Auxetic Steel-Concrete Structures

A Major Qualifying Project Report:

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by

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Abstract

Traditionally, engineers use rods or simple structures to reinforce concrete pillars. However, this simple design cannot support the significant flaw of the concrete, which is the weak performance against the tensile loading. A new surge of studies on auxetic structures has recently started in both academic and industrial applications. The benefit of auxetic materials is that compression in one direction results in compression in another. Thus, it can improve the performance of reinforced structures considerably.

Incorporating auxetic steel into concrete structures improves their mechanical properties significantly, making them more resistant to compressive loads and deformations. Furthermore, the natural adaptability of auxetic materials allows for the design of structures that can actively and flexibly react to changing loads and climate conditions, promoting the development of more intelligent and efficient building processes.

Executive Summary

Goal

This project/experiment aim to determine which auxetic shape reacts better under compression in terms of ductility and strength, and its deformation under this experiment.

Background

Civil engineers have used simple rebars and steel rods for years as concrete reinforcement. Although the reinforcement design has improved through the years, it still leaves large concrete parts open to transversal expansion. Recently, researchers have tried to use polymer-based auxetic structures in concrete to improve the transversal expansion resistance and reduce the final cost of the structure. However, due to the brittleness of these polymers, they cannot perform as well as steel. Recently, aluminum and steel based auxetic materials have been tested as reinforcement in concrete. In this work, the performance of two auxetic structures has been tested.

Methodology

Brick, honeycomb bowtie, and tubular auxetic shapes were the three types of auxetic shapes that were utilized for this project. Laser-cutting technology was used to produce all three stainless steel shapes. This technology allows for accurately cutting the raw material into appropriate shapes. In addition to that, these particular shapes were molded using silicone. After that, the concrete mixture was poured into the molds, and after that, some vibration was used to ensure that all of the voids were filled up. Following the curing time of 28 days of all samples, each was subjected to a displacement-controlled compression loading to obtain an accurate measurement of the deformation that the object experienced as a result of this process.

Results/Analysis

After completing the compression tests, each of the three sample shapes produced extraordinary results. The brick and the honeycomb bowtie possess compressive strengths of around one hundred megapascals (MPa). Furthermore, the tubular shape, which resulted in a value that was slightly greater than one hundred and sixty MPa, was the one that produced the highest yield strength. Due to its higher negative Poisson ratio compared to bowtie structure, compressing this shape results in compression of both the axial and transverse directions. Due to its modular shape, it is easy to incorporate this structure into industrial applications; and due to the lack of sharp corners, it performs better than most other auxetic structures. Because supplying high compressive strengths in buildings can reduce the size of columns, this phenomenon is of utmost significance for both the ongoing project and the construction industry in the future. This is because it makes it possible to increase the height of structures, which is very helpful for skyscrapers and other particularly complex projects.

Conclusion

Auxetic steel-concrete constructions are the future of Civil engineering structures. This is due to their improved resilience, higher structure life, reduced need for regular maintenance and lower environmental effect during construction. Auxetic steel concrete structures are at the forefront of civil engineering research due to their capacity to push the boundaries of ordinary building materials and technology. These structures represent a promising approach to safer, more sustainable, and future-ready built environments. Finally, their superior design reduces the need for expensive and rare alloys.

MQP Design Statement

Worcester Polytechnic Institute's Major Qualifying Project (MQP) is a capstone project that encapsulates the project-based education style that is present at the university. MQPs are high-level research projects that typically fall under the discipline in which the student is majoring. They are required to be completed to fulfill the completion of WPI's undergraduate curriculum. Such projects generally take place in teams, are supervised by a professor proficient in a field relevant to the project, and are coordinated by the student's academic department.

This MQP was a single-student project that included the educational disciplines of biology, chemistry, material science, and civil engineering. This project satisfies the student's MQP requirements for fulfillment in completion of a Bachelor of Science Degree with its design of an auxetic steel cement composite. While this was a single-student MQP, there was active communication and collaboration with the project advisor and many Ph.D. students in the bioinspired design laboratory. The Accreditation Board for Engineering and Technology (ABET) has required that Baccalaureate degree curricula must "provide a capstone or integrating experience that develops student competencies in applying both technical and non-technical skills in solving problems." (Criteria for Accrediting Engineering Technology Programs, 2024 – 2025). This MQP completes the capstone requirement in fulfillment of a Bachelor of Science Degree listed on the ABET website for 2024-2025.

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1.0 Introduction

The significance of civil engineering today is of the utmost importance because it is founded on the infrastructure around us and the location in which we reside. Since the first instance of using the fundamentals, such as concrete, masonry, and steel, all subject to high-impact loads, the construction procedures have been very similar. Major innovations must be performed to increase our demand and develop more effective techniques for building materials capable of meeting our requirements. A consequence of these inventions, the materials, structures, and fabrics referred to as auxetics exhibit an unexpected behavior when subjected to mechanical stresses and strains. When stretched in the longitudinal direction, they expand in thickness in one or more width-wise directions perpendicular to the stretching direction. If exposed to uniaxial compression, they display a “thinning” in one or more transverse directions (Comet, C. S., 2024).

1.1 Poisson’s Ratio

A material sample that undergoes one-way stretching typically becomes thinner in the lateral direction; alternatively, a sample that is compressed in one direction typically becomes thicker in the lateral direction. Poisson’s ratio is defined as the ratio between the relative extension strain (or axial strain) in the direction of the applied load and the relative contraction strain (transverse, lateral, or radial strain) normal to the applied load (The Engineering ToolBox, 2008).

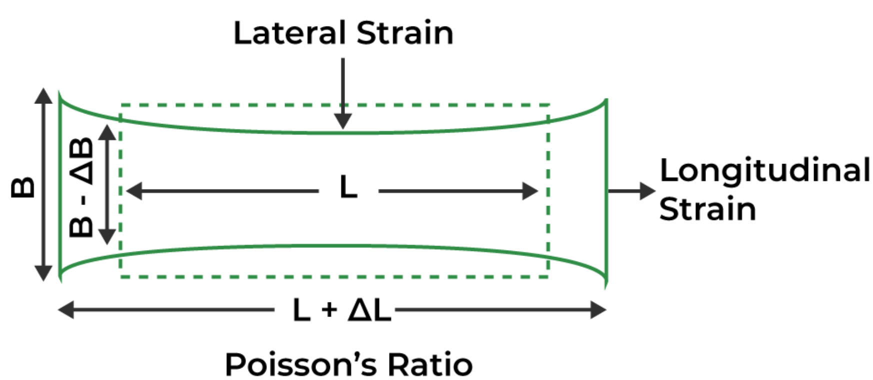


Figure 1: Diagram of Poisson’s Ratio

1.2 Negative Poisson’s Ratio

Using the same argument in reverse, this phenomenon follows the same logic. A relatively recent development of engineering is investigating the possibility of altering Poisson’s ratio of a material to negative values. This is a relatively new advancement. Based on elastic theory, it has been hypothesized that the Poisson’s ratio for isotropic materials can exist anywhere between 1 and 0.5. A substantial amount of research has been carried out over the past several years, which has led to the discovery, investigation, and development of a wide range of auxetics (Mir, M., Ali, M. N., Sami, J., & Ansari, U., 2014 and Ellul , B., Muscat, M., & Grima, J. N., 2009). Simply said, having a solid understanding of the idea of auxetic materials is of the utmost importance. When these materials are subjected to compressive strains, they undergo a unique trait known as negative Poisson ratio (NPR), which indicates that they contract along the sides. On the other hand, when they are stretched, they can expand. Poisson's ratio (Cho, H., Seo, D., & Kim, D.-N., 2018), which measures the planar deformative pattern of materials by measuring the ratio of lateral strain to longitudinal strain, is another factor that should be considered. It is essential to take this parameter into account. Because of negative (Cho, H., Seo, D., & Kim, D.-N., 2018) numbers in auxetic behavior, it is possible to accomplish certain types of failure and + desired mechanical aspects in the overall framework. This contrasts with the expected positive values observed in many natural occurrences (Gan, Z., & Asad, M., 2022).

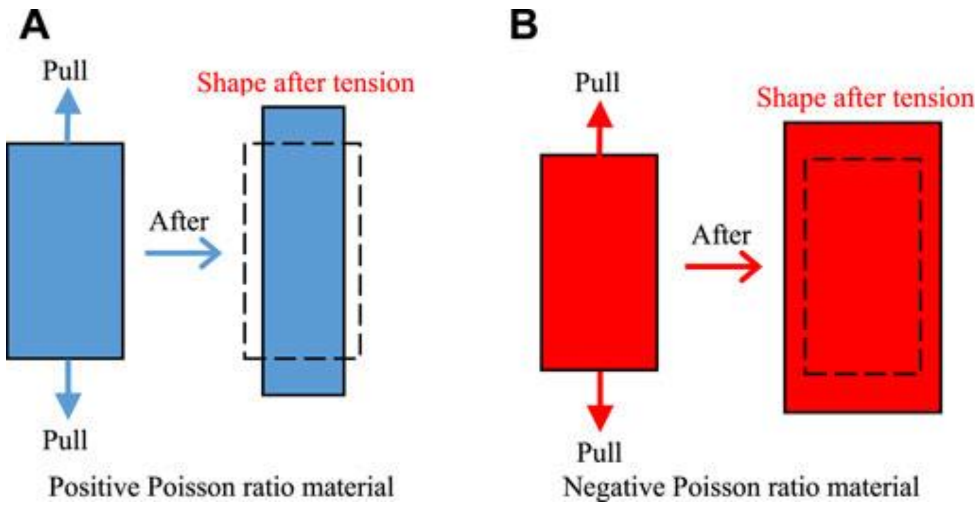


Figure 2: Representation between a positive and negative Poisson's ratio

1.3 Mechanical Properties of Auxetic

The mechanical properties of this reinforced concrete that combines the compressive strength of concrete with the tensile strength of steel reinforcements is a particular characteristic of various structural applications, from buildings and bridges to dams and roads. These properties are:

- Increased energy absorption because auxetic structures exhibit an advanced damping and sound absorption in compared to conventional material (A V Mazaev, O Ajeneza, M V Shitikova).
- In addition, a high shear stiffness also falls into this category of properties, because when a negative magnitude increases the Poisson's, the shear modulus rises to a higher value. As the shear modulus enhances, the shear strength approaches enormous value, when the coefficient of the Poisson's ratio approaches approximately -1. Therefore, the shear resistance significantly increases (A V Mazaev, O Ajeneza, M V Shitikova).
- Equally with the high fracture toughness, auxetic have the phenomenon when a load is applied to any structure uniformly distributing the stress concentration. In auxetic material, the propagation of a fracture demands a greater amount of energy, and the strength of the material can alter depending on the Poisson's ratio. As a result, the

material becomes exceptionally resistant when the Poisson's ratio is near -1 (A V Mazaev, O Ajeneza, M V Shitikova).

- Finally, enhanced indentation resistance is the result of the high shear stiffness and a phenomenon that when an impactor makes contact with a surface, all auxetic material tends to move to where the load is being applied, which obviously increases the density of these areas/regions (A V Mazaev, O Ajeneza, M V Shitikova).

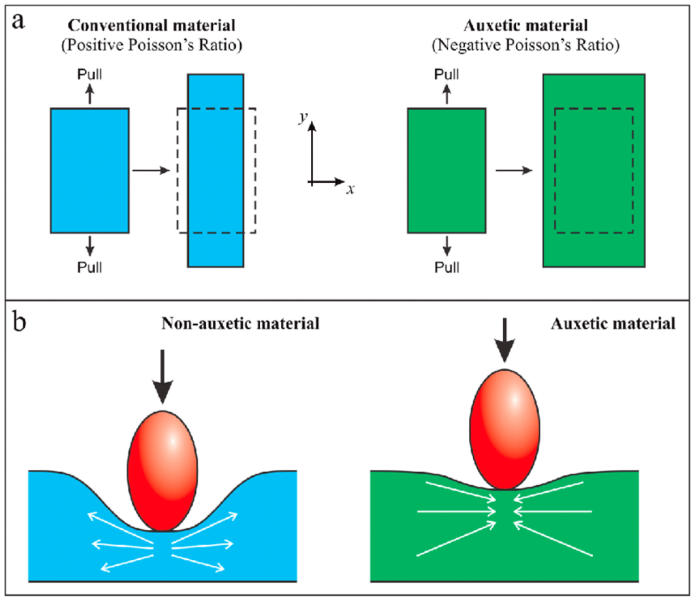


Figure 3: Deformation behavior within both materials and stress concentration difference

Because of its adaptability, cost-effectiveness, and strength, reinforced concrete is utilized in various commercial and industrial applications. The foundations, beams, columns, slabs, and other load-bearing parts of structures, and infrastructure projects like bridges and highways are familiar places where it is utilized. There are also many more applications for it.

In reinforced concrete, the interaction between concrete and steel is a beautiful illustration of how mixing diverse materials may form a composite that capitalizes on the strengths of each component while limiting the deficiencies of each component individually. Because of this, engineers and architects have been able to construct safer, more durable, and taller structures than ever before.

1.4 Abaqus Software

In the field of computational mechanics, Abaqus stands out as a sophisticated piece of software that is capable of modeling complicated events. One example of this is the compression testing of materials like reinforced concrete. It is essential to do this kind of study to evaluate the structural integrity of concrete and the failure mechanisms that occur when it is loaded.

2.0 Description, Materials and Method

Three auxetic shapes/patterns operated on this project such as, the bowtie honeycomb, the tubular, and the brick are all made from stainless steel cut with a 3D laser for higher accuracy and clean shapes. The stainless-steel also provides a high strength capacity.

2.1 Laboratory/Experiment Preparation

<u>Material Preparation:</u>

Materials Used: Stainless steel for shape cutting, silicone for molding, and concrete for casting.

Equipment Used: Laser cutter for shaping the stainless steel, 3D printer that molds shaping silicone, and a vibrational tool to ensure void-free casting.

<u>Shape Fabrication:</u>

Design of Shapes: Three shapes were designed: brick, honeycomb bowtie, and tubular.

Laser Cutting: Each stainless-steel shape was accurately cut using a laser cutting machine to replicate the desired auxetic patterns precisely.

<u>Molding and Casting:</u>

Silicone Molding: A 3D printer was used to create silicone mold.

Concrete Pouring: Concrete was poured into the silicone molds. Vibration was applied to each mold to fill voids and ensure uniform density.

<u>Curing Process:</u>

Duration: All concrete samples were cured for 28 days for optimal hardness and durability.

<u>Compression Testing:</u>

Testing Setup: A displacement-controlled compression test was set up for each cured concrete sample to obtain accurate deformation measurements for each auxetic structure under applied stress.

2.2 Performance and Properties of the Shapes

Three auxetic shapes/patterns operated on this project such as, the bowtie honeycomb, the tubular, and the brick are all made of steel for a higher strength capacity. In a bowtie honeycomb and brick construction, the tilted re-entrant sides of a unit cell are aligned and expanded in the same direction when tensile loads are applied to the unit cell’s top and bottom horizontal ribs. These re-entrant vertices shift horizontally to lengthen, pushing the adjacent cells outward through the neutral ribs that run horizontally, causing them to increase laterally. (Cho, H., Seo, D., & Kim, D.-N., 2018)

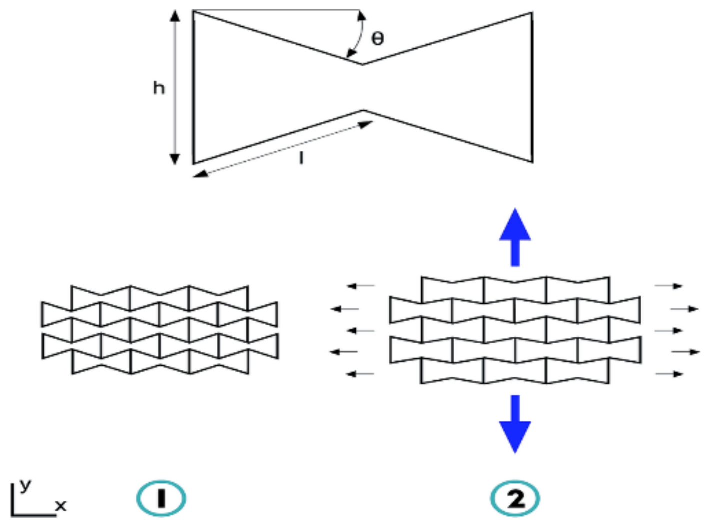


Figure 4: Represents the pattern of the bowtie under tensile loading.

Among the many mechanical components utilized in engineering, tubular structures are the most frequently used. Although the cross-sectional shape of the pipe can be almost undefined, the most typical design is the circular design.

Many investigations indicate that tubular structures have superior mechanical qualities when viewed alongside solid sectional components when consumed with the same quantity of material. This is particularly true regarding the aspect of impact energy absorption. Tubular structures, even though they possess remarkable features, have significant problems regarding practical applications. Regarding engineering, tubular constructions experience progressive buckling or general instability, leading to insufficient energy absorption when subjected to impact. In the meantime, developing more sophisticated manufacturing techniques has made it possible to build various auxetic tubular structures with different geometrical configurations with relatively little effort. In a wide variety of industries, including biomedical, aerospace, automotive, marine, and offshore sectors, auxetic tubular constructions have the potential to bring about substantial advancements (Luo, C., Han, C., Zhang, X., Zhang, X., & Xie, X., 2021).

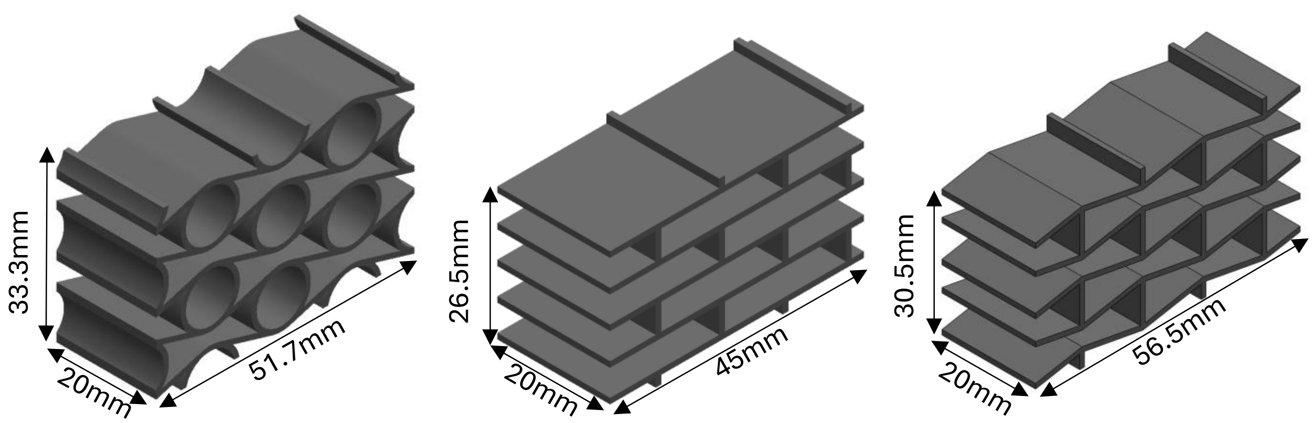


Figure 5: Dimensions of tubular, brick, and honeycomb bowtie

2.3 Abaqus Simulation

Furthermore, Abaqus simulation software was used to simulate the real-life experiment to have various results as precise as possible (Touolak, B., 2022).

Geometry and Assembly of the Shapes:

SolidWorks was used to build the reinforced concrete shapes and then transferred to Abaqus. The specimen shape includes the amount of concrete and where the reinforcement is placed. The reinforcement can be modeled as discrete rebar or embedded elements, depending on how precise and complicated the analysis needs to be. The reinforcement was placed in the concrete core in a way that followed standard procedures for designing with reinforced concrete.

Include Material Properties:
Defining the materials was very important for making sure the modeling was accurate. The density, elastic modulus, Poisson's ratio, and a damaged plasticity model were used to describe the concrete. The model was used to simulate how it would behave under high compressive loads, including factors like fragmenting and fracturing. The support, usually made of steel, was described by its density, Young's modulus, yield stress, and final tensile strength, which show how it behaves when it's loaded.

Meshing: Once everything was put together, the Mesh tool in Abaqus was used to separate and reinforce the concrete. The element type and mesh size were chosen to accurately represent the complicated interactions between the concrete and the reinforcement when it was loaded. This ensured the mesh was small enough in places with high stress while maintaining computational efficiency.

Steps and Their Work: A static general analysis step was set up to model the application of compression loads. The interactions between the concrete and reinforcing were carefully modeled, including contact pairs and the right amount of friction. This allowed for a realistic simulation of physical behaviors like slippage and bonding failures.

Applications of Load and Boundary Conditions: Boundary conditions were used to make the object feel like it would in a normal compression test. The sample's base was set in all directions, but the top face could only move vertically as a compression load was put on it. It was done slowly, just like in an actual compression test, so that, the load would be progressively given.

Simulation of the Results: The model was run, and the computing job was closely watched to ensure it converged and worked correctly. Any problems during the study were fixed by changing the solution settings and mesh density as needed. The results were then shown visually to check the patterns of displacement, stress, and strain. This helped find weak spots and determine the object's strength (Touolak, B., 2022).

3.0 Results and Analysis

A control sample of only concrete was created to have a general idea of the compressive strength of concrete with no reinforcement; this sample generated a value of around 30 MPa which is relatively small compared to our values, and it would not resist strong loads. Furthermore, another sample (this time it was reinforced) of steel fiber inside the concrete was tested, generating a value of around 80 MPa.

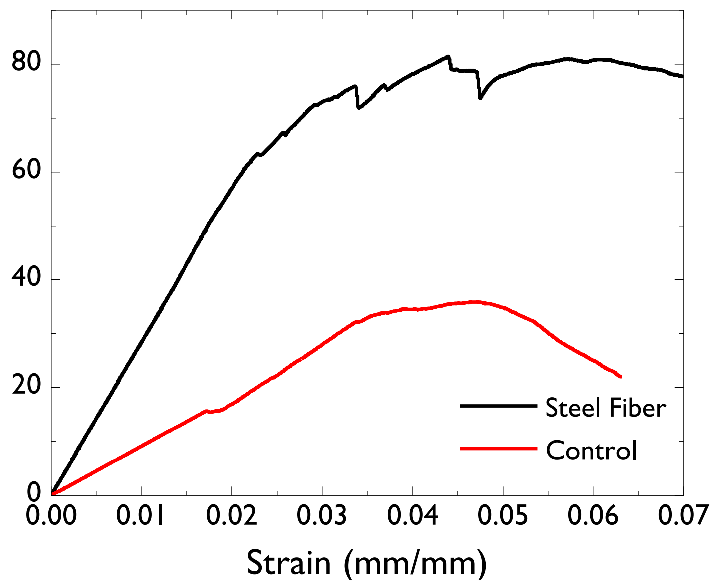


Figure 6: Stress vs Strain; compressive strength of control and steel fiber samples

The benefits of steel-reinforced concrete have only grown since ancient builders began incorporating horsehair into their mudbricks. The fibers increase the slab's longevity and prevent cracking, but these aren't the only benefits of employing reinforced concrete in your next project. Using steel fibers results in a thinner concrete slab. It can save building costs while guaranteeing that the slab meets the project specifications. You won't have to worry about changing project dimensions to fit a thick concrete slab. One of the most notable benefits of using steel fibers in concrete is the lower cost the greater durability results in lower maintenance expenses.

Furthermore, using steel fibers allows for a more straightforward joint location, potentially resulting in fewer joints and lower material and construction costs. Steel fibers in concrete create a robust surface resistant to impact fractures. Consequently, you will have fewer difficulties with bleed holes, which can compromise structural integrity (DWR Reinforcing and Steel Solutions., 2023).

Figure 7: Representation of steel fiber inside of concrete

In contrast, following the conclusion of the compression testing of each auxetic form, we discovered remarkable compressive strength levels for the brick, bowtie, and notably the tubular shape. These results were obtained after the compression tests were completed. The bowtie and brick produced values of about 100 MPa, which is an exceptionally high number, especially when compared to steel fibers due to the greater strength values these materials possess. In addition, we obtained a result of about 170 MPa for the tubular form, which is even more astonishing than the previous measurement.

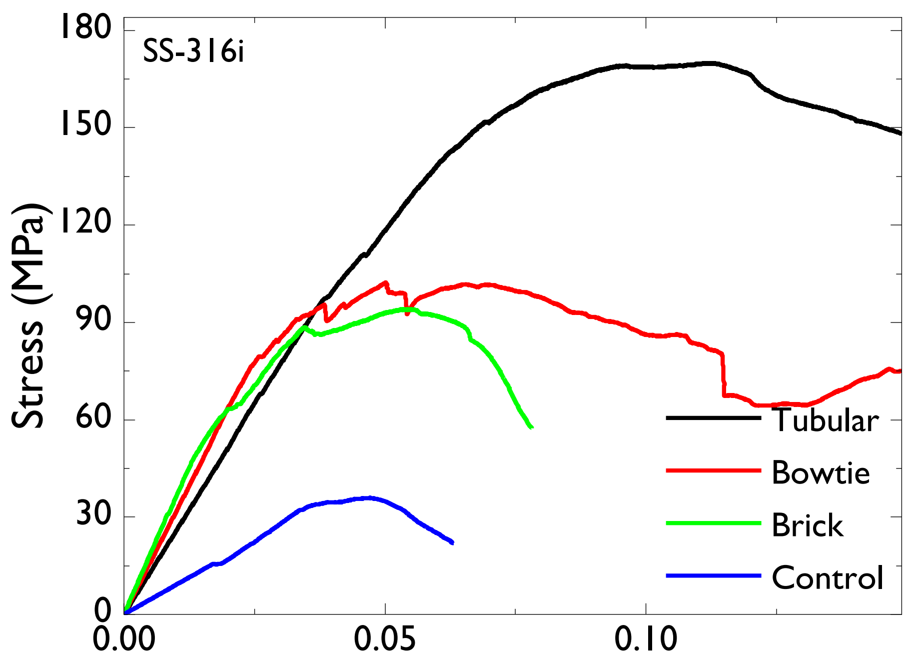
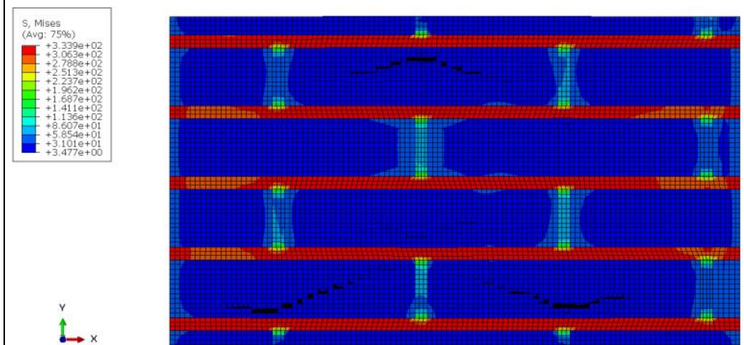
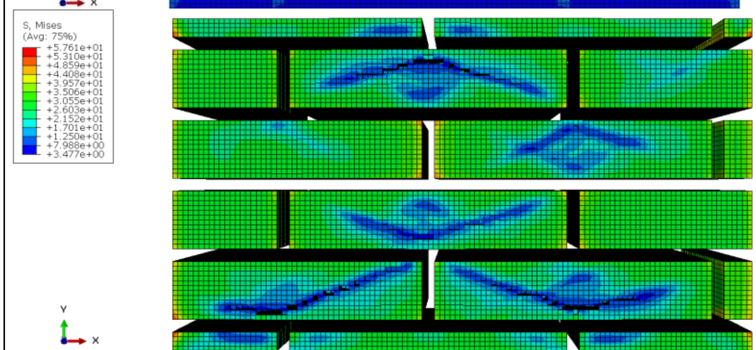
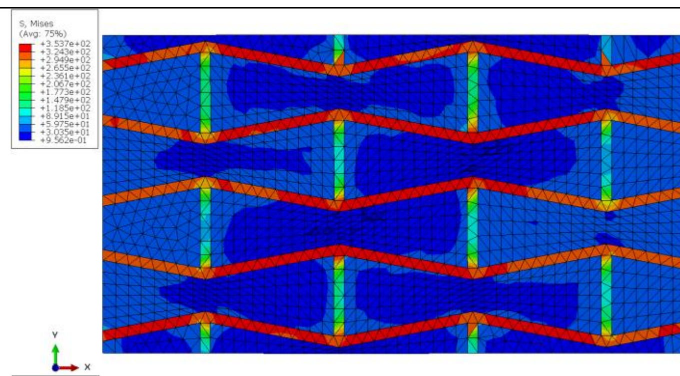
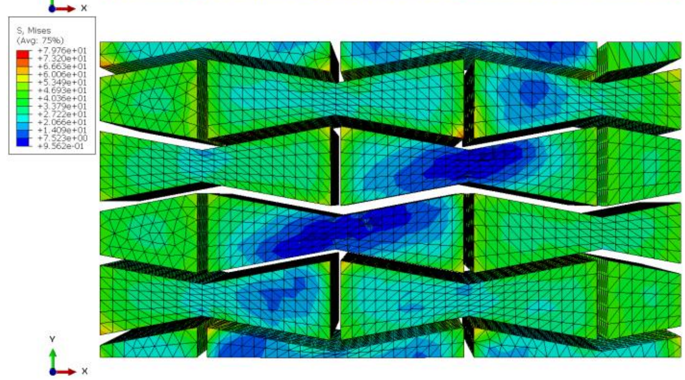


Figure 8: Stress vs Strain relationship of the three different auxetic shapes

3.1 Abaqus Results and Analysis

Auxetic Shape	Simulation
Brick	 
Honeycomb Bowtie	 

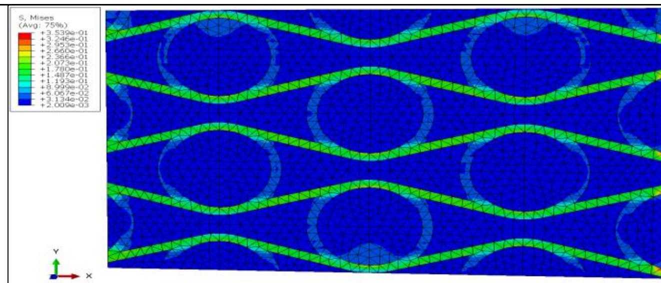
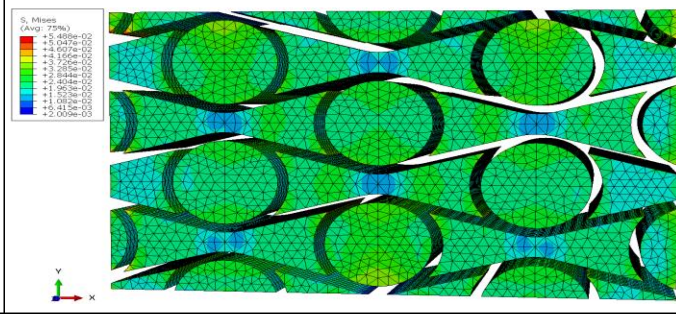
Tubular	 

Table 1: Compressive failure and distributed deformation

3.2 Distributed deformation

One reason for this remarkable difference is that it is connected to the angles these forms offer. To put it another way, the brick, and the bowtie both have right angles inside their dimensions, which means that once subjected to compression, they are more likely to bend in the direction closer to their center due to the NPR feature. Additionally, the tubular form, made with circular shapes in its characteristics, is designed in the same way as its name and description describe it. Because of the energy absorption capabilities that this shape can consume, it exhibits a pattern of behavior that is distinct when subjected to compressions. This is because it is less likely to bend. According to a study (Li, T., Huang, J., Zhu, D., Gao, P., & Zhou, A., 2020), "The test results showed that the compressive strengths of confined specimens increased by 20%–71% for circular columns and by 23%–41% for square columns. Similarly, the ultimate strains improved by 49%–296% for circular specimens and by 45%–145% for square specimens" in which they provided the exact differences between circular and square shapes can correlate to our study.

3.3 Compressive Failure

The compressive failure that is displayed in Table 1 is an illustration of the notion of how auxetic material responds when it is brought under compression. When these compressions began, concrete was the first material to crack within the samples because of its brittle properties. After that, the stainless steel bent or deformed in a manner that was equal to a negative Poisson's ratio, which means that it contracted in a manner that was perpendicular to the direction of the compression. Looking at the green photographs in Table 1 will allow us to ascertain this information on the brick and bowtie. The green images show that the brick shape begins to fail mainly in the corners of each square contained within the specimen. Furthermore, the bowtie started to fail at its thinnest dimensions, where the right angles are situated, and where there is no excessive concrete mix. Finally, the tubular structure had a failure type comparable to the bowtie.

This is because there was not an excessive amount of concrete, and the circular forms of the tubular structure prevented a higher failure. As a result, this is the best choice with the highest compressive strength. (Solak , K., & Orhan, S. N., 2023)

4.0 Conclusion

After further review and analysis, these composites are defined by a negative Poisson's ratio, which results in increased energy absorption, greater elastic modulus, and improved bonding characteristics. Auxetic composites were studied for their possible uses in the construction, mainly as a protective characteristic for building materials. The primary objective of this study was to investigate these prospective applications. To accomplish this goal, samples of reinforced concrete that included auxetic materials made of stainless steel were constructed and subjected to intense testing. Both physical compression tests and simulations using Abaqus Software were performed on these materials, and the results showed that the compressive strengths ranged from 80 MPa to almost 170 MPa. The results of the experiments demonstrated that auxetic materials with a tubular form were displayed.

4.1 Importance of Auxetic Materials

It is impossible to overstate the significance of auxetic materials; the characteristics and outcomes of this phenomenon are fascinating concerning potential future research. The following are some of the characteristics of the material: high energy absorption, uniform distribution of stress concentration over a structure to prevent cracks, and a high correlation between compressive and tensile strength, which can result in a reduction in the number of columns in a building.

4.2 Possible Applications and Future Work

The enormous qualities of auxetic materials can result in the development of intricate undertakings in the actual world. Furthermore, this behavior has only been examined on a limited scale, within the context of scientific research, prototypes, and laboratory testing. No tests have been conducted on larger scales, such as in the building industry. Because tubular supplied us with the highest compressive strength, possible future work connected to this study may include testing a tubular auxetic form in a structure, for instance. This is because the tubular shape provided us with the highest compressive strength. An analysis of the cost of this compared to steel fiber, for instance, should also be considered when it comes to the financial aspect. This may assist in enhancing and attracting construction businesses to establish whether or not it is a practical investment and further progressed constructions.

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