Numerical Modeling of Steel/Concrete Foam Composites

A Major Qualifying Project

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Abstract

The goal of Numerical Modeling of Steel/Concrete Foam Composites was to study a new high function composite know as foamed steel reinforced with concrete. Two different foamed steel structures were given to be studied under compressive forces in the program Abaqus. The two foamed steel structures were then compared to determine where each structure was most likely to fail, and which structure better supported the compressive load.

Executive Summary

One of the most utilized building materials in modern day construction is concrete reinforced with steel. Usually, concrete reinforced with steel comes in the form of steel bars running through a concrete slab or steel mesh with concrete poured over the top. This forms a product that is much stronger than the original two components on their own. The new reinforced material combines the strength of the steel under tensile forces with the concrete strength under compression. However, engineers have always been searching for a combination of steel and concrete that is stiffer and stronger. This new material comes in the form of a high function composite known as foamed steel. Foamed steel is created when there are many air pockets that are left in the steel when it is setting, creating a material that is similar in structural properties as regular steel but with a fraction of the weight. Along with this, foamed steel can be reinforced with concrete to create an even stronger material.

This Major Qualifying Project focuses on a computational study of the compressive strength of two different steel foamed structures reinforced with concrete. The first structure is a uniform structure that gives a basic understanding into how the foamed steel reinforced with concrete would behave under compression. The second structure is a more complex structure with higher mechanical properties. These two structures are then compared to each other to determine their failure, and ultimate strength.

1.0 Introduction

Throughout human history, people have been trying to innovate and improve on everything that the people before them had created. This applies to all aspects, from technology, to weapons to even building materials. Two materials that have been instrumental through human history are forms of steel and concrete. Both materials were developed thousands of years ago and throughout their history humans have constantly been improving on them. Even today material scientists and civil engineers are constantly trying to improve the properties of these materials to maximize their effectiveness. One of the newest developments for these materials comes in the form of steel foam. When steel foam is reinforced with concrete it can maximize the material properties of both materials.

In this report, a background on steel, concrete, reinforced concrete, steel foam and reinforced steel foam were given. Along with this compression tests were completed on steel foam structures reinforced with concrete in the program Abaqus and the results from those tests will be given below.

2.0 background

2.1 Steel

Steel is a very strong metal used for a variety of different things. Steel is produced from a high carbon iron alloy known as pig iron. Pig iron is made when iron ore is smelted in a blast furnace, with some carbonous material, usually coke acting as a reducing agent for the iron ore. To remove the rest of impurities in the pig iron limestone is added. Steel is then produced from the pig iron when the carbon atoms in the pig iron are replaced with chromium, copper, tungsten, vanadium, titanium, manganese and nickel at certain ratios to gain a specific steel alloy. *(Fenton, 2015)*

Figure 1: Steel Skeleton of a Building (Metinvest, 2022)

The humble beginning of steel goes all the way back to the thirteenth century BC when blacksmiths discovered that iron becomes much harder and more durable when it is heated, and carbon is introduced during the smelting process. This marked the beginning of the iron age. At this point iron is mostly used for weapons and armor. By the third and fourth century AD, steel became more and more commonplace, and China began mass producing steel. The use of steel and steel making techniques begin to spread across the globe. Trade with the middle east brought these steel making techniques to Europe during the ninth century. The Vikings used these steel making processes to create their "Ulfberht" swords. It seems like steel making techniques were then lost during the dark ages and it took all the way until 1740 when Benjamin Huntsman rediscovered steel making techniques. Steel became a huge component in the industrial revolution and both world wars and today much of the mechanical properties of steel have been maximized to their potential. *(Gregerson, 2015)*

Today steel is used for everything from manufacturing to constructions. This is because of steel's great structural properties. Steel is very strong under tension, and pretty strong under compression and torsional forces. The biggest strength of steel is that it is a ductile material. This means it will bend and contort before it fails. Also being a ductile material, steel can be bent and molded into all kinds of different shapes while keeping its structural integrity. Steel is also fire resistive but will melt if left in extreme heat for long amounts of time. The only real structural weakness for steel is that it corrodes when it encounters water. But if steel is well insulated it makes a great building material due to its structural strength along with its ductility.

2.2 Concrete

Concrete is a hard rock like material used mainly in construction. Concrete is made from a mixture of a paste and an aggregate. Aggregates are coarse rock like materials that vary in size and shape based on the desired material properties for the concrete. In concrete the paste is usually a combination of portland cement and water, this paste then coats the aggregates. When the paste dries it glues the aggregates into place, changing the concrete from a thick liquid substance to a hard rock like substance. *(Concrete, 2017)*

Figure 2: Wet Concrete (Omex, 2021)

Just like forms of steel, forms of concrete have been around for thousands of years. The earliest known uses of concrete like substances were around sixty-five hundred years ago. By 3000 BC, the Ancient Egyptians were using concrete in all kinds of building projects. Their most famous use of concrete was in the Pyramids. By around 300 BC, the secrets of concrete had made it to the Romans, who greatly improved on the formula. The Romans mixed slaked lime and volcanic ash into the concrete mixture to create an even stronger version of the Egyptians concrete. This new Roman concrete was very similar to modern concrete that is used today. By the third century AD, the Romans had used concrete in the construction of both the Colosseum and the Pantheon. The secrets of concrete fell along with the Roman Empire in the Sixth

Century, and it wasn't until 1756 that John Smeaton rediscovered hydraulic concrete. The benefits of using concrete were quickly realized and it was used all over the world again by the twentieth century. In 1912 concrete was used in the construction of the Erie Canal and it was used again in 1935 in the construction of the Hoover Dam. *(Gromicko)*

Figure 3: A Hardened Concrete Block (Azusa, 1966)

Today concrete is used in many aspects of building and construction. Concrete's main benefits come with its strength under compressive forces. It can support huge loads before it will fail. On the other hand, concrete is extremely weak under tensile forces and rotational forces. Concrete is a very brittle material so tensile and torsional forces cause concrete structures to crack and then fail. Concrete also handles the elements very well, it is fire resistance, water resistant and resistant to many types of acids. Concrete’s strength under compression and resistance to the elements makes it a very important building material.

2.3 Reinforced Concrete

As humans reached the limits of how strong they could make their steel and concrete they realized that the two materials could be used together to make an even stronger material known as reinforced concrete. Usually, concrete is poured around steel rods or steel mesh, and then when the concrete dries, it hardens around the concrete fusing the two materials together creating reinforced concrete.

Figure 4: Reinforced Concrete Slabs (Advantages and Disadvantages of Reinforced Concrete, 2022)

Reinforced concrete was discovered by Joseph Monier. He was a gardener who used many concrete pots and tubs. He realized in 1849 that when he used steel mesh to reinforce his concrete garden pots and tubs that they became much stronger and more durable than on their own. By 1867 he had patented the idea, which allowed the rest of the world to build on it. People realized reinforced concrete was stronger than the sum of the components, so it became a main building component throughout the world. By 1904 the Ingalls Building in Cincinnati, Ohio was built which was the first skyscraper to utilize this new technology. *(Day)*

Steel and concrete make very good partners because they both make up for the other one's weaknesses, while also having similar chemical properties. The brittleness of concrete greatly limits what it can be used for in construction. Concrete can sustain large compressive forces, but tensile forces can cause it to crack cand fail. Contrarily, steel can bend under large compressive forces, changing the steel structures shape and weakening it until failure. Steel has much better elasticity than concrete allowing it to handle tensile forces much better than concrete. By combining the two they almost eliminate each other's weaknesses. The reinforced concrete keeps its strength in compression while adding the steel's ability to handle the majority of the tensile and rotational forces. The concrete on the other hand protects steel from corrosion and extreme heats by being the insulator for the steel.

The similar chemical properties between concrete and steel also make them great partners in construction. Steel and concrete not only bond together exceptionally well but they also have a similar coefficient of thermal expansion. This means both materials will expand and contract in heat at close to the same rate. Along with this steel and concrete have a similar strain relationship meaning that they will stretch at similar rates until the concrete fails. The final chemical property that makes steel and concrete go so well together is that they bond together very easily.

2.4 Metal Foam

As time has continued people have been continuously trying to improve on building materials. Recently there has been an innovation in foamed metals. This is a new structure design that creates metal products with air pockets or voids in the material, instead of the usual solid metal product. This is beneficial because it allows one to control the density of the metal. The density controls the weight-to- stiffness ratio which coincides along with the weight to strength ratio. This gives a metal that is very customizable to fit any certain job. There has been extensive research done on Aluminum and the results have been very promising that foamed Aluminum greatly outperforms regular Aluminum. Steel foam is still in its relative infancy, but it has also been seen as a promising new building material. (Smith et al., 2011)

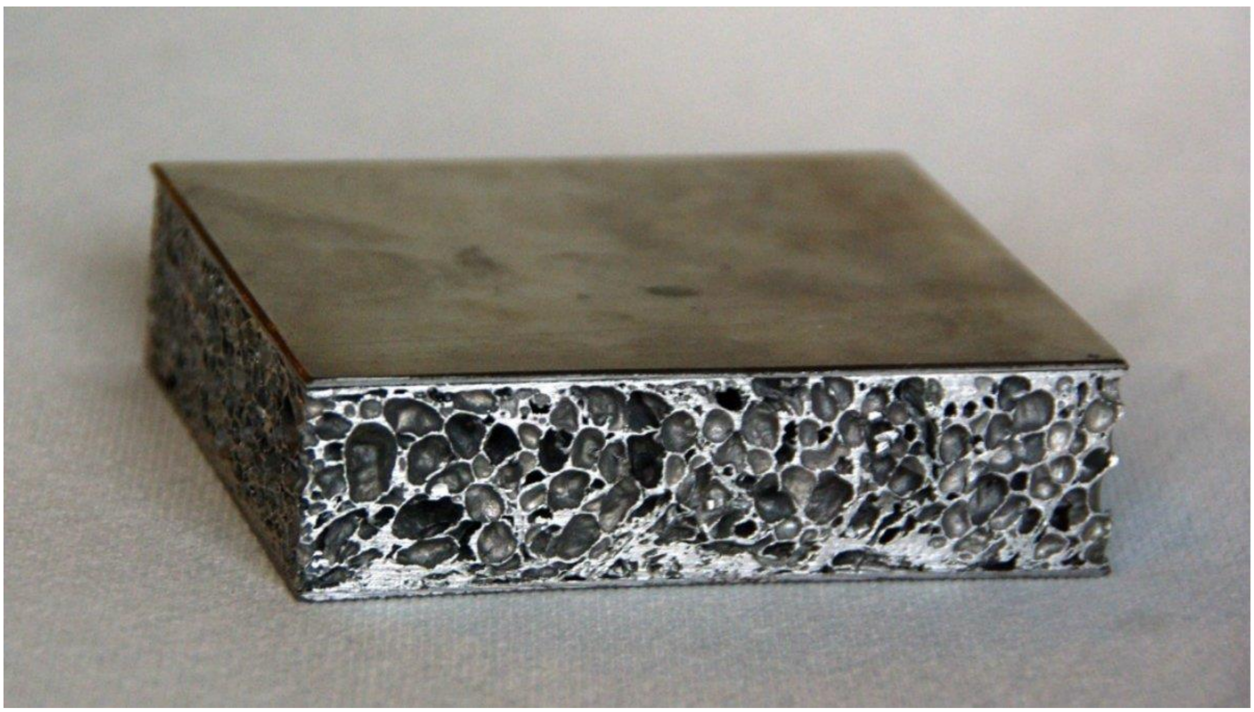

Figure 5: Cross Section of a Metal Foam Slab (Surrey, 2018

Foamed steel allows for very new possibilities on what can be done with steel. The air pockets in the microstructure allow steel foam to be much lighter than regular steel. Along with this it adds density as a design variable for steel making steel much more customizable. The foaming process also changes many of steel’s structural properties. First, foamed steel minimizes the weight of the steel along with maximizing the stiffness of the steel. This makes the steel much stronger against torsional and compressive forces because it will be less likely to bend. The foamed steel also has much better energy dissipation and mechanical damping than regular steel. (Smith et al., 2011)

2.5 Reinforced Steel Foam

With the introduction of steel foam, there has been the idea of reinforcing steel foam with concrete. This would theoretically increase the benefits from plain reinforced concrete, creating an even stronger material. To create this new material, concrete would be placed inside of the steel foams air pockets creating a solid material with the concrete and steel woven throughout it.

This project investigates the structural aspects of this new material. Two different foam structures were studied, both with a uniform structure. True metal foam is usually not uniform but uniform structures were chosen that were complex enough to represent the real material while not being too complex. Both structures received a compression test, with a pressure force on the top of the structure and a fixed end on the bottom of the structure, in the program Abaqus. Shown below are pictures of the two metal foam structures.

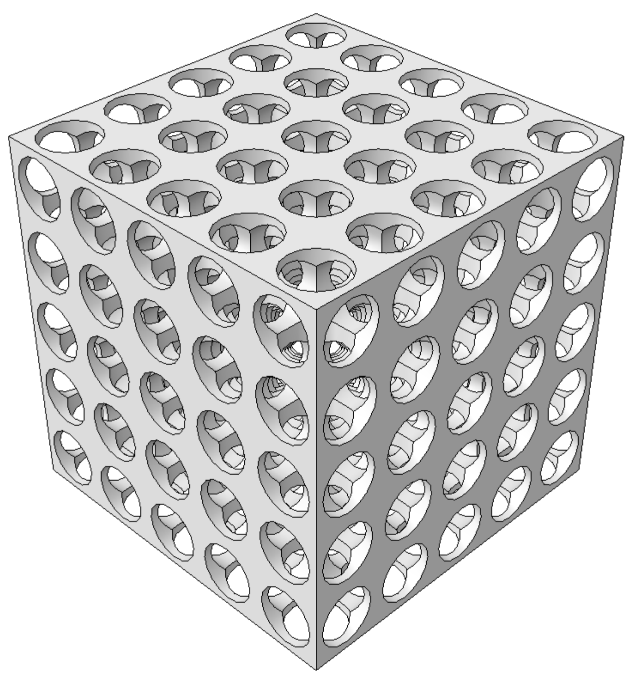

Figure 6: Steel foam Structure 1

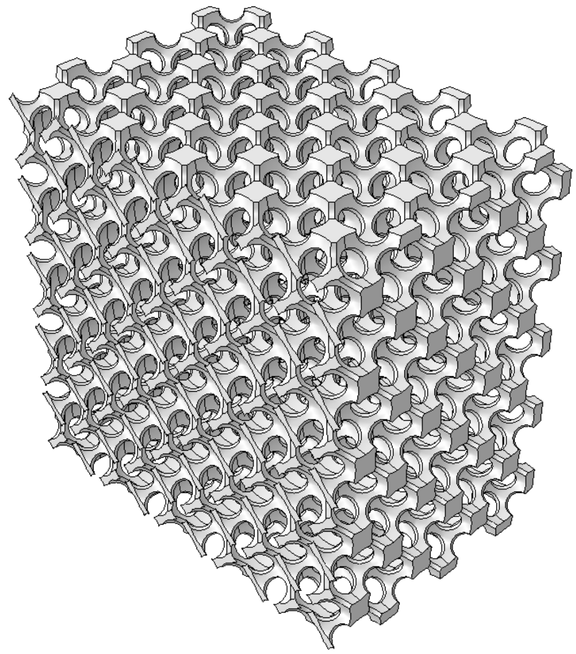

Figure 7: Steel Foam Structure 2

3.0 Methods

This section will contain how the compressive tests were conducted. The steps from creating the cement parts in Solidworks to transferring the part and the foam structure over to Abaqus and the resulting compressive test in Abaqus will all be discussed. Both structures had very similar methods so they will be discussed simultaneously with diagrams and pictures of both parts being shown during each step.

3.1 SolidWorks

First, the metal foam structure was uploaded into solid works. The metal foam and the cement part fit together to form a perfect cube. To accomplish this a solid cube with the same dimensions as the metal foam part was created as a part. Both the metal foam part and the solid cube part were uploaded into the assembly tab of solid works. The solid cube part was set as the fixed point on the origin and the metal foam part was the free part. Next the metal foam part was mated so that it would be sitting directly inside of the cube. Then the edit components tab was selected to edit the cube part. Then the cavity feature was chosen, and the metal foam part was subtracted from the solid cube leaving behind the cement part.

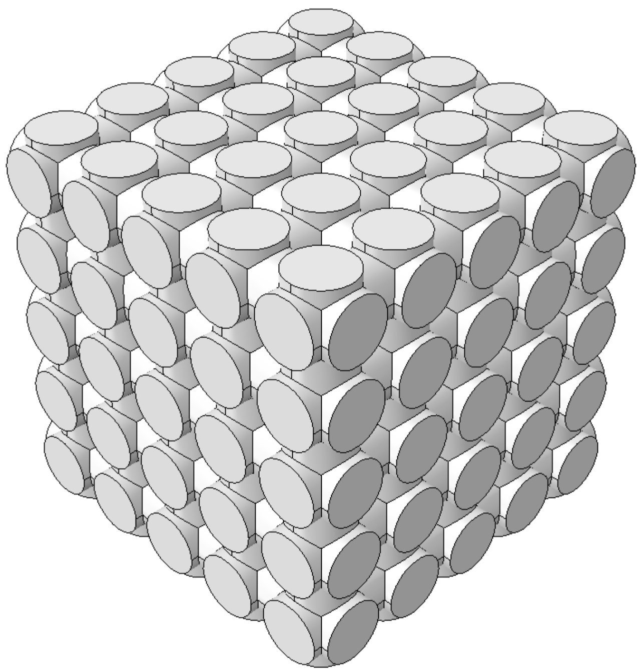

Figure 8: Concrete Structure 1

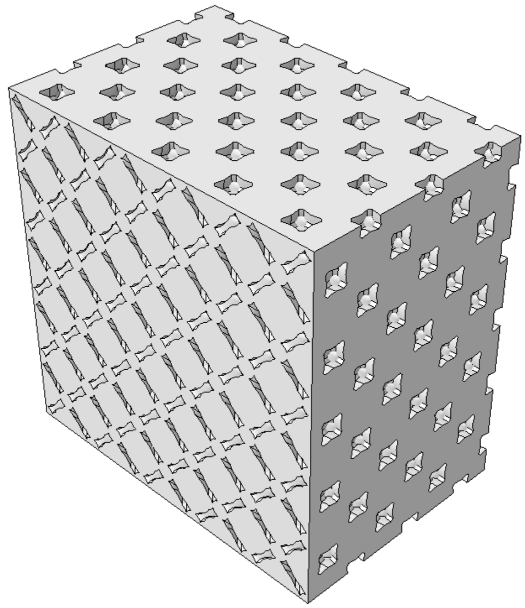

Figure 9: Concrete structure 2

3.2 Abaqus

Next, both the steel foam structures, and the cement parts were saved in Solidworks as .step files. They were then transferred over into Abaqus where the stress analysis tests would be conducted.

3.2.1 Property

Once everything was uploaded into Abaqus, material properties were created. Both foam structure one and foam structure two were assigned the same properties so that the two parts could be compared at the end to see which is a better foam structure. The elastic properties for both parts were 120 GPa for the Young's Modulus of steel and .3 for Poisson's ratio. For the concrete the Young's Modulus was 40 GPa and the Poisson's ratio was chosen to be .2.

3.2.2 Assembly

For the Assembly, both parts were added into this tab by creating instances with both the steel foam part and the cement part. For both structures, the steel foam part was placed at the origin and the cement part placed along on the z-axis. The cement part was then translated across the z-axis so that it would sit inside the steel foam part creating a cube. The two completed assemblies are shown below.

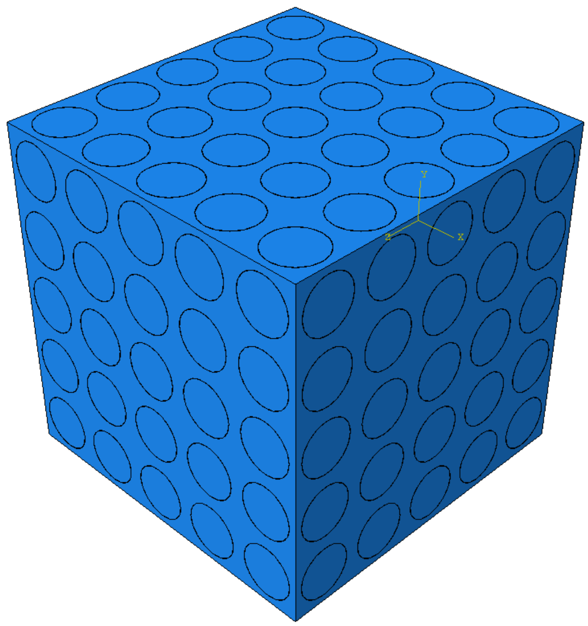

Figure 10: Assembly 1

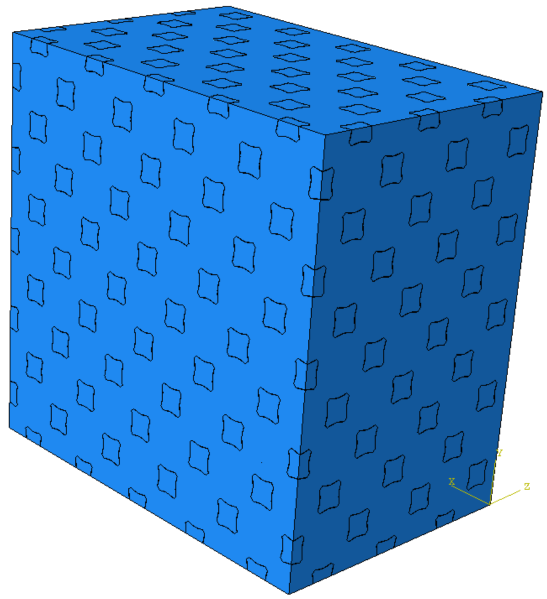

Figure 11: Assembly 2

3.2.3 Step

Next a new step needed to be created along with the initial step. The compressive load step was added so that Abaqus would know to run the compressive load after the fixed end.

3.2.4 Interaction

Next the steel foam part and the concrete part need to be tied together so that Abaqus would know that they interact as one. To do this a surface-to-surface interaction was created between the two parts. The Steel foam part was the master surface, and the cement part was the slave surface for both foam structures. This made sure that the parts would act accordingly to how they would in real life once they were under the compression. For both structures the finite sliding option was chosen to allow a little bit of sliding similar to real life.

3.2.5 Load

In order to represent a compression test one side of the foamed steel and cement assembly needs to be locked into place on all of its axis. This required a fixed end boundary condition to be placed on the bottom of the assembly. The fixed end boundary condition can be seen below on the bottom of both structures, where the arrows are pointing in all directions, not allowing the assembly to move. To represent the compressive force on the top a uniform pressure was added to the top of the structure. This can be seen on the top of the structure, represented by the downward pointing arrows.

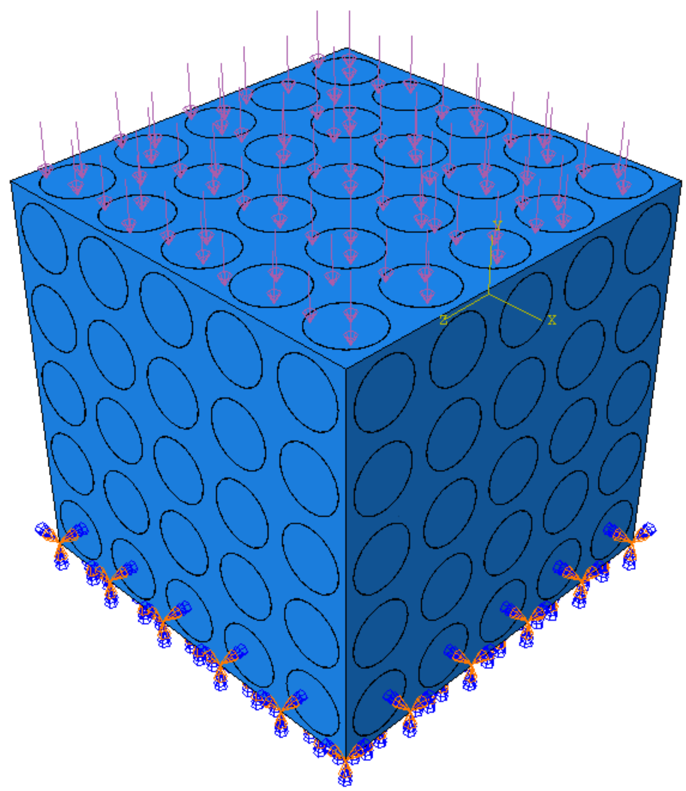

Figure 12: Assembly 1 with Fixed End Condition and Compressive Pressure Force

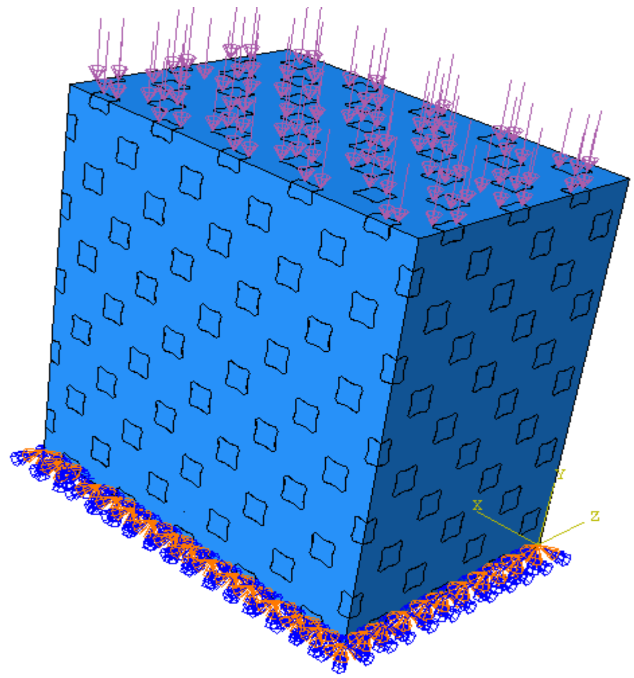

Figure 13: Assembly 2 with Fixed End Condition and Compressive Pressure Force

3.2.6 Mesh

A mesh was created for both assemblies to show the deformation once the compressive test is completed. Since both the steel foam and the cement assembly are relatively complex the mesh was created based on the individual parts and not on the assembly. This also allows the deformation in the individual parts to be shown. The individual parts are also relatively complex which meant the simple hexagonal mesh was not able to be used. Instead, the tetrahedral mesh was chosen. The seed size for the parts in assembly one was 1 for the concrete part and 1 for the steel foam part. The seed size was a little smaller for assembly two since assembly two is even more complex than assembly one and the seed size for the concrete was 1 and the seed size for the steel foam was 1.

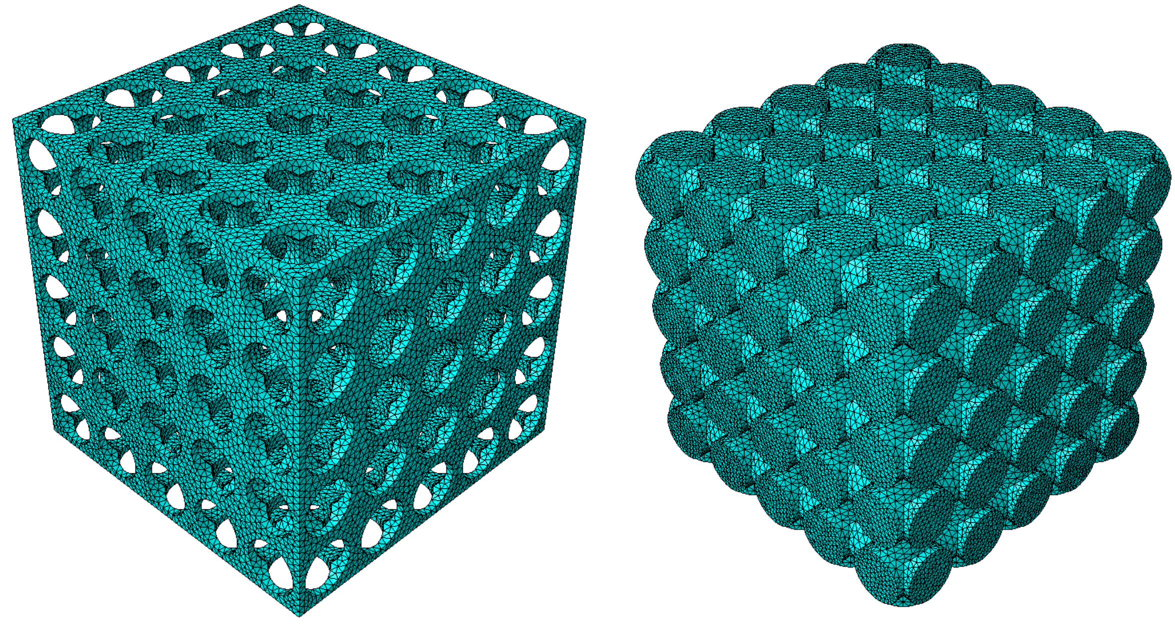

Figure 14: Tetrahedral Meshes on Concrete and Steel Structure 1

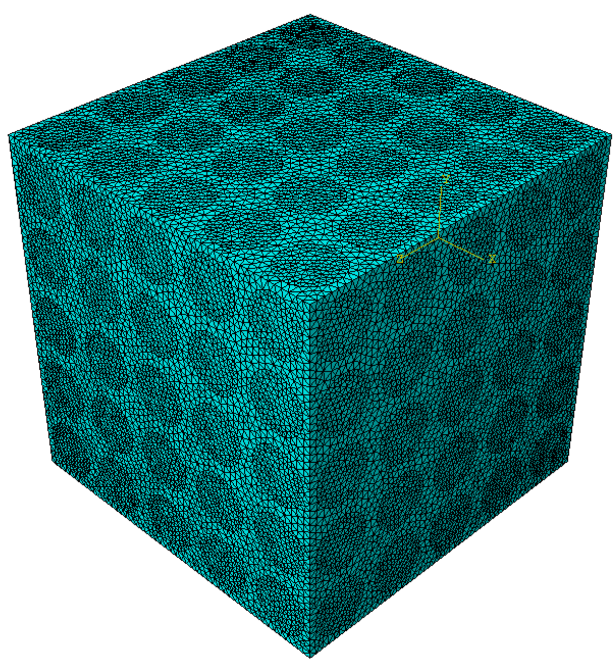

Figure 15: Tetrahedral Mesh on Assembly 1

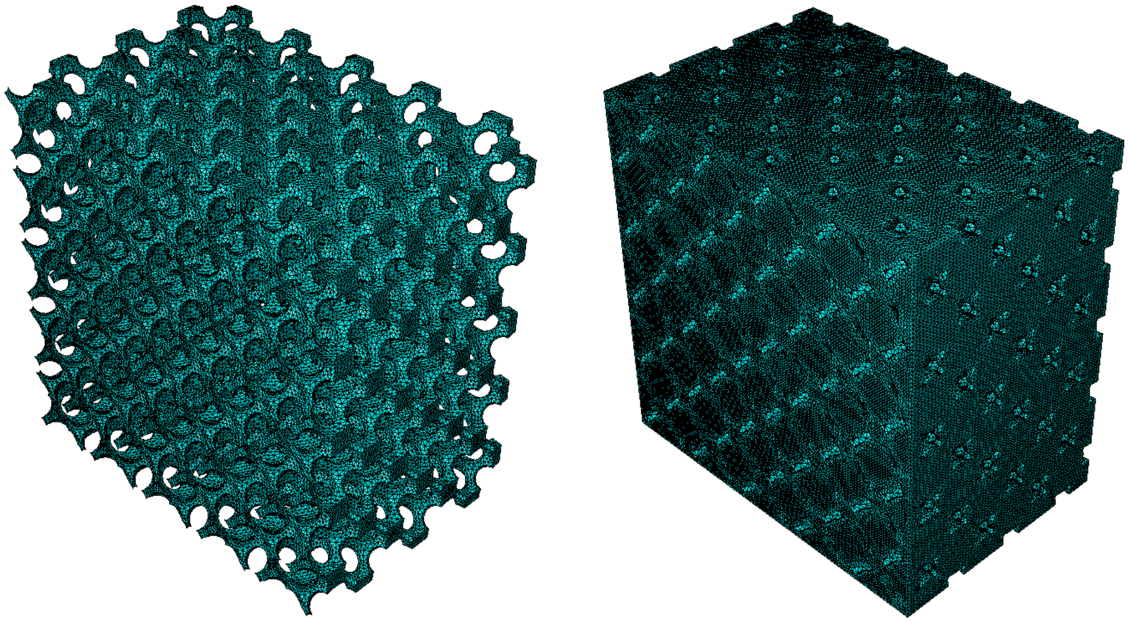

Figure 16: Tetrahedral Meshes on Concrete and Steel Structure 2

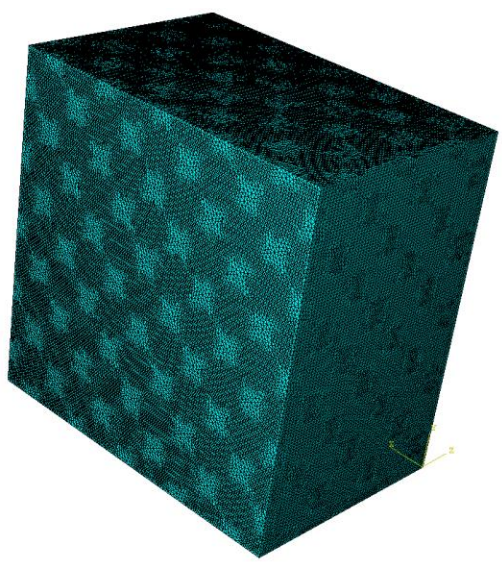

Figure 17: Tetrahedral Mesh on Assembly 1

3.2.7 Job

The only thing left for the preparation for the compressive test was to create the job and then run the job.

4.0 Results

4.1 Steel Foam Assembly 1

4.1.1 Steel Foam Structure

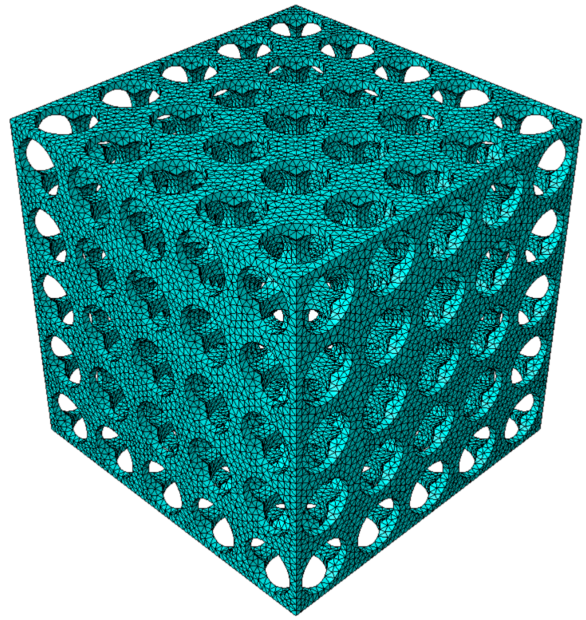

Figure 18: Steel Foam Structure 1 with Tetrahedral Mesh Before Simulation

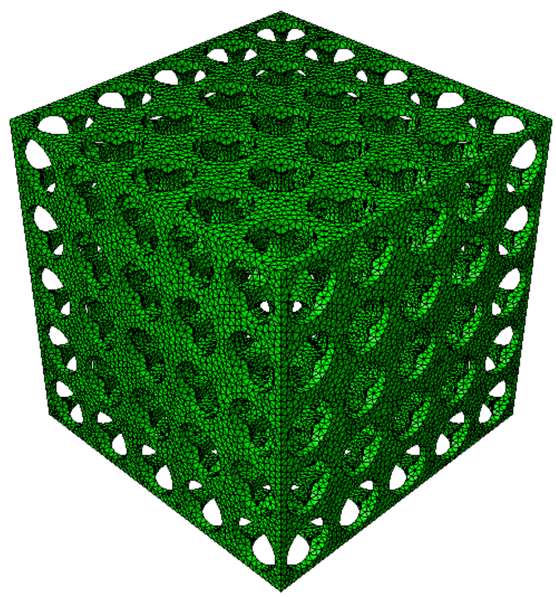

Figure 19: Steel Foam Structure 1 with Tetrahedral Mesh After Simulation with Deformation

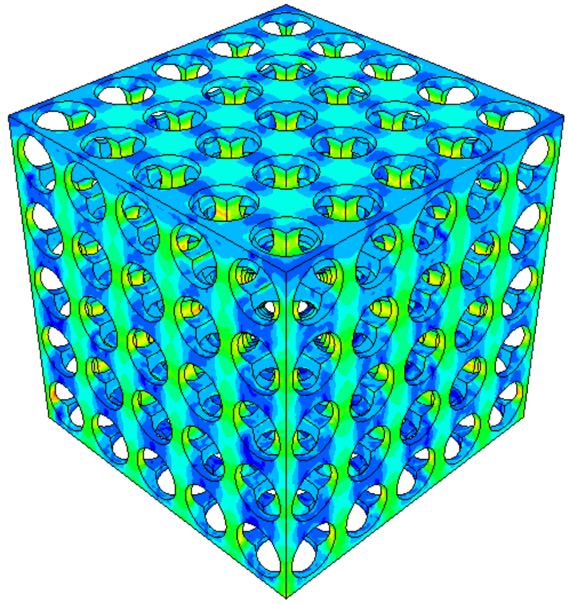

Figure 20: Steel Foam Structure 1 After Simulation with Shading

As seen above in Figures 17 and 18 there is little deformation in the mesh of the steel foam. The lack of deformation means the steel and concrete assembly holds up well to the compressive forces. Figure 19 shows where the structure supports the highest amount of stress and where it supports the lowest. The yellow color is where the stress is the highest and the blue is where the stress is the lowest with green in the middle. The long strips of steel marked in the yellowish green, in between the holes where the concrete belongs, have the most stress from the compressive load. This is where the concrete is receiving the least amount of support from the concrete structure.

4.1.2 Concrete Structure

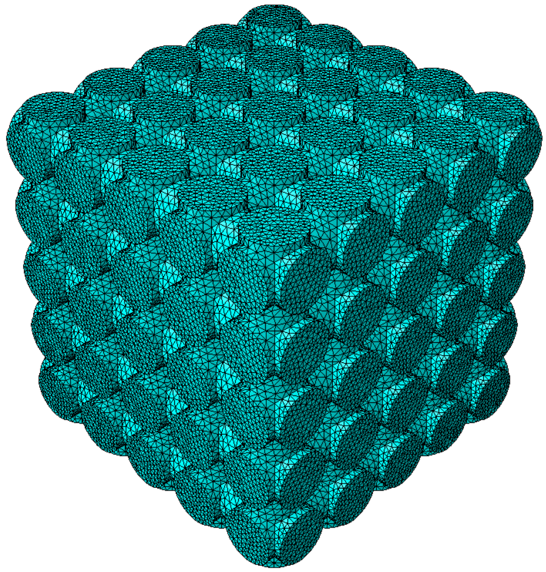

Figure 21: Concrete structure 1 with Tetrahedral Mesh Before Simulation

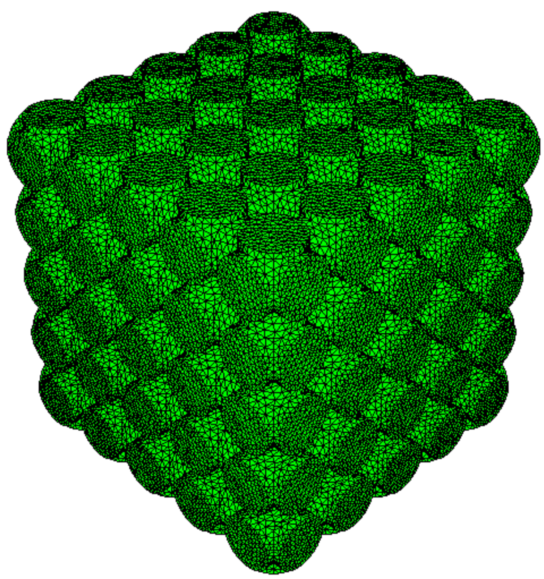

Figure 22: Concrete Structure 1 with Tetrahedral Mesh After Simulation with Deformation

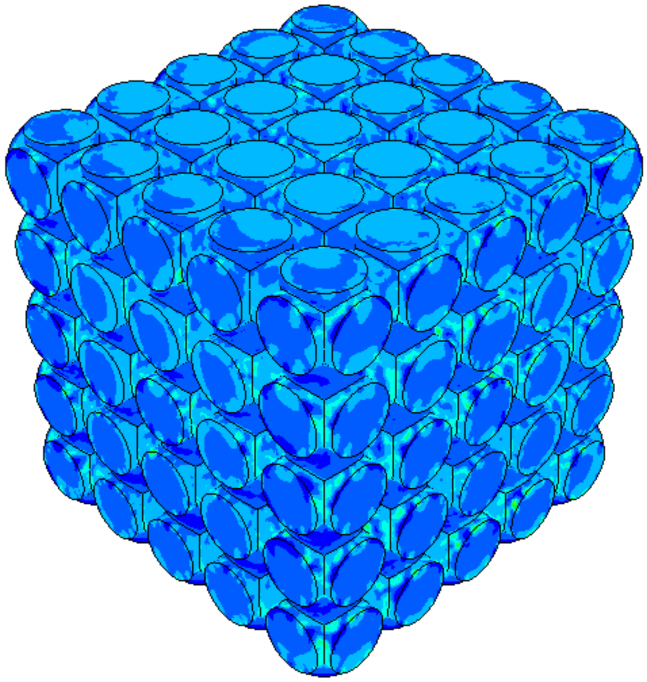

Figure 23: Concrete Structure 1 After Simulation with Shading

Just like the steel foam there is very little if any deformation of the mesh. The concrete holds up very well to the compressive load as predicted. When looking at Figure 21, The shading shows where the part has the highest amount of stress and where it has the lowest. The lighter blue color is where the stress is the highest and the blue is where the stress is the lowest. The concrete structure handles the compressive load very well. The high levels of stress occur on the edges of the concrete where it meets the steel foam. This is where the steel foam structure is transferring the load to the concrete structure.

4.1.3 Steel Foam and Cement Assembly

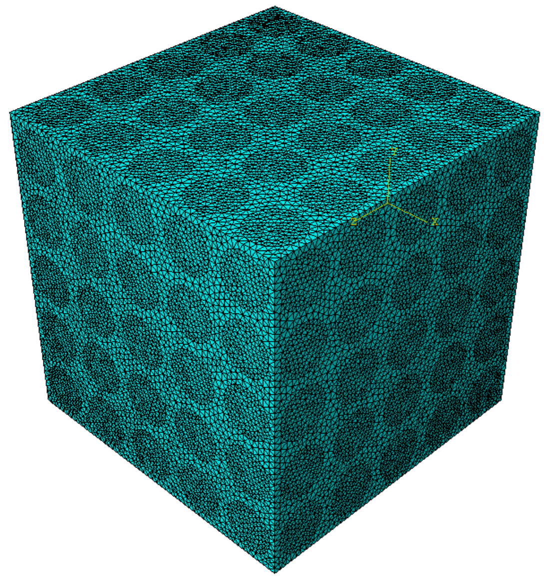

Figure 24: Assembly 1 with Tetrahedral Mesh Before Simulation

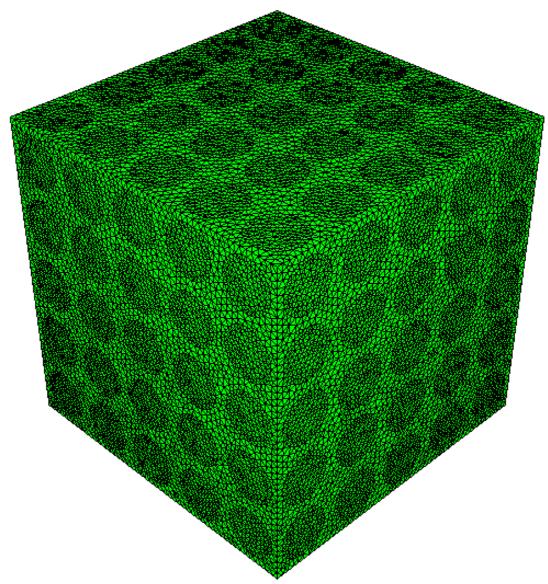

Figure 25: Assembly 1 with Tetrahedral Mesh After Simulation with Deformation

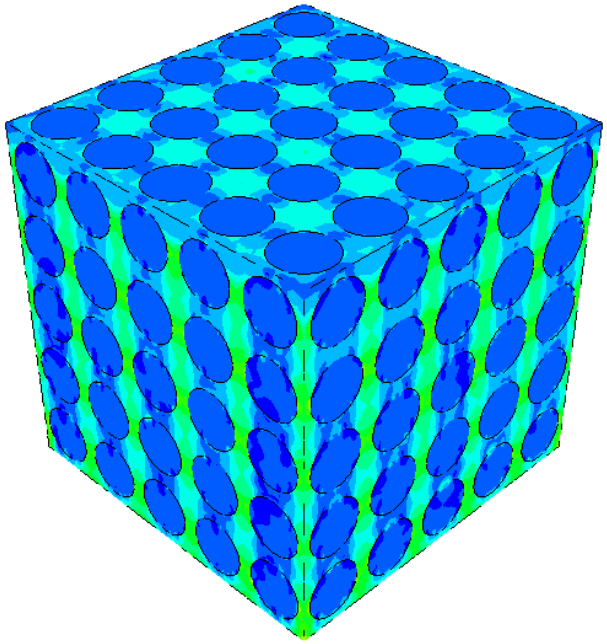

Figure 26: Concrete Structure 1 After Simulation with Shading

As seen in Figures 21 and 22, there is very little deformation in the structure. Overall, this structure holds up very well to the compressive force. When looking at Figure 23, there is a much clearer picture of where the stress is the highest on the structure. The greenish yellow streaks are where the stress is the highest and that resides in strictly the steel foam structure. This backs up the statements earlier stating the steel was under the most stress in this compression test.

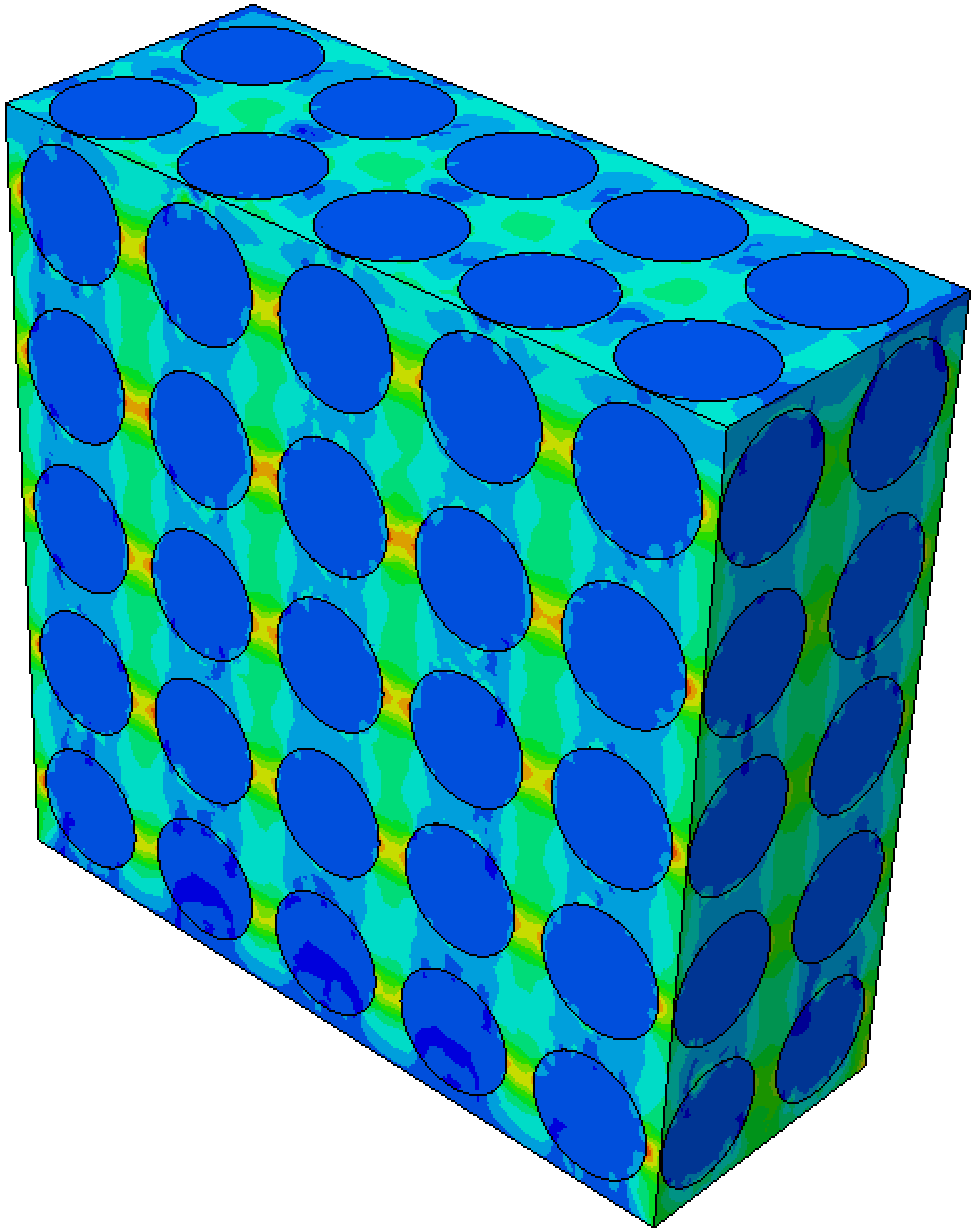

Figure 27: Assembly 1 with Shading and a Cut Along the Z-Axis

Figure 26 shows structure one with a cut along the z axis through the structure to show the areas with the highest stress. The red areas show the highest stresses throughout the whole assembly. It is interesting that these are the areas where the steel is under the highest stress in the areas that have the smallest width and the least support from surrounding concrete. Overtime the red areas would be where the structure would most likely start to fail.

4.2 Steel Foam Assembly 2

The second steel foam structure was unable to be completed in the time allowed for this MQP. As stated above the second structure was much more complex than the first structure. This created numerous problems once the structure was moved over into Abaqus. All of the set up for this simulation worked but once it came to running the program, Abaqus would continue to crash and fail the simulation over and over again. Many adjustments were made including making the original steel foam part much smaller in order to decrease the complexity of the part but ultimately a solution was not able to be found in the allowed time for this project

4.3 Comparison with Analytical Calculations

The stress from the calculations can be compared with a rebar concrete that is being used in construction applications. The stress in the traditional rebars can be calculated using the equation below:

$$P = f_c(A_c + nA_{st}), f_s = \left(\frac{E_s}{E_c}\right) f_c = nf_c$$

This means if we have area, the stress in the concrete is the force divided by the area and the stress in the steel is equal to concrete stress times the ratio of young's moduli. Using this equation, the numerical value of the stress is going to be equal to 15 MPa. However, the maximum stress happening in the concrete from the simulations is at maximum 13.4 MPa. This means that the stress in the concrete for the foam steel structure is less than that of normal rebar system. So, they are more favorable and the stress that is felt by the concrete is lower.

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