	412	410	408
514	2	412	406	405	410
515	2	406	415	414	405
516	2	415	418	416	414
517	2	418	388	387	416
518	2	388	427	426	387
519	2	427	430	428	426
520	2	430	424	423	428
521	2	424	433	432	423
522	2	433	436	434	432
523	2	436	421	420	434
524	2	421	442	441	420
525	2	442	445	443	441
526	2	445	439	438	443
527	2	439	448	447	438
528	2	448	451	449	447
529	2	451	385	384	449
530	2	385	463	461	384
531	2	463	460	459	461
532	2	460	466	465	459
533	2	466	469	467	465
534	2	469	457	456	467
535	2	457	475	474	456
536	2	475	478	476	474
537	2	478	472	471	476
538	2	472	481	480	471
539	2	481	484	482	480
540	2	484	454	453	482
541	2	454	493	492	453
542	2	493	496	494	492
543	2	496	490	489	494
544	2	490	499	498	489
545	2	499	502	500	498
546	2	502	487	486	500
547	2	487	508	507	486
548	2	508	511	509	507
549	2	511	505	504	509
550	2	505	514	513	504
551	2	514	517	515	513
552	2	517	382	381	515
553	2	331	395	396	332
554	2	395	393	392	396
555	2	393	399	398	392
556	2	399	401	402	398
557	2	401	390	389	402
558	2	390	408	407	389
559	2	408	410	411	407
560	2	410	405	404	411
561	2	405	414	413	404
562	2	414	416	417	413
563	2	416	387	386	417
564	2	387	426	425	386
565	2	426	428	429	425
566	2	428	423	422	429
567	2	423	432	431	422
568	2	432	434	435	431
569	2	434	420	419	435
570	2	420	441	440	419
571	2	441	443	444	440
572	2	443	438	437	444
573	2	438	447	446	437
574	2	447	449	450	446
575	2	449	384	383	450
576	2	384	461	462	383
577	2	461	459	458	462
578	2	459	465	464	458
579	2	465	467	468	464

580	2	467	456	455	468
581	2	456	474	473	455
582	2	474	476	477	473
583	2	476	471	470	477
584	2	471	480	479	470
585	2	480	482	483	479
586	2	482	453	452	483
587	2	453	492	491	452
588	2	492	494	495	491
589	2	494	489	488	495
590	2	489	498	497	488
591	2	498	500	501	497
592	2	500	486	485	501
593	2	486	507	506	485
594	2	507	509	510	506
595	2	509	504	503	510
596	2	504	513	512	503
597	2	513	515	516	512
598	2	515	381	380	516
599	2	332	396	334	333
600	2	396	392	335	334
601	2	392	398	336	335
602	2	398	402	337	336
603	2	402	389	338	337
604	2	389	407	339	338
605	2	407	411	340	339
606	2	411	404	341	340
607	2	404	413	342	341
608	2	413	417	343	342
609	2	417	386	344	343
610	2	386	425	345	344
611	2	425	429	346	345
612	2	429	422	347	346
613	2	422	431	348	347
614	2	431	435	349	348
615	2	435	419	350	349
616	2	419	440	351	350
617	2	440	444	352	351
618	2	444	437	353	352
619	2	437	446	354	353
620	2	446	450	355	354
621	2	450	383	356	355
622	2	383	462	357	356
623	2	462	458	358	357
624	2	458	464	359	358
625	2	464	468	360	359
626	2	468	455	361	360
627	2	455	473	362	361
628	2	473	477	363	362
629	2	477	470	364	363
630	2	470	479	365	364
631	2	479	483	366	365
632	2	483	452	367	366
633	2	452	491	368	367
634	2	491	495	369	368
635	2	495	488	370	369
636	2	488	497	371	370
637	2	497	501	372	371
638	2	501	485	373	372
639	2	485	506	374	373
640	2	506	510	375	374
641	2	510	503	376	375
642	2	503	512	377	376
643	2	512	516	378	377
644	2	516	380	379	378
645	3	333	334	237	236
646	3	334	335	238	237

647	3	335	336	239	238
648	3	336	337	240	239
649	3	337	338	241	240
650	3	338	339	242	241
651	3	339	340	243	242
652	3	340	341	244	243
653	3	341	342	245	244
654	3	342	343	246	245
655	3	343	344	247	246
656	3	344	345	248	247
657	3	345	346	249	248
658	3	346	347	250	249
659	3	347	348	251	250
660	3	348	349	252	251
661	3	349	350	253	252
662	3	350	351	254	253
663	3	351	352	255	254
664	3	352	353	256	255
665	3	353	354	257	256
666	3	354	355	258	257
667	3	355	356	259	258
668	3	356	357	260	259
669	3	357	358	261	260
670	3	358	359	262	261
671	3	359	360	263	262
672	3	360	361	264	263
673	3	361	362	265	264
674	3	362	363	266	265
675	3	363	364	267	266
676	3	364	365	268	267
677	3	365	366	269	268
678	3	366	367	270	269
679	3	367	368	271	270
680	3	368	369	272	271
681	3	369	370	273	272
682	3	370	371	274	273
683	3	371	372	275	274
684	3	372	373	276	275
685	3	373	374	277	276
686	3	374	375	278	277
687	3	375	376	279	278
688	3	376	377	280	279
689	3	377	378	281	280
690	3	378	379	282	281
691	3	189	188	334	333
692	3	188	187	335	334
693	3	187	186	336	335
694	3	186	185	337	336
695	3	185	184	338	337
696	3	184	183	339	338
697	3	183	182	340	339
698	3	182	181	341	340
699	3	181	180	342	341
700	3	180	179	343	342
701	3	179	178	344	343
702	3	178	177	345	344
703	3	177	176	346	345
704	3	176	175	347	346
705	3	175	174	348	347
706	3	174	173	349	348
707	3	173	172	350	349
708	3	172	171	351	350
709	3	171	170	352	351
710	3	170	169	353	352
711	3	169	168	354	353
712	3	168	167	355	354
713	3	167	166	356	355

```
     714       3     166     165     357     356
     715       3     165     164     358     357
     716       3     164     163     359     358
     717       3     163     162     360     359
     718       3     162     161     361     360
     719       3     161     160     362     361
     720       3     160     159     363     362
     721       3     159     158     364     363
     722       3     158     157     365     364
     723       3     157     156     366     365
     724       3     156     155     367     366
     725       3     155     154     368     367
     726       3     154     153     369     368
     727       3     153     152     370     369
     728       3     152     151     371     370
     729       3     151     150     372     371
     730       3     150     149     373     372
     731       3     149     148     374     373
     732       3     148     147     375     374
     733       3     147     146     376     375
     734       3     146     145     377     376
     735       3     145     144     378     377
     736       3     144     143     379     378
$
$ ============
$ DEFINE cards
$ ============
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 1
$ ------------------------------------------------
$ Loading definition 2 : Nodal force vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Nodal force                (Units: Force)
$
$ Usage: Transient analysis
$
         1         0  1.667E-3       1.0       0.0       0.0         0
               0.0               0.0
               1.0         59158.398
            6600.0         59158.398
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 17
$ ------------------------------------------------
$ Body load definition <No label>: Base Z acceleration vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Base Z acceleration        (Units: Acceleration)
$
$ Usage: Transient analysis
$
        17         0  1.667E-3       1.0       0.0       0.0         0
               0.0               0.0
               1.0               1.0
            6600.0               1.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 18
$ ------------------------------------------------
$ Loading definition 1 : Nodal force vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Nodal force                (Units: Force)
$
$ Usage: Transient analysis
```

```
$
        18         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0           164.10001
              6600.0           164.10001
$
$ ==============
$ BOUNDARY cards
$ ==============
$
*BOUNDARY_SPC_SET
         1         0         1         1         1         1         1         1
$
$ Cross-reference summary for Set_node 1
$ -------------------------------------
$ BOUNDARY_SPC 1
$
*SET_NODE_LIST
         1       0.0       0.0       0.0       0.0
       332       331       330       382       381       380
$
*BOUNDARY_SPC_SET
        16         0         0         1         0         0         0         0
$
$ Cross-reference summary for Set_node 16
$ --------------------------------------
$ BOUNDARY_SPC 2
$
*SET_NODE_LIST
        16       0.0       0.0       0.0       0.0
        43       100         7       136       496       130        37       106
        31       112        19       124        25       118
$
$ ==========
$ LOAD cards
$ ==========
$
*LOAD_BODY_Z
        17      9.81         0
*LOAD_NODE_SET
         2         3        18      -1.0         0
$
$ Cross-reference summary for Set_node 2
$ -------------------------------------
$ LOAD_NODE 1
$
*SET_NODE_LIST
         2       0.0       0.0       0.0       0.0
       329       328       327       326       325       324       323       322
       321       320       319       318       317       316       315       314
       313       312       311       310       309       308       307       306
       305       304       303       302       301       300       299       298
       297       296       295       294       293       292       291       290
       289       288       287       286       285       284       283
$
*LOAD_NODE_SET
         3         3         1      -1.0         0
$
$ Cross-reference summary for Set_node 3
$ -------------------------------------
$ LOAD_NODE 2
$
*SET_NODE_LIST
         3       0.0       0.0       0.0       0.0
       318       294
*END
```

G.2. Elevated Temperature Analysis

```
*KEYWORD
$
$ Created on Thu Nov 07 14:32:14 2002
$
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$
*TITLE
ELEVATED TEMPERATURE ANALYSIS
$
$ =============
$ CONTROL cards
$ =============
$
*CONTROL_DYNAMIC_RELAXATION
       500    1.0E-3     0.995       0.0       0.0         0    4.0E-2        -1
*CONTROL_ENERGY
         2         2         1         1
*CONTROL_OUTPUT
         1         3         0         0       0.0         0       100      5000
         0
*CONTROL_SHELL
      20.0         1        -1         1         2         2         1         0
       0.0         0         0
*CONTROL_TERMINATION
      11.0         0       0.0       0.0       0.0
$
$ ==============
$ DATABASE cards
$ ==============
$
*DATABASE_GLSTAT
    5.0E-3
*DATABASE_SPCFORC
    5.0E-3
*DATABASE_BINARY_D3DRLF
         5
*DATABASE_BINARY_D3PLOT
    5.0E-2         0         0         0
*DATABASE_BINARY_D3THDT
    5.0E-3         0
*DATABASE_BINARY_XTFILE
       0.0
$
$ ====================
$ MAT (Material) cards
$ ====================
$
*MAT_ELASTIC_PLASTIC_THERMAL
         1    7850.0
       0.0     125.0     250.0     375.0     500.0     625.0     750.0     875.0
    2.0E11   1.96E11   1.78E11   1.49E11   1.06E11   5.07E10       0.1       0.1
      0.32      0.32      0.32      0.32      0.32      0.32      0.32      0.32
   1.21E-5   1.25E-5   1.29E-5   1.33E-5   1.38E-5   1.42E-5   1.46E-5   1.51E-5
    2.54E8    2.29E8    2.04E8    1.73E8    1.31E8    6.87E8       0.1       0.1
       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$
$ =============
$ SECTION cards
$ =============
$
*SECTION_SHELL
         1         2       1.0         2       3.0       0.0         0         1
    1.0E-2    1.0E-2    1.0E-2    1.0E-2       0.0       0.0
$
```

```
         2         2       1.0         2       3.0       0.0         0         1
    6.0E-3    6.0E-3    6.0E-3    6.0E-3       0.0       0.0
$
         3         2       1.0         2       3.0       0.0         0         1
    1.0E-2    1.0E-2    1.0E-2    1.0E-2       0.0       0.0
$
$ ==========
$ PART cards
$ ==========
$
*PART
Top Flange
         1         1         1         0         0         0         0         0
$
*PART
Web
         2         2         1         0         0         0         0         0
$
*PART
Bottom Flange
         3         3         1         0         0         0         0         0
$
$ ==========
$ NODE cards
$ ==========
$
*NODE
       2      -7.9651170       86.474998       12.295490       0       0
       3      -8.0661650       86.474998       12.295490       0       0
       4      -8.1672115       86.474998       12.295490       0       0
       5      -8.2682610       86.474998       12.295490       0       0
       6      -8.3693085       86.474998       12.295490       0       0
       7      -8.4703560       86.474998       12.295490       0       0
       8      -8.5714045       86.474998       12.295490       0       0
       9      -8.6724520       86.474998       12.295490       0       0
      10      -8.7734985       86.474998       12.295490       0       0
      11      -8.8745480       86.474998       12.295490       0       0
      12      -8.9755955       86.474998       12.295490       0       0
      13      -9.0766430       86.474998       12.295490       0       0
      14      -9.1776915       86.474998       12.295490       0       0
      15      -9.2787390       86.474998       12.295490       0       0
      16      -9.3797855       86.474998       12.295490       0       0
      17      -9.4808350       86.474998       12.295490       0       0
      18      -9.5818825       86.474998       12.295490       0       0
      19      -9.6829300       86.474998       12.295490       0       0
      20      -9.7839785       86.474998       12.295490       0       0
      21      -9.8850260       86.474998       12.295490       0       0
      22      -9.9860725       86.474998       12.295490       0       0
      23      -10.087120       86.474998       12.295490       0       0
      24      -10.188170       86.474998       12.295490       0       0
      25      -10.289220       86.474998       12.295490       0       0
      26      -10.390260       86.474998       12.295490       0       0
      27      -10.491310       86.474998       12.295490       0       0
      28      -10.592360       86.474998       12.295490       0       0
      29      -10.693410       86.474998       12.295490       0       0
      30      -10.794460       86.474998       12.295490       0       0
      31      -10.895500       86.474998       12.295490       0       0
      32      -10.996550       86.474998       12.295490       0       0
      33      -11.097600       86.474998       12.295490       0       0
      34      -11.198650       86.474998       12.295490       0       0
      35      -11.299700       86.474998       12.295490       0       0
      36      -11.400740       86.474998       12.295490       0       0
      37      -11.501790       86.474998       12.295490       0       0
      38      -11.602840       86.474998       12.295490       0       0
      39      -11.703890       86.474998       12.295490       0       0
      40      -11.804930       86.474998       12.295490       0       0
      41      -11.905980       86.474998       12.295490       0       0
```

42	-12.007030	86.474998	12.295490	0	0
43	-12.108080	86.474998	12.295490	0	0
44	-12.209130	86.474998	12.295490	0	0
45	-12.310170	86.474998	12.295490	0	0
46	-12.411220	86.474998	12.295490	0	0
47	-12.512270	86.474998	12.295490	0	0
48	-12.613320	86.474998	12.295490	0	0
95	-12.613320	86.639847	12.295490	0	0
96	-12.512270	86.639847	12.295490	0	0
97	-12.411220	86.639847	12.295490	0	0
98	-12.310170	86.639847	12.295490	0	0
99	-12.209130	86.639847	12.295490	0	0
100	-12.108080	86.639847	12.295490	0	0
101	-12.007030	86.639847	12.295490	0	0
102	-11.905980	86.639847	12.295490	0	0
103	-11.804930	86.639847	12.295490	0	0
104	-11.703890	86.639847	12.295490	0	0
105	-11.602840	86.639847	12.295490	0	0
106	-11.501790	86.639847	12.295490	0	0
107	-11.400740	86.639847	12.295490	0	0
108	-11.299700	86.639847	12.295490	0	0
109	-11.198650	86.639847	12.295490	0	0
110	-11.097600	86.639847	12.295490	0	0
111	-10.996550	86.639847	12.295490	0	0
112	-10.895500	86.639847	12.295490	0	0
113	-10.794460	86.639847	12.295490	0	0
114	-10.693410	86.639847	12.295490	0	0
115	-10.592360	86.639847	12.295490	0	0
116	-10.491310	86.639847	12.295490	0	0
117	-10.390260	86.639847	12.295490	0	0
118	-10.289220	86.639847	12.295490	0	0
119	-10.188170	86.639847	12.295490	0	0
120	-10.087120	86.639847	12.295490	0	0
121	-9.9860725	86.639847	12.295490	0	0
122	-9.8850260	86.639847	12.295490	0	0
123	-9.7839785	86.639847	12.295490	0	0
124	-9.6829300	86.639847	12.295490	0	0
125	-9.5818825	86.639847	12.295490	0	0
126	-9.4808350	86.639847	12.295490	0	0
127	-9.3797855	86.639847	12.295490	0	0
128	-9.2787390	86.639847	12.295490	0	0
129	-9.1776915	86.639847	12.295490	0	0
130	-9.0766430	86.639847	12.295490	0	0
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     498      -8.7734985       86.557426       12.145120       0       0
     499      -8.7734985       86.557426       12.220310       0       0
     500      -8.6724520       86.557426       12.145120       0       0
     501      -8.6724520       86.557426       12.069940       0       0
     502      -8.6724520       86.557426       12.220310       0       0
     503      -8.2682610       86.557426       12.069940       0       0
     504      -8.2682610       86.557426       12.145120       0       0
     505      -8.2682610       86.557426       12.220310       0       0
     506      -8.4703560       86.557426       12.069940       0       0
     507      -8.4703560       86.557426       12.145120       0       0
     508      -8.4703560       86.557426       12.220310       0       0
     509      -8.3693085       86.557426       12.145120       0       0
     510      -8.3693085       86.557426       12.069940       0       0
     511      -8.3693085       86.557426       12.220310       0       0
     512      -8.1672115       86.557426       12.069940       0       0
     513      -8.1672115       86.557426       12.145120       0       0
     514      -8.1672115       86.557426       12.220310       0       0
     515      -8.0661650       86.557426       12.145120       0       0
     516      -8.0661650       86.557426       12.069940       0       0
     517      -8.0661650       86.557426       12.220310       0       0
$
$ ============
$ ELEMENT cards
$ ============
$
*ELEMENT_SHELL
     369       1     329     328      96      95
     370       1     328     327      97      96
     371       1     327     326      98      97
     372       1     326     325      99      98
     373       1     325     324     100      99
     374       1     324     323     101     100
     375       1     323     322     102     101
     376       1     322     321     103     102
     377       1     321     320     104     103
     378       1     320     319     105     104
     379       1     319     318     106     105
     380       1     318     317     107     106
     381       1     317     316     108     107
```

```
     382       1     316     315     109     108
     383       1     315     314     110     109
     384       1     314     313     111     110
     385       1     313     312     112     111
     386       1     312     311     113     112
     387       1     311     310     114     113
     388       1     310     309     115     114
     389       1     309     308     116     115
     390       1     308     307     117     116
     391       1     307     306     118     117
     392       1     306     305     119     118
     393       1     305     304     120     119
     394       1     304     303     121     120
     395       1     303     302     122     121
     396       1     302     301     123     122
     397       1     301     300     124     123
     398       1     300     299     125     124
     399       1     299     298     126     125
     400       1     298     297     127     126
     401       1     297     296     128     127
     402       1     296     295     129     128
     403       1     295     294     130     129
     404       1     294     293     131     130
     405       1     293     292     132     131
     406       1     292     291     133     132
     407       1     291     290     134     133
     408       1     290     289     135     134
     409       1     289     288     136     135
     410       1     288     287     137     136
     411       1     287     286     138     137
     412       1     286     285     139     138
     413       1     285     284     140     139
     414       1     284     283     141     140
     415       1      48      47     328     329
     416       1      47      46     327     328
     417       1      46      45     326     327
     418       1      45      44     325     326
     419       1      44      43     324     325
     420       1      43      42     323     324
     421       1      42      41     322     323
     422       1      41      40     321     322
     423       1      40      39     320     321
     424       1      39      38     319     320
     425       1      38      37     318     319
     426       1      37      36     317     318
     427       1      36      35     316     317
     428       1      35      34     315     316
     429       1      34      33     314     315
     430       1      33      32     313     314
     431       1      32      31     312     313
     432       1      31      30     311     312
     433       1      30      29     310     311
     434       1      29      28     309     310
     435       1      28      27     308     309
     436       1      27      26     307     308
     437       1      26      25     306     307
     438       1      25      24     305     306
     439       1      24      23     304     305
     440       1      23      22     303     304
     441       1      22      21     302     303
     442       1      21      20     301     302
     443       1      20      19     300     301
     444       1      19      18     299     300
     445       1      18      17     298     299
     446       1      17      16     297     298
     447       1      16      15     296     297
     448       1      15      14     295     296
```

449	1	14	13	294	295
450	1	13	12	293	294
451	1	12	11	292	293
452	1	11	10	291	292
453	1	10	9	290	291
454	1	9	8	289	290
455	1	8	7	288	289
456	1	7	6	287	288
457	1	6	5	286	287
458	1	5	4	285	286
459	1	4	3	284	285
460	1	3	2	283	284
461	2	329	328	397	330
462	2	328	327	394	397
463	2	327	326	400	394
464	2	326	325	403	400
465	2	325	324	391	403
466	2	324	323	409	391
467	2	323	322	412	409
468	2	322	321	406	412
469	2	321	320	415	406
470	2	320	319	418	415
471	2	319	318	388	418
472	2	318	317	427	388
473	2	317	316	430	427
474	2	316	315	424	430
475	2	315	314	433	424
476	2	314	313	436	433
477	2	313	312	421	436
478	2	312	311	442	421
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480	2	310	309	439	445
481	2	309	308	448	439
482	2	308	307	451	448
483	2	307	306	385	451
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485	2	305	304	460	463
486	2	304	303	466	460
487	2	303	302	469	466
488	2	302	301	457	469
489	2	301	300	475	457
490	2	300	299	478	475
491	2	299	298	472	478
492	2	298	297	481	472
493	2	297	296	484	481
494	2	296	295	454	484
495	2	295	294	493	454
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497	2	293	292	490	496
498	2	292	291	499	490
499	2	291	290	502	499
500	2	290	289	487	502
501	2	289	288	508	487
502	2	288	287	511	508
503	2	287	286	505	511
504	2	286	285	514	505
505	2	285	284	517	514
506	2	284	283	382	517
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508	2	397	394	393	395
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513	2	409	412	410	408
514	2	412	406	405	410
515	2	406	415	414	405

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523	2	436	421	420	434
524	2	421	442	441	420
525	2	442	445	443	441
526	2	445	439	438	443
527	2	439	448	447	438
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529	2	451	385	384	449
530	2	385	463	461	384
531	2	463	460	459	461
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535	2	457	475	474	456
536	2	475	478	476	474
537	2	478	472	471	476
538	2	472	481	480	471
539	2	481	484	482	480
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555	2	393	399	398	392
556	2	399	401	402	398
557	2	401	390	389	402
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559	2	408	410	411	407
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561	2	405	414	413	404
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568	2	432	434	435	431
569	2	434	420	419	435
570	2	420	441	440	419
571	2	441	443	444	440
572	2	443	438	437	444
573	2	438	447	446	437
574	2	447	449	450	446
575	2	449	384	383	450
576	2	384	461	462	383
577	2	461	459	458	462
578	2	459	465	464	458
579	2	465	467	468	464
580	2	467	456	455	468
581	2	456	474	473	455
582	2	474	476	477	473

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584	2	471	480	479	470
585	2	480	482	483	479
586	2	482	453	452	483
587	2	453	492	491	452
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589	2	494	489	488	495
590	2	489	498	497	488
591	2	498	500	501	497
592	2	500	486	485	501
593	2	486	507	506	485
594	2	507	509	510	506
595	2	509	504	503	510
596	2	504	513	512	503
597	2	513	515	516	512
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613	2	422	431	348	347
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615	2	435	419	350	349
616	2	419	440	351	350
617	2	440	444	352	351
618	2	444	437	353	352
619	2	437	446	354	353
620	2	446	450	355	354
621	2	450	383	356	355
622	2	383	462	357	356
623	2	462	458	358	357
624	2	458	464	359	358
625	2	464	468	360	359
626	2	468	455	361	360
627	2	455	473	362	361
628	2	473	477	363	362
629	2	477	470	364	363
630	2	470	479	365	364
631	2	479	483	366	365
632	2	483	452	367	366
633	2	452	491	368	367
634	2	491	495	369	368
635	2	495	488	370	369
636	2	488	497	371	370
637	2	497	501	372	371
638	2	501	485	373	372
639	2	485	506	374	373
640	2	506	510	375	374
641	2	510	503	376	375
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644	2	516	380	379	378
645	3	333	334	237	236
646	3	334	335	238	237
647	3	335	336	239	238
648	3	336	337	240	239
649	3	337	338	241	240

650	3	338	339	242	241
651	3	339	340	243	242
652	3	340	341	244	243
653	3	341	342	245	244
654	3	342	343	246	245
655	3	343	344	247	246
656	3	344	345	248	247
657	3	345	346	249	248
658	3	346	347	250	249
659	3	347	348	251	250
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661	3	349	350	253	252
662	3	350	351	254	253
663	3	351	352	255	254
664	3	352	353	256	255
665	3	353	354	257	256
666	3	354	355	258	257
667	3	355	356	259	258
668	3	356	357	260	259
669	3	357	358	261	260
670	3	358	359	262	261
671	3	359	360	263	262
672	3	360	361	264	263
673	3	361	362	265	264
674	3	362	363	266	265
675	3	363	364	267	266
676	3	364	365	268	267
677	3	365	366	269	268
678	3	366	367	270	269
679	3	367	368	271	270
680	3	368	369	272	271
681	3	369	370	273	272
682	3	370	371	274	273
683	3	371	372	275	274
684	3	372	373	276	275
685	3	373	374	277	276
686	3	374	375	278	277
687	3	375	376	279	278
688	3	376	377	280	279
689	3	377	378	281	280
690	3	378	379	282	281
691	3	189	188	334	333
692	3	188	187	335	334
693	3	187	186	336	335
694	3	186	185	337	336
695	3	185	184	338	337
696	3	184	183	339	338
697	3	183	182	340	339
698	3	182	181	341	340
699	3	181	180	342	341
700	3	180	179	343	342
701	3	179	178	344	343
702	3	178	177	345	344
703	3	177	176	346	345
704	3	176	175	347	346
705	3	175	174	348	347
706	3	174	173	349	348
707	3	173	172	350	349
708	3	172	171	351	350
709	3	171	170	352	351
710	3	170	169	353	352
711	3	169	168	354	353
712	3	168	167	355	354
713	3	167	166	356	355
714	3	166	165	357	356
715	3	165	164	358	357
716	3	164	163	359	358

```
     717       3     163     162     360     359
     718       3     162     161     361     360
     719       3     161     160     362     361
     720       3     160     159     363     362
     721       3     159     158     364     363
     722       3     158     157     365     364
     723       3     157     156     366     365
     724       3     156     155     367     366
     725       3     155     154     368     367
     726       3     154     153     369     368
     727       3     153     152     370     369
     728       3     152     151     371     370
     729       3     151     150     372     371
     730       3     150     149     373     372
     731       3     149     148     374     373
     732       3     148     147     375     374
     733       3     147     146     376     375
     734       3     146     145     377     376
     735       3     145     144     378     377
     736       3     144     143     379     378
$
$ ============
$ DEFINE cards
$ ============
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 1
$ -----------------------------------------------
$
$ Loading definition 14 : Nodal force vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Nodal force                (Units: Force)
$
$ Usage: Transient analysis
$
         1         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0           59158.398
              6600.0           59158.398
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 2
$ -----------------------------------------------
$
$ Loading definition 5 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         2         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                27.0
               600.0                43.0
               900.0                63.0
              1200.0                79.0
              1500.0                91.0
              1800.0               118.0
              2100.0               143.0
              2400.0               166.0
              2700.0               191.0
              3000.0               213.0
              3300.0               235.0
              3600.0               263.0
```

```
              3900.0               277.0
              4200.0               296.0
              4500.0               316.0
              4800.0               329.0
              5100.0               346.0
              5400.0               360.0
              5700.0               374.0
              6000.0               388.0
              6300.0               402.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 3
$ ----------------------------------------------
$
$ Usage: Transient analysis
$
         3         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                24.0
               600.0                43.0
               900.0                68.0
              1200.0                82.0
              1500.0                99.0
              1800.0               124.0
              2100.0               146.0
              2400.0               168.0
              2700.0               191.0
              3000.0               216.0
              3300.0               241.0
              3600.0               266.0
              3900.0               282.0
              4200.0               302.0
              4500.0               318.0
              4800.0               335.0
              5100.0               352.0
              5400.0               366.0
              5700.0               382.0
              6000.0               393.0
              6300.0               407.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 4
$ ----------------------------------------------
$
$ Loading definition 1 : Temp multiplier vs time
$ X axis : Time                      (Units: Time)
$ Y axis : Temperature multiplier    (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         4         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                18.0
               600.0                27.0
               900.0                38.0
              1200.0                46.0
              1500.0                54.0
              1800.0                66.0
              2100.0                71.0
              2400.0                77.0
              2700.0                79.0
              3000.0                88.0
              3300.0                91.0
```

```
             3600.0              93.0
             3900.0             102.0
             4200.0             121.0
             4500.0             138.0
             4800.0             154.0
             5100.0             174.0
             5400.0             193.0
             5700.0             213.0
             6000.0             232.0
             6300.0             254.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 5
$ ----------------------------------------------
$
$ Loading definition 6 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         5         0  1.667E-3       1.0       0.0       0.0         0
                0.0               0.0
                1.0              16.0
              300.0              29.0
              600.0              54.0
              900.0              79.0
             1200.0              96.0
             1500.0             129.0
             1800.0             171.0
             2100.0             216.0
             2400.0             263.0
             2700.0             310.0
             3000.0             352.0
             3300.0             391.0
             3600.0             429.0
             3900.0             463.0
             4200.0             496.0
             4500.0             527.0
             4800.0             552.0
             5100.0             577.0
             5400.0             599.0
             5700.0             621.0
             6000.0             641.0
             6300.0             660.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 6
$ ----------------------------------------------
$
$ Usage: Transient analysis
$
         6         0  1.667E-3       1.0       0.0       0.0         0
                0.0               0.0
                1.0              16.0
              300.0              41.0
              600.0              66.0
              900.0              91.0
             1200.0             116.0
             1500.0             154.0
             1800.0             196.0
             2100.0             241.0
             2400.0             288.0
             2700.0             335.0
             3000.0             377.0
```

```
              3300.0              416.0
              3600.0              454.0
              3900.0              491.0
              4200.0              521.0
              4500.0              549.0
              4800.0              574.0
              5100.0              602.0
              5400.0              624.0
              5700.0              646.0
              6000.0              666.0
              6300.0              682.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 7
$ ----------------------------------------------
$
$ Loading definition 9 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Loading definition 10 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         7         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                38.0
               600.0                66.0
               900.0                91.0
              1200.0               110.0
              1500.0               143.0
              1800.0               188.0
              2100.0               232.0
              2400.0               271.0
              2700.0               307.0
              3000.0               343.0
              3300.0               374.0
              3600.0               402.0
              3900.0               432.0
              4200.0               460.0
              4500.0               485.0
              4800.0               507.0
              5100.0               527.0
              5400.0               546.0
              5700.0               566.0
              6000.0               579.0
              6300.0               593.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 8
$ ----------------------------------------------
$
$ Loading definition 2 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         8         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                24.0
```

```
              600.0               35.0
              900.0               49.0
             1200.0               63.0
             1500.0               74.0
             1800.0               82.0
             2100.0               88.0
             2400.0               93.0
             2700.0              107.0
             3000.0              127.0
             3300.0              143.0
             3600.0              160.0
             3900.0              182.0
             4200.0              202.0
             4500.0              213.0
             4800.0              227.0
             5100.0              235.0
             5400.0              252.0
             5700.0              266.0
             6000.0              282.0
             6300.0              296.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 9
$ ----------------------------------------------
$
$ Loading definition 7 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
         9         0  1.667E-3       1.0       0.0       0.0         0
                0.0                0.0
                1.0               16.0
              300.0               32.0
              600.0               60.0
              900.0               54.0
             1200.0              102.0
             1500.0              135.0
             1800.0              174.0
             2100.0              218.0
             2400.0              266.0
             2700.0              313.0
             3000.0              357.0
             3300.0              396.0
             3600.0              435.0
             3900.0              471.0
             4200.0              504.0
             4500.0              535.0
             4800.0              563.0
             5100.0              588.0
             5400.0              613.0
             5700.0              632.0
             6000.0              652.0
             6300.0              668.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 10
$ ----------------------------------------------
$
$ Usage: Transient analysis
$
        10         0  1.667E-3       1.0       0.0       0.0         0
                0.0                0.0
                1.0               16.0
```

```
              300.0               38.0
              600.0               63.0
              900.0               88.0
             1200.0              116.0
             1500.0              154.0
             1800.0              199.0
             2100.0              241.0
             2400.0              288.0
             2700.0              332.0
             3000.0              377.0
             3300.0              418.0
             3600.0              457.0
             3900.0              491.0
             4200.0              524.0
             4500.0              554.0
             4800.0              582.0
             5100.0              610.0
             5400.0              628.0
             5700.0              647.0
             6000.0              663.0
             6300.0              679.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 11
$ -----------------------------------------------
$
$ Loading definition 11 : Temp multiplier vs time
$ X axis : Time                      (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
        11         0  1.667E-3       1.0       0.0       0.0         0
                0.0                0.0
                1.0               16.0
              300.0               41.0
              600.0               66.0
              900.0               88.0
             1200.0              110.0
             1500.0              149.0
             1800.0              199.0
             2100.0              235.0
             2400.0              277.0
             2700.0              318.0
             3000.0              357.0
             3300.0              385.0
             3600.0              413.0
             3900.0              443.0
             4200.0              471.0
             4500.0              499.0
             4800.0              524.0
             5100.0              543.0
             5400.0              563.0
             5700.0              579.0
             6000.0              599.0
             6300.0              657.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 12
$ -----------------------------------------------
$
$ Loading definition 3 : Temp multiplier vs time
$ X axis : Time                      (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
```

```
$ Usage: Transient analysis
$
        12         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                27.0
               600.0                38.0
               900.0                54.0
              1200.0                71.0
              1500.0                82.0
              1800.0                88.0
              2100.0                96.0
              2400.0               113.0
              2700.0               129.0
              3000.0               152.0
              3300.0               174.0
              3600.0               204.0
              3900.0               232.0
              4200.0               249.0
              4500.0               268.0
              4800.0               282.0
              5100.0               291.0
              5400.0               302.0
              5700.0               310.0
              6000.0               318.0
              6300.0               324.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 13
$ -----------------------------------------------
$
$ Loading definition 8 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
        13         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                38.0
               600.0                66.0
               900.0                93.0
              1200.0               124.0
              1500.0               166.0
              1800.0               213.0
              2100.0               260.0
              2400.0               310.0
              2700.0               354.0
              3000.0               396.0
              3300.0               435.0
              3600.0               471.0
              3900.0               504.0
              4200.0               535.0
              4500.0               566.0
              4800.0               588.0
              5100.0               613.0
              5400.0               635.0
              5700.0               657.0
              6000.0               677.0
              6300.0               699.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 14
$ -----------------------------------------------
```

```
$
$ Usage: Transient analysis
$
        14         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                43.0
               600.0                71.0
               900.0               107.0
              1200.0               143.0
              1500.0               185.0
              1800.0               229.0
              2100.0               274.0
              2400.0               324.0
              2700.0               371.0
              3000.0               413.0
              3300.0               454.0
              3600.0               493.0
              3900.0               527.0
              4200.0               557.0
              4500.0               585.0
              4800.0               610.0
              5100.0               635.0
              5400.0               660.0
              5700.0               679.0
              6000.0               702.0
              6300.0               721.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 15
$ -----------------------------------------------
$
$ Loading definition 12 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
        15         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                41.0
               600.0                68.0
               900.0                88.0
              1200.0               104.0
              1500.0               141.0
              1800.0               246.0
              2100.0               235.0
              2400.0               277.0
              2700.0               316.0
              3000.0               354.0
              3300.0               382.0
              3600.0               416.0
              3900.0               443.0
              4200.0               468.0
              4500.0               493.0
              4800.0               516.0
              5100.0               538.0
              5400.0               554.0
              5700.0               574.0
              6000.0               593.0
              6300.0               610.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 16
```

```
$ -----------------------------------------------
$
$ Loading definition 4 : Temp multiplier vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Temperature multiplier     (Units: Scalar, no units)
$
$ Usage: Transient analysis
$
        16         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                16.0
               300.0                27.0
               600.0                41.0
               900.0                52.0
              1200.0                68.0
              1500.0                82.0
              1800.0                91.0
              2100.0                93.0
              2400.0               102.0
              2700.0               113.0
              3000.0               132.0
              3300.0               160.0
              3600.0               182.0
              3900.0               202.0
              4200.0               216.0
              4500.0               232.0
              4800.0               249.0
              5100.0               263.0
              5400.0               274.0
              5700.0               291.0
              6000.0               302.0
              6300.0               316.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 17
$ -----------------------------------------------
$
$ Body load definition <No label>: Base Z acceleration vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Base Z acceleration        (Units: Acceleration)
$
$ Usage: Transient analysis
$
        17         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0                 1.0
              6600.0                 1.0
$
*DEFINE_CURVE
$
$ Cross-reference summary for Load-curve 18
$ -----------------------------------------------
$
$ Loading definition 13 : Nodal force vs time
$ X axis : Time                       (Units: Time)
$ Y axis : Nodal force                (Units: Force)
$
$ Usage: Transient analysis
$
        18         0  1.667E-3       1.0       0.0       0.0         0
                 0.0                 0.0
                 1.0           164.10001
              6600.0           164.10001
$
$ ==============
$ BOUNDARY cards
```

```
$ ==============
$
*BOUNDARY_SPC_SET
         1         0         1         1         1         1         1         1
$
$ Cross-reference summary for Set_node 1
$ --------------------------------------
$ BOUNDARY_SPC 1
$
*SET_NODE_LIST
         1       0.0       0.0       0.0       0.0
       332       331       330       382       381       380
$
*BOUNDARY_SPC_SET
        16         0         0         1         0         0         0         0
$
$ Cross-reference summary for Set_node 16
$ ---------------------------------------
$ BOUNDARY_SPC 2
$
*SET_NODE_LIST
        16       0.0       0.0       0.0       0.0
        43       100         7       136       496       130        37       106
        31       112        19       124        25       118
$
$ ==========
$ LOAD cards
$ ==========
$
*LOAD_BODY_Z
        17      9.81         0
*LOAD_NODE_SET
         2         3        18      -1.0         0
$
$ Cross-reference summary for Set_node 2
$ --------------------------------------
$ LOAD_NODE 13
$
*SET_NODE_LIST
         2       0.0       0.0       0.0       0.0
       329       328       327       326       325       324       323       322
       321       320       319       318       317       316       315       314
       313       312       311       310       309       308       307       306
       305       304       303       302       301       300       299       298
       297       296       295       294       293       292       291       290
       289       288       287       286       285       284       283
$
*LOAD_NODE_SET
         3         3         1      -1.0         0
$
$ Cross-reference summary for Set_node 3
$ --------------------------------------
$ LOAD_NODE 14
$
*SET_NODE_LIST
         3       0.0       0.0       0.0       0.0
       318       294
$
*LOAD_THERMAL_VARIABLE
         4         0         0
       0.0       1.0         4       0.0       0.0         0
$
$ Cross-reference summary for Set_node 4
$ --------------------------------------
$ LOAD_THERMAL 1
$
*SET_NODE_LIST
```

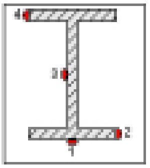
```
         4       0.0       0.0       0.0       0.0
        43        44        45        46        47        48        95        96
        97        98        99       100       324       325       326       327
       328       329       136         2         3         4         5         6
         7       137       138       139       140       141       283       284
       285       286       287       288
$
*LOAD_THERMAL_VARIABLE
         5         0         0
       1.0       0.0         8       0.0       0.0         0
$
$ Cross-reference summary for Set_node 5
$ ---------------------------------------
$ LOAD_THERMAL 2
$
*SET_NODE_LIST
         5       0.0       0.0       0.0       0.0
        31        32        33        34        35        36        37        38
        39        40        41        42       102       103       104       105
       106       107       108       109       110       111       112       312
       313       314       315       316       317       318       319       320
       321       322       323       101
$
*LOAD_THERMAL_VARIABLE
         6         0         0
       1.0       0.0        12       0.0       0.0         0
$
$ Cross-reference summary for Set_node 6
$ ---------------------------------------
$ LOAD_THERMAL 3
$
*SET_NODE_LIST
         6       0.0       0.0       0.0       0.0
        20        21        22        23        24        25        26        27
        28        29        30       113       114       115       116       117
       118       119       120       121       122       123       301       302
       303       304       305       306       307       308       309       310
       311
$
*LOAD_THERMAL_VARIABLE
         7         0         0
       1.0       0.0        16       0.0       0.0         0
$
$ Cross-reference summary for Set_node 7
$ ---------------------------------------
$ LOAD_THERMAL 4
$
*SET_NODE_LIST
         7       0.0       0.0       0.0       0.0
         8         9        10        11        12        13        14        15
        16        17        18        19       124       125       126       127
       128       129       130       131       132       133       134       135
       289       290       291       292       293       294       295       296
       297       298       299       300
$
*LOAD_THERMAL_VARIABLE
         8         0         0
       1.0       0.0         2       0.0       0.0         0
$
$ Cross-reference summary for Set_node 8
$ ---------------------------------------
$ LOAD_THERMAL 5
$
*SET_NODE_LIST
         8       0.0       0.0       0.0       0.0
       184       185       186       187       188       189       236       237
       238       239       240       241       333       334       335       336
```

```
      337       338       143       144       145       146       147       148
      277       278       279       280       281       282       374       375
      376       377       378       379
$
*LOAD_THERMAL_VARIABLE
        9         0         0
      1.0       0.0         5       0.0       0.0         0
$
$ Cross-reference summary for Set_node 9
$ -------------------------------------
$ LOAD_THERMAL 6
$
*SET_NODE_LIST
        9       0.0       0.0       0.0       0.0
      172       173       174       175       176       177       178       179
      180       181       182       183       242       243       244       245
      246       247       248       249       250       251       252       253
      339       340       341       342       343       344       345       346
      347       348       349       350
$
*LOAD_THERMAL_VARIABLE
       10         0         0
      1.0       0.0         9       0.0       0.0         0
$
$ Cross-reference summary for Set_node 10
$ --------------------------------------
$ LOAD_THERMAL 7
$
*SET_NODE_LIST
       10       0.0       0.0       0.0       0.0
      161       162       163       164       165       166       167       168
      169       170       171       254       255       256       257       258
      259       260       261       262       263       264       351       352
      353       354       355       356       357       358       359       360
      361
$
*LOAD_THERMAL_VARIABLE
       11         0         0
      1.0       0.0        13       0.0       0.0         0
$
$ Cross-reference summary for Set_node 11
$ --------------------------------------
$ LOAD_THERMAL 8
$
*SET_NODE_LIST
       11       0.0       0.0       0.0       0.0
      149       150       151       152       153       154       155       156
      157       158       159       160       265       266       267       268
      269       270       271       272       273       274       275       276
      362       363       364       365       366       367       368       369
      370       371       372       373
$
*LOAD_THERMAL_VARIABLE
       12         0         0
      1.0       0.0         7       0.0       0.0         0
$
$ Cross-reference summary for Set_node 12
$ --------------------------------------
$ LOAD_THERMAL 9
$
*SET_NODE_LIST
       12       0.0       0.0       0.0       0.0
      330       331       332       389       390       391       392       393
      394       395       396       397       398       399       400       401
      402       403       380       381       382       503       504       505
      506       507       508       509       510       511       512       513
      514       515       516       517
```

```
$
*LOAD_THERMAL_VARIABLE
        13         0         0
       1.0       0.0         7       0.0       0.0         0
$
$ Cross-reference summary for Set_node 13
$ ---------------------------------------
$ LOAD_THERMAL 10
$
*SET_NODE_LIST
        13       0.0       0.0       0.0       0.0
       386       387       388       404       405       406       407       408
       409       410       411       412       413       414       415       416
       417       418       419       420       421       422       423       424
       425       426       427       428       429       430       431       432
       433       434       435       436
$
*LOAD_THERMAL_VARIABLE
        14         0         0
       1.0       0.0        11       0.0       0.0         0
$
$ Cross-reference summary for Set_node 14
$ ---------------------------------------
$ LOAD_THERMAL 11
$
*SET_NODE_LIST
        14       0.0       0.0       0.0       0.0
       383       384       385       437       438       439       440       441
       442       443       444       445       446       447       448       449
       450       451       455       456       457       458       459       460
       461       462       463       464       465       466       467       468
       469
$
*LOAD_THERMAL_VARIABLE
        15         0         0
       1.0       0.0        15       0.0       0.0         0
$
$ Cross-reference summary for Set_node 15
$ ---------------------------------------
$ LOAD_THERMAL 12
$
*SET_NODE_LIST
        15       0.0       0.0       0.0       0.0
       452       453       454       470       471       472       473       474
       475       476       477       478       479       480       481       482
       483       484       485       486       487       488       489       490
       491       492       493       494       495       496       497       498
       499       500       501       502
$
*END
```

APPENDIX H. LS-DYNA INPUT TEMPERATURES FROM FIRE TEST

Beam Temperatures: Bletzacker Test 7



Time			North End								North 1/4 Point								Midspan								South 1/4 Point							
			1		2		3		4		1		2		3		4		1		2		3		4		1		2		3		4	
[s]	[min]	[hrs]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]	[°F]	[°C]
0	0	0.000	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16	60	16
300	5	0.083	80	27	75	24			65	18	85	29	105	41	100	38	75	24	90	32	100	38	105	41	80	27	100	38	110	43	105	41	80	27
600	10	0.167	110	43	110	43			80	27	130	54	150	66	150	66	95	35	140	60	145	63	150	66	100	38	150	66	160	71	155	68	105	41
900	15	0.250	145	63	155	68			100	38	175	79	195	91	195	91	120	49	130	54	190	88	190	88	130	54	200	93	225	107	190	88	125	52
1200	20	0.333	175	79	180	82			115	46	205	96	240	116	230	110	145	63	215	102	240	116	230	110	160	71	255	124	290	143	220	104	155	68
1500	25	0.417	195	91	210	99			130	54	265	129	310	154	290	143	165	74	275	135	310	154	300	149	180	82	330	166	365	185	285	141	180	82
1800	30	0.500	245	118	255	124			150	66	340	171	385	196	370	188	180	82	345	174	390	199	390	199	190	88	415	213	445	229	475	246	195	91
2100	35	0.583	290	143	295	146			160	71	420	216	465	241	450	232	190	88	425	218	465	241	455	235	205	96	500	260	525	274	455	235	200	93
2400	40	0.667	330	166	335	168			170	77	505	263	550	288	520	271	200	93	510	266	550	288	530	277	235	113	590	310	615	324	530	277	215	102
2700	45	0.750	375	191	375	191			175	79	590	310	635	335	585	307	225	107	595	313	630	332	605	318	265	129	670	354	700	371	600	316	235	113
3000	50	0.833	415	213	420	216			190	88	665	352	710	377	650	343	260	127	675	357	710	377	675	357	305	152	745	396	775	413	670	354	270	132
3300	55	0.917	455	235	465	241			195	91	735	391	780	416	705	374	290	143	745	396	785	418	725	385	345	174	815	435	850	454	720	382	320	160
3600	60	1.000	505	263	510	266			200	93	805	429	850	454	755	402	320	160	815	435	855	457	775	413	400	204	880	471	920	493	780	416	360	182
3900	65	1.083	530	277	540	282			215	102	865	463	915	491	810	432	360	182	880	471	915	491	830	443	450	232	940	504	980	527	830	443	395	202
4200	70	1.167	565	296	575	302			250	121	925	496	970	521	860	460	395	202	940	504	975	524	880	471	480	249	995	535	1035	557	875	468	420	216
4500	75	1.250	600	316	605	318			280	138	980	527	1020	549	905	485	415	213	995	535	1030	554	930	499	515	268	1050	566	1085	585	920	493	450	232
4800	80	1.333	625	329	635	335			310	154	1025	552	1065	574	945	507	440	227	1045	563	1080	582	975	524	540	282	1090	588	1130	610	960	516	480	249
5100	85	1.417	655	346	665	352			345	174	1070	577	1115	602	980	527	455	235	1090	588			1010	543	555	291	1135	613	1175	635	1000	538	505	263
5400	90	1.500	680	360	690	366			380	193	1110	599	1155	624	1015	546	485	252	1135	613			1045	563	575	302	1175	635	1220	660	1030	554	525	274
5700	95	1.583	705	374	720	382			415	213	1150	621	1195	646	1050	566	510	266	1170	632			1075	579	590	310	1215	657	1255	679	1065	574	555	291
6000	100	1.667	730	388	740	393			450	232	1185	641	1230	666	1075	579	540	282	1205	652			1110	599	605	318	1250	677	1295	702	1100	593	575	302
6300	105	1.750	755	402	765	407			490	254	1220	660	1260	682	1100	593	565	296	1235	668			1215	657	615	324	1290	699	1330	721	1130	610	600	316