

Experimentation and Structural Analysis of OZ Saferooms

Critical Design Report



Team 04024

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Executive Summary

This report summarizes the progress made by the OZ Saferoom Senior Design Team. The goal of this project is to structurally analyze and determine the survivability of OZ Saferooms. This project will assist Zagorski Forms Specialists, Inc. by providing them with structural analysis and experimental data. Oz Saferooms are continuously poured, above ground, steel-reinforced concrete structures designed to withstand natural disasters. The existing OZ Saferooms have outside dimensions of 78 in. x 78 in. x 92 in., and are made of 5000 psi concrete. These structures are primarily built in tornado prone areas.

The team used the Engineering Design Guide (EDGE™) methodology to structurally analyze and design experimentation for OZ Saferooms. All five facets of this process have been completed. The first facet or chapter of the report, recognize and quantify the need and statement of work, discuss the goals and motivation for the project. The second chapter presents an overview of the three deliverables and subsequent concepts the team has developed. The third chapter presents the feasibility assessment the team conducted on all deliverables and concepts. The fourth section presents a detailed description of the goals and specifications of the project. The fifth and sixth sections present the analysis and synthesis of each concept designs. The final chapter of the report provides suggestions and opportunities for further analysis of OZ Saferooms.

Through this design process, many ideas evolved regarding different ways to analyze and sense damage to an OZ Saferoom structure. Three ideas include ASTM standard mechanical properties testing of concrete samples, finite element analysis, and experimental impact testing of an existing OZ Saferoom structure. Testing was conducted on concrete samples provided by the project sponsor, as well as experimental impact testing of an existing structure located in Macedon, NY. This was done to determine the mechanical properties of concrete and the dynamic response of the OZ Saferoom structure subjected to an impact test.

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1 Assessment

Safe rooms are emergency occupancy structures designed to provide occupants a high probability of protection from injury or loss of life resulting from the forces, debris impacts, and other effects that are generated by tornados. More than 1,200 tornados have been reported each year since 1995. Since 1950, tornados have caused an average of 89 deaths and 1,521 injuries annually (FEMA 361, 1-3). Oz Saferooms™ are monolithic concrete structures built with no joints or seams designed to withstand natural disasters. The OZ Saferoom shown in Figure 1 was located in Moore, Oklahoma and survived the passage of an F5 tornado on May 8, 2003.



Figure 1: OZ Saferoom after Tornado Impact

These structures are made of concrete with a minimum of 5,000 psi compressive strength, and have 8 in. thick walls, a 12 in. thick ceiling, a 12 in. foundation and a sliding entry door made of 12-gauge steel with three-quarter inch plywood on each side.

Zagorski Forms Specialists, Inc. manufactures OZ Saferooms. The company, headquartered in Rochester, NY has installed 53 safe rooms during the time period from 2000 to 2004. These structures have been built in New York, Oklahoma, and Texas.

The mission of this design project team is to structurally analyze OZ Saferooms. This will be done using finite element analysis as well as a theoretical analysis. The team will also conduct an impact test to measure the structure's deflection and frequency response. In addition, the team will research and develop a sensor package for analyzing an existing structure subjected to an impact test.

The sensor package will be designed for impact analysis of an OZ Saferoom. The sensors will be mounted on the inside of an existing OZ Saferoom located in Macedon, NY. The data acquisition system will be used to assess the structure's deflection during an impact test. ASTM 3-point bending and compression testing of concrete samples provided by Zagorski Forms will also be conducted to determine the mechanical properties of the concrete used in making OZ Saferooms. Finally, the finite element analysis will be conducted to assess stress, deflection and frequency response of an existing OZ Saferoom, as well as other structures specified by Zagorski Forms.

This project shall not validate the safety of OZ Saferooms. In addition, the team will not analyze or test the door of the structure. The testing of the door is limited by financial and resource feasibility. Primarily, the focus of this project is to quantify the maximum strength of the concrete substructure of the entire OZ Saferoom.

1.1 Scope Limitations

The project budget for this senior design project shall not exceed two thousand dollars for all materials and testing. The sensor package and all accompanying work shall be completed and deliverables submitted to the primary customer no later than May 21, 2004. These deliverables will include a sensor package which is capable of measuring the deflections associated with an experimental test of an OZ Saferoom. Furthermore, finite element analysis of multiple sized OZ Saferooms will be delivered to analyze their stability after being subjected to tornado-like conditions.

The senior design team shall not validate the safety of OZ Saferooms. In addition, the team will not analyze or test the door of the structure. The testing of the door is limited by financial and resource feasibility. Primarily, the focus of this project is to structurally analyze and determine the survivability of these structures.

1.2 Stakeholders

Stakeholders who have an interest in this senior design project include Zagorski Forms Specialists, Inc., families and owners of safe rooms, the Federal Emergency Management Agency (FEMA), Rochester Institute of Technology, local authorities, and rescue workers.

1.3 Key Business Goals of Zagorski Forms Specialists, Inc.

Through this project, Zagorski Forms Specialists hope to obtain a quantification of the strength and durability of their structure. This will aid them in becoming the premier builder of tornado shelters for residential and municipal applications. It will also allow

funding from the Oklahoma State Government in order make OZ Saferooms more affordable to everyone. These goals are further detailed below:

- Providing sensor, data acquisition, and instrumentation in support of refining OZ Saferooms
- Impact test on the structure to quantify its survivability
- Analysis will encourage FEMA to primarily support Zagorski Forms Specialists, Inc.
- Analysis will encourage consumers to buy product
- Revise FEMA guidelines to raise safe room standards
- Increase state funding for rebates upon purchase

1.4 Financial Analysis

The following parameters describe the dominant issues relating to the sensor package.

- Cost of sensor package
- Experimental testing cost
- Number of sensors for experimental testing
- Data acquisition hardware and software
- Implementation costs

1.5 Statement of Work

Senior Design team 04024 shall deliver the following by May 21, 2004:

- Structural analysis of steel-reinforced concrete structure

- Finite element analysis on existing 6'-6" x 6'-6" x 7'-8" structure, as well as 8'-6" x 8'-6" x 7'-8" and 10'-6" x 10'-6" x 7'-8" structures (Note: All outside dimensions)
- Finite element analysis on Zagorski Forms' preliminary design of a 20'x30' structure
- ASTM standards C 39 and C 78-02 for compression and three-point bending test data to determine the mechanical properties of the concrete used in making OZ Saferooms.
- Impact testing on an existing OZ Saferoom to provide data in determining the deflections associated with various impact loads.
- Design of a sensor package for analyzing future OZ Saferoom structures subjected to an impact test.
- Technical report documenting all structural analysis, test results, the instrumentation package, and recommendations for future work.

2 Concept Development

The objective of this project is to develop methods to quantify survivability of the OZ Saferoom structure, excluding the door. With this in mind, the first brainstorming session began with a list of all possible ideas to achieve the tasks appointed by our sponsor. All preliminary suggestions were accepted without discretion. The proposals were then voted on by all team members, yielding the top three choices to be developed. Each of the three concepts were then sketched on paper and expanded upon by every member to develop the specific details. All team members were given two minutes to input additional details. Sub-teams were then assigned the task of preparing assembly

sketches and reporting back to the group. The three sketches were revised and presented into a more formal set of drawings. These ideas consisted of mechanical properties testing of concrete, finite element analysis, and experimental impact testing of an OZ Saferoom.

These concepts were further developed using the “Empathy Method”. In this exercise, each member played the role of a component of the selected concept. By running through the required steps and communicating with the other ‘components,’ many details were expanded further. This ensured that all aspects were inspected and nothing was overlooked. The developed concepts are detailed in the following sections.

2.1 Concrete Sample Testing Concept

ASTM (American Society for Testing and Materials) is an organization that sets testing method standards for many engineering applications and materials. Concrete standards must be followed to ensure that concrete is correctly made, cured, and able to withstand applied stresses. ASTM standard C 39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, is the procedure that will be used for compression testing of concrete. This test method covers determination of compressive strength of cylindrical concrete specimens. This method consists of applying a compressive axial load to molded cylinders at a specific rate until failure occurs. The compressive strength of the specimen can then be calculated by dividing the maximum load attained by the cross-sectional area of the specimen. The compression testing concept is shown below in Figure 2.

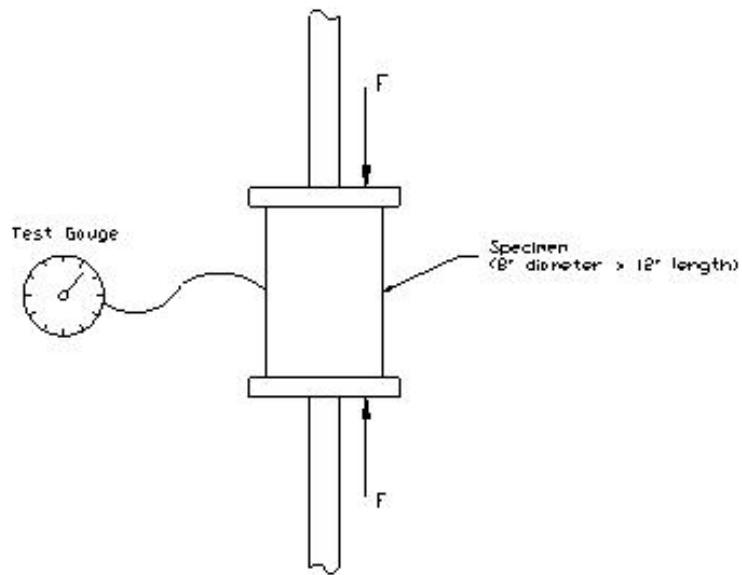


Figure 2: Compression Test Concept

The samples used for the compression testing will be provided by Zagorski Forms Specialist, Inc. According to the standard, the team will test nine, 6 in. diameter x 12 in. height, concrete cylinders (5000 psi) after 28 days of the curing process. After the data from the tests are collected, the compressive strength can be determined

ASTM standard C 78-02, *Standard Test Method for Flexural Strength of Concrete (using simple beam with third-point loading)*, is the procedure that will be used for the three-point bending test. This test method covers the determination of the flexural strength of concrete by the use of a simple beam with third-point loading. The fixture and apparatus is shown below in Figure 3.

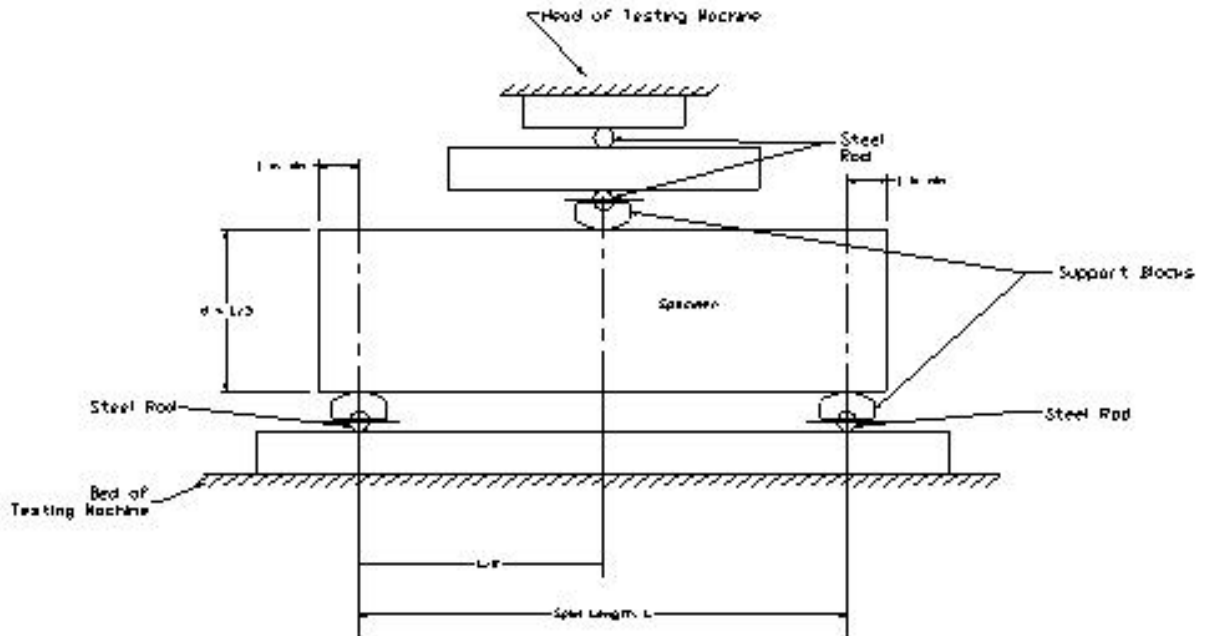


Figure 3: 3-Point Bending Setup

The samples used for this testing will also be provided by Zagorski Forms Specialist, Inc. According to the standard, the team will test nine, 14 in. x 4 in. x 4 in., concrete samples (5000 psi) after 28 days of the curing process. After the data from the tests are collected, the flexural strength or modulus of rupture can be determined.

2.2 Finite Element Analysis Concept

Finite element analysis (FEA) is a numerical approach to solving systems. Generally, it is performed on complex systems with no closed form solution. FEA is used to discretize a continuous system into many simpler elements. This yields a finite number of equations that are solved simultaneously to approximate the general solution. For this application, FEA is used to find areas of maximum/minimum stress and strain of the OZ Saferoom.

The finite element analysis will be conducted using I-DEAS. This is a computer program used for the structural analysis of proposed designs. The software assists in calculating stress, shear force, loads, deflections, and other parameters. The first step in FEA is to decompose the structure into many small meshes. Each mesh is then analyzed individually to gain a larger perspective of what is happening to the model. I-DEAS was selected because it is the program that team is familiar with.

The FEA conducted will be used to find stresses, deflections and the frequency response of the structure. In order to verify the model, various mesh sizes will be implemented. After the impact test is conducted, the results will be compared with the FEA. The FEA will also be used to quantify the limitations of OZ Saferooms.

The team will use I-DEAS to conduct finite element analysis for four different sized structures. These structures include:

- Existing 78 in. x 78 in. x 92 in. (outside dimensions) safe room
- 102 in. x 102 in. x 92 in. (outside dimensions) safe room
- 126 in. x 126 in. x 92 in. (outside dimensions) safe room
- 20 ft. x 30 ft. x 92 in. (outside dimensions) safe room

2.3 Experimental Impact Testing Concept

2.3.1 Laser Pointer Concept

To measure the deflection of the roof under static loading, a laser pointer will be mounted flat against the ceiling. The laser pointer will then be calibrated to project perpendicularly onto a wall. The wall will be marked so that as the test is being done, the change in the angle projected onto the wall by the laser pointer will be measured. The test will be done by applying a static load to the structure using a hydraulic ram. As the

ram deflects the wall, the change in angle of the laser pointer will be used to calculate the deflection of the structure. The experimental test data will be compared with the finite element I-DEAS model. If the finite element model correlates with the hydraulic ram test, the finite element model can then be tested to failure. This will help the team in determining the weakest points of the structure. The hydraulic ram test will ultimately help to determine where to place the accelerometers during an impact test.

2.3.2 Strain Gauge Concept

The purpose of this experiment is to apply forces to the OZ Saferoom in order to assess the stress of the structure during a tornado. This test will involve applying static loads to the roof of the structure. To calculate the stress induced on the structure, a strain gauge will be used. The structure will be loaded using a uniform weight, at a predetermined force, simulating tornado debris. Sufficient simulation and research will be conducted to ensure proper experimental loading. A uniform weight is appropriate to ensure control and repeatability. The strain gauge and data acquisition system will be purchased from Durham Geo. The experimental test data will be compared to the finite element I-DEAS model.

2.3.3 Accelerometer Concept

The purpose of this experiment is to apply forces simulating those imposed during an F5 tornado, and measure the response of the structure's roof. The test will involve raising a large uniform load to a specified height, and releasing it. From the data recorded during the impact test, the induced stress will be calculated and compared with the theoretical maximum stresses of the OZ Saferoom's roof. The data will also be used

to compare the frequency response and deflection of the structure's roof with the FEA. While obtaining the frequency response is not the primary objective, it will provide another basis of comparison with the FEA.

To measure the force on the structure during the test, an accelerometer will be placed on the ceiling of the safe room. This will yield the acceleration of the structure and the time duration of impact. Through dynamic principles, the resulting impact force can then be calculated.

In order to simulate actual tornado debris, research will be conducted to ensure the proper loading is chosen. The accelerometers will be purchased by funds allotted by Zagorski Forms Specialists, Inc. The corresponding data acquisition system and signal conditioning will be provided by RIT. The experimental test data will be compared with a simulated structure modeled with the I-DEAS software package.

3 Feasibility Assessment

All of the concepts presented in the previous chapter are the results of the team brainstorming sessions and initial investigation. Once each idea was clearly defined and well understood by all members of the team, a feasibility assessment was conducted on each concept. The feasibility assessment was governed by a list of questions which covered technical, economic, schedule, resource and performance issues that can be equally applied to each design concept.

3.1 Concrete Sample Testing Feasibility

The bending and compression experiments will be used to assess the strength of concrete samples provided by our sponsor. The constraints to be considered are time, cost, and resource availability.

According to ASTM Standard C39-01 for compression testing, the specimens must be tested after 28 days of the concrete curing process. In the interest of keeping the experiment consistent, this will be adhered to for both the bending and compression tests.

Time will be the biggest constraint posed for these series of tests. The RIT spring break scheduled for the first week of March 2004 needs to be considered when planning to begin the experiments. The team must consider that the 28-day tests do not conflict with the Spring break. Aside from this constraint, the only other time concern would be the numerous classes that are being conducted in the Mechanics lab at RIT.

The cost involved with these tests should be minimal. The specimens to be tested will be provided by the team's sponsor, and all equipment needed is already in place. The only necessity is the construction of a fixture for the 3-point bend test, which has been constructed from scrap found in the RIT machine shop.

Item	Qty	Description	Supplier	Price
1	1	Tinius Olsen machine	Mechanics Lab	-
2	1	Computer	Mechanics Lab	-
3	9	6" diameter x 12" height cylindrical concrete samples	Sponsor	-
4	9	4"x4"x14" concrete beam samples	Sponsor	-
5	1	3 steel rods for three-point bending fixture	Machine Shop	-
6	1	3-Point Bending Fixture	Machine Shop	-
			Total Price \$	-

Figure 4: Concrete Sample Testing BOM

3.2 FEA Feasibility

There are many technical aspects of the finite element analysis. The knowledge to create the model and perform the FEA is essential to this concept. Utilizing the I-DEAS software package enables the team to complete the FEA. The team is relatively familiar with this program and a large volume of information is available. The correct material properties will have to be determined to ensure success of the analysis. Once the FEA is complete, the values will be compared with tested and calculated data.

Next, the economic feasibility was assessed. The I-DEAS software package is readily available in the Mechanical Engineering computer lab. The labor cost for FEA is non-existent because it will all be done in house, and no additional resources are needed. The tutorials and instruction manuals also have no cost associated with them.

All necessary resources to complete the FEA are available. The material properties that must be entered during the meshing phase of the FEA are available in many textbooks and located on many engineering websites dealing with material properties. The resources used to guide the team members during the FEA are readily available. All resources used in the post-processing phase of the FEA are also accessible, including the appropriate text books for computing material properties and structural forces. These are based on sample tests and real world experiments.

The FEA must be done throughout the duration of the project. The initial FEA will precede any experimental testing in order to verify its feasibility and aid in preliminary design decisions. Future FEA will follow as additional testing is done to verify models and assist in sensor placement decisions. The timing of each FEA will accord with project scheduling. This will allow each FEA to comply with team

scheduling issues and provide the benefit of having each FEA ready to be used when necessary. In summation, the scheduling of this facet of the project should not be an issue.

3.3 Experimental Impact Testing Feasibility

Specific attributes were assessed for the three impact testing concepts presented in section 2.3. The technical attributes include the ability to implement and the availability of documentation and standards. The cost of all materials as well as the cost of assembly for each concept was assessed for the economic issues. In addition, sufficient skills and sufficient equipment to accomplish the goals of the project represented the resource attributes needed. The performance criteria include the dynamic loading capabilities, data acquisition needed and projectiles involved for testing each concept. Finally, schedule feasibility of meeting intermediate milestones was also assessed. The team created a weighted scale to be used to in answering each question, which can be seen in Figure 5 below.

	ATTRIBUTES	ROW TOTAL	COLUMN TOTAL	ROW + COLUMN	RELATIVE WEIGHT
R1	Sufficient Skills	6	3.5	9.5	0.173
R2	Sufficient Equipment to launch projectiles	3.5	3.5	7	0.127
E1	Total Cost	4.5	0	4.5	0.082
E2	Cost of Assembly	2	0	2	0.036
S1	Meeting Milestones	0	7.5	7.5	0.136
T1	Ability to Implement	6	3	9	0.164
T2	Documentation/Standards	1	2	3	0.055
P1	Dynamic Loading	4.5	0	4.5	0.082
P2	Projectiles	2	0.5	2.5	0.045
P3	Data Acquisition	2	3.5	5.5	0.100
			COLUMN TOTAL	55	1

Figure 5: Estimation of Relative Importance of Attributes

Each question was compared to the project baseline, which is the laser pointer concept. The questions were graded on a scale of one to five, with a score of three representing the same as the baseline, one being unfeasible, and five being the most feasible. The team used these factors to rank the three experimental testing concepts and decide which direction the team wanted to move. A table and radar chart comparing all the attributes of each concept can be seen below in Figures 6 and 7, respectively.

	ATTRIBUTES	RELATIVE WEIGHT	CONCEPT 1 (Accelerometer)	CONCEPT 2 (Strain Gauge)	BASELINE CONCEPT (Laser Pointer)
R1	Sufficient Skills	0.173	3	3	3
R2	Sufficient Equipment to launch projectiles	0.127	4	4	3
E1	Total Cost	0.082	2	1	3
E2	Cost of Assembly	0.036	2	2	3
S1	Meeting Milestones	0.136	4	3	3
T1	Ability to Implement	0.164	3	3	3
T2	Documentation/Standards	0.055	5	5	3
P1	Dynamic Loading	0.082	5	3	3
P2	Projectiles	0.045	5	5	3
P3	Data Acquisition	0.100	5	4	3
		RAW SCORE	3.71	3.23	3.00
		NORMALIZED SCORE	1.24	1.08	1.00

Figure 6: Impact Testing Concept Comparison

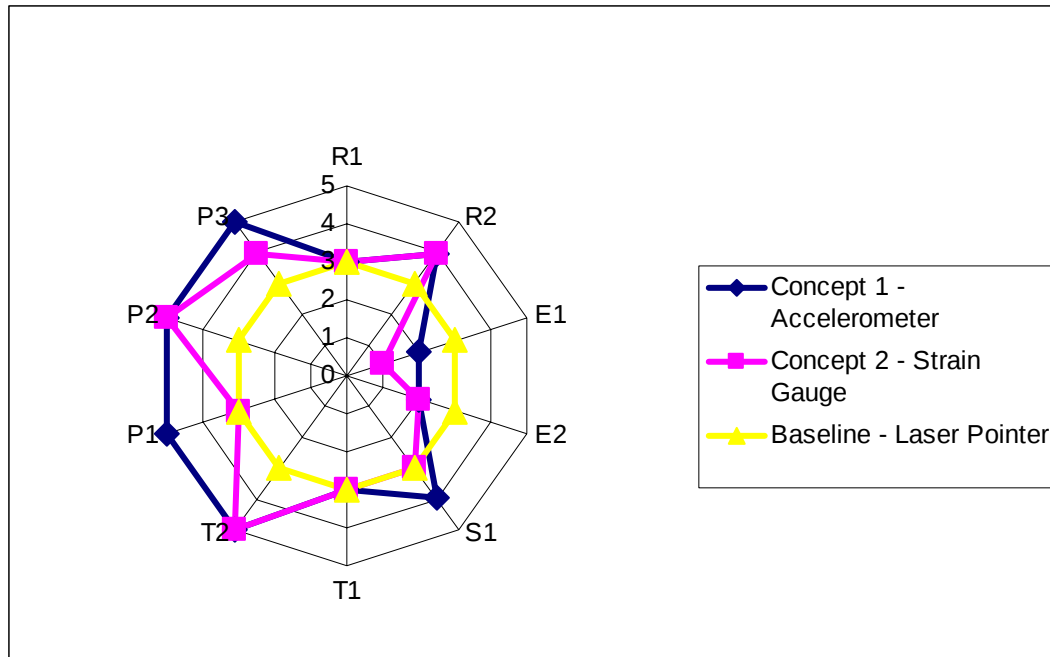


Figure 7: Impact Testing Radar Chart

3.3.1 Laser Pointer Feasibility

Under current conditions, this laser pointer test would be relatively easy to perform. The equipment needed to conduct this test exists and the technical aspects of this concept are not very advanced. The largest cost associated with a test of this nature would be the hydraulic ram. Rental of this equipment would not exceed budget requirements. All of the resources necessary to complete this experiment are available and the team possesses the appropriate skills to test the structure and calculate its deflections. There are enough team members to carry out the test safely and accurately, and the equipment needed to perform this experiment is readily available. The scheduling of this test would lie solely on the timing of the rental of the hydraulic ram.

The feasibility of executing this test is high, but it scores last on the team's weighted method concept development exercise. This can easily be explained by the fact

that this test does not calculate the dynamic loads that the structure would be experience in an actual tornado. Dynamic loading is a key element to the project because of the momentary contact point loads experienced by the structure during a tornado. The test could be used to calculate the strength properties of the structure, but would not be very useful for achieving the team's objectives.

3.3.2 Strain Gauge Feasibility

The impact testing utilizing strain gauges was compared to a baseline of measuring deflection via laser pointers and the corresponding changes in angle.

First, feasibility relating to the resource of the impact testing utilizing strain gauges was conducted. The senior design team has sufficient skills to conduct the impact testing. However, concerns were raised regarding how projectiles would be fired at the wall and door of the structure. Air cannons typically used in this type of testing is not feasible for the scope of this project. A uniform weight will be dropped on the roof of the structure pending sponsor confirmation of a crane and load. The resource assessment received a score above the baseline.

Next, the economic assessment was conducted. The team decided on purchasing three strain gauges to be placed in specified areas on the structure. However, the team's budget is capable of procuring only one strain gauge and one mini-logger system. A budget for any additional components would not be available. The economic assessment received a score below baseline.

P/N	Description	\$/per	Qty	Total	Supplier
52650306	Surface mount Strain gauge	\$120.00	3	\$360.00	Durham Slope
52650330	Mounting plates for concrete (2)	\$24.00	3	\$72.00	Durham Slope
52650380	Installation tool*	\$90.00	1	\$90.00	Durham Slope
50613324F	Signal Cable (/ft.)	\$0.55	30	\$16.50	Durham Slope
52613310	VW Minilogger	\$540.00	3	\$1,620.00	Durham Slope
			TOTAL	\$2,158.50	

Figure 8: Strain Gauge and Data Acquisition System BOM

The next assessment conducted related to technical feasibility. The senior design team has the ability to implement this testing and is more than capable of meeting documentation standards. However, concerns were raised that strain gauges are not suitable for the dynamic loading. The technical assessment received a score equal to baseline.

The final assessment conducted related to process feasibility. The team was confident that the data acquisition system would work for our application. The strain gauges and DAQ are portable and easy to use. Durham Slope experts also indicated they were confident the data acquisition system would suit this application. Strain gauges are better suited than the baseline concept. However, strain gauges are not suitable for projectile testing and dynamic loading.

3.3.3 Accelerometer Feasibility

An accelerometer will be used to measure the applied force. This was compared to the baseline concept of using a laser pointer to measure the deflection angle at the applied contact point. The original design for an experimental test consisted of an applied static load. Although dynamic forces can be simulated statically, material behavior is altered by sudden changes. Thus, after further research and consideration, a dynamic test was deemed more accurate and appropriate. Comparisons between the two

ideas were based on the top ten key attributes of the project, which were voted on by each group member. These characteristics are divided into four categories: resources, performance, economic and technical feasibility. Each aspect of the project is assessed as it relates to the appropriate subdivision.

The resources for this experiment are sufficient. The project team, which consists of six student engineers (four mechanical, one electrical, one industrial) is capable of implementing an appropriate sensor package. The equipment needed to conduct the experiment (crane, load, structure) will be provided by the project sponsor. Both mentioned attributes were equal in comparison with the baseline concept.

The performance feasibility of the accelerometer was rated much higher than the baseline idea. Unlike the baseline concept, the use of accelerometers will allow for a dynamic measurement which is appropriate for this experiment. Accelerometers are necessary to obtain accurate data for measuring applied force and displacement. The baseline concept, originally developed to measure only deflection angle, is unsuitable for a dynamic test. This dynamic test is necessary to ensure accurate loads similar to those of tornado debris. The last performance attribute is the data acquisition system. In the first concept, the deflection angle would be measured by the change in distance from the initial laser location on the wall, to the final location. However, by using a DAQ in conjunction with an accelerometer, the data is more accurate and reliable.

The economic feasibility of the accelerometers and corresponding DAQ rated lower than the baseline. Although this system is costly, it is still feasible. Cost of assembly also rated lower than the baseline. These expenses fit the project's budget and account for the majority of the allotted funds. Three accelerometers will be purchased.

One will be used for the actual impact test and the remaining two will only be used in case of accelerometer failure or damage.

P/N	Description	\$/per	Qty	Total	Supplier
353B03	Accelerometer	\$285.00	3	\$855.00	PCB
003EB100AC	Cable (100ft)	\$171.00	1	\$171.00	PCB
6052E	PC Interface Card	-	1	-	National Instruments
SCXI 1531	Signal Conditioner	-	1	-	National Instruments
-	SCXI Chassis	-	1	-	National Instruments
-	Labview Software	-	1	-	National Instruments
081B05	10-32 Mounting Stud	-	1	-	PCB
			TOTAL	\$1026.00	

Figure 9: Accelerometer and Data Acquisition System BOM

The last category to consider is the technical feasibility of this design concept. Although the ease of implementation ranked equal with that of the baseline concept, the test is more technically accurate and justifiable.

3.4 Feasibility Conclusion

Based on the analysis presented above, the team was able to examine each concept and decide whether the idea should be further developed. The team decided to continue to develop the experimental test using the accelerometer concept because it is most appropriate for dynamic testing. The FEA and concrete sample testing will also be implemented to analyze the structure.

4 Performance Objectives and Specifications

In order for the team to measure the performance of each concept, certain objectives and specifications had to be determined. These objectives and specifications can be seen below.

4.1 Design Objectives

There are a number of design objectives that need to be specified in order for the team to have a list of goals and aims to achieve. These objectives are listed below.

- 1) The impact test shall be designed to simulate tornado forces applied to the OZ Saferoom. This is important for proper evaluation of the OZ Saferoom.
- 2) The team must research the most severe tornado conditions.
- 3) Ensure the accelerometers and data acquisition system used are appropriate for the dynamic load applied through preliminary testing.
- 4) Recommendations for installation of sensor package into safe room design
- 5) Use CAD blueprints provided by Zagorski Forms to correctly model the existing structure in I-DEAS.
- 6) Finite element analysis shall assess the stresses and displacements induced by the simulated tornado load. Preliminary analysis of the larger structure specified by our sponsor is also included in this objective.
- 7) Four different size structures will be modeled and analyzed using I-DEAS.
- 8) Impact test data will be compared to the FEA results.
- 9) The stress imposed on the structure's roof will be compared with theoretical calculations.
- 10) Sample testing will be used to determine the modulus of elasticity. This will be used in the final finite element analysis models.
- 11) The results from all tests will provide data that will be reviewed by our sponsor.

4.2 Performance Specifications

A number of performance specifications must be met in order to fulfill the project objectives and successfully complete the project. These minimal requirements are listed below.

- 1) Results of the impact test shall allow for determination of deflection and induced stress on the structure.
- 2) The results obtained from finite element analysis and impact testing should be within 10% of one another.
- 3) The mechanical properties obtained from the compression and 3-point bending tests shall be compared with known concrete properties.
- 4) The data from the impact test and finite element analysis should be comparable with the analytical solution.

5 Analysis of Problem and Synthesis of Design

After all final concepts of the design were chosen, several aspects of each concept were analyzed. The team partitioned the analysis into three main sections: the design of concrete sample testing, finite element analysis, and experimental impact testing. The first section of this chapter analyzes the design and test methods for determining the mechanical properties of the concrete used in OZ Saferooms. This will be done by testing concrete samples provided by Zagorski Forms Specialists, Inc. The next section of this chapter focuses on the finite element analysis and structural integrity of various OZ Saferoom structures. This final section focuses on the design of the experimental impact testing concept, which includes the methodology of applying the correct loads to

the structure, as well as the sensing and data acquisition system needed to analyze the structure's response.

5.1 Concrete Sample Testing

For a valid finite element analysis to be conducted, the mechanical properties of the concrete used, need to be determined. Two factors that directly influence the performance of concrete are the bending and compressive strength. ASTM standards C 78-02 and C-39 were used for conducting three-point bending and compression testing respectively. From the sample testing experimentation, the Modulus of Elasticity and mass density of the concrete can be determined.

5.1.1 Three-Point Bending

ASTM standard C 78-02, *Standard Test Method for Flexural Strength of Concrete (using simple beam with third-point loading)*, was the procedure used for the three-point bending test. This test method covers the determination of the flexural strength of concrete by the use of a simple beam with third-point loading. The three-point bending concept and fixture is shown below in Fig. 10.

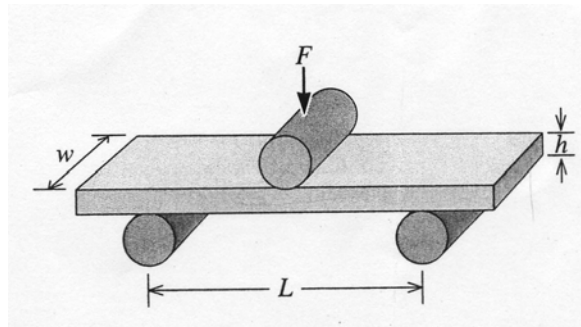


Figure 10: 3-point bending setup

Zagorski Forms supplied nine rectangular samples with 14 in. length, 4 in. width, and 4 in. height. All testing was conducted using a Tinius Olsen machine located in the Mechanics Lab at Rochester Institute of Technology.

The flexural strength, or modulus of rupture, describes the material's strength in tension. The averages of all the sample weights, maximum loads, and flexural strengths can be seen in Figure 11.

$$\sigma_{\text{bend}} = \frac{3FL}{2wh^2}$$

	W (lb)	Load _{max} (lb)	σ _{bend} (psi)
AVG =	19.075	2528	711
STDDEV =	0.121	501	141

Figure 11: 3-point bending results

5.1.2 Compression Testing

ASTM standard C 39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, was the procedure used for compression testing of concrete. This test method covers determination of compressive strength of cylindrical concrete specimens. This method consists of applying a compressive axial load to molded cylinders at a specific rate until failure occurs. The compressive strength of the specimen can then be calculated by dividing the maximum load attained by the cross-sectional area of the specimen.

$$f'_c = \frac{4F}{\pi d^2}$$

Zagorski Forms supplied nine cylindrical concrete samples with 6 in. diameter, and 12 in. height. The first four samples were tested using the Tinius Olsen machine

located at RIT. However, meaningful data could not be extracted due to the maximum load constraints on the machine. The remaining five samples were tested at CME Associates, Inc. (located in Rochester, NY) and the results can be seen below. These test results in Figure 12 show a maximum compressive strength of 8,034 psi which exceeds the 5,000 psi maximum compressive strength specified by OZ Saferooms.

	W (lb)	Load_{max} (lb)	f'_c (psi)
AVG =	27.65	227157	8034
STDDEV =	0.137	8868	314

Figure 12: Compression testing results

5.1.3 Data Analysis

From the geometry and weight of the cylindrical concrete samples, the mass density, ρ , was calculated to be 141 lb/ft³. According to MacGregor, for concrete with a density of 145 lb/ft³, ACI (American Concrete Institute) Sec. 8.5.1 gives the modulus of elasticity as

$$E_c = 57,000\sqrt{f'_c}$$

where f'_c is the compressive strength in psi (MacGregor, 47-55). From the average compressive strength of 8,034 psi shown in Figure 12, the modulus of elasticity of the concrete is 5.11×10^6 psi.

MacGregor also states that Poisson's ratio, ν , for concrete usually falls in the range 0.15 to 0.20. According to tests of biaxially loaded concrete, Kupfer et al.³⁻¹⁸ report values of Poisson's ratio of 0.18 to 0.20 for concrete loaded in tension and compression. Poisson's ratio of 0.18 was chosen and remains approximately constant under sustained loads.

5.2 Preliminary Finite Element Analysis

The team will use finite element analysis to test the structural integrity of four various sized OZ Saferooms. The computer program I-DEAS and analytical calculations will be used to perform the finite element analysis. The following information is known:

- The existing safe room's (OZ-01) outside dimensions are: 78 in. x 78 in. x 92 in.
- Saferoom (OZ-02) outside dimensions are: 102 in. x 102 in. x 92 in.
- Saferoom (OZ-03) outside dimensions are: 126 in. x 126 in. x 92 in.
- Saferoom (OZ-04) outside dimensions are: 20 ft. x 30 ft. x 92 in.
- Thickness of all walls are 8 inches
- Thickness of all roofs are 12 inches
- Thickness of all floors are 12 inches
- The safe rooms are constructed with 5000 psi concrete

Modulus of Elasticity E (psi)	Poisson's Ratio	Shear Modulus G (psi)
3.19E+06	0.12	1.42E+06

NOTE: Values given above were found on the website www.efunda.com
Values were based on the fact that the safe rooms use 5000 psi concrete

The team is searching for the area on the OZ Saferoom structure where the Von Mises stresses and deflections are a maximum. The team would also like to find out what size loads and wind pressures the safe rooms can withstand. From the finite element analysis, the team will locate the areas of the safe room that are the weakest. Two variables that can be assigned throughout the problem will be the size and location of the loads the team will place on the structure. The goal is to start with an analytically calculated load that will be distributed across the roof of each structure. The team will then place calculated wind pressure forces against the exterior walls.

One assumption made for finite element analysis is that the safe rooms have been erected by a monolithic concrete pour, which allow for no cracks or joints throughout the

structure. The safe rooms are assumed isotropic to simplify the analysis for the problem at hand. Since the rebar is not pre-tensioned, this assumption is valid. The team also assumed that the CAD drawings supplied by the sponsor are correct.

Preliminary assumptions made regarding the results are that the maximum deflection will occur at the location of the load. The walls and floor will have little to no deflection or stress and the roof will be weaker than the walls and floor.

The first step in generating an FEA in I-DEAS is to create a model in the *Master Modeler*. After the model is complete, the *Simulation* program can be activated. In the *Simulation* program, the boundary conditions are applied. Upon assigning boundary conditions, the mesh is generated. To verify the mesh our team will conduct a series of finite element analyses using different size meshes for each trial. The series of analyses will help the team conclude which mesh size is optimal for our application. After completing this step, the *Model Solution* sub-routine can be initiated. Once the model has run through the simulation, the *Post Processing* sub-routine is employed to create visual models of the structure showing the results of the simulation.

Figures 13, 14, 15, and 16 show the output values for each analyzed structure. In examining the h-convergence, the percent differences of stress and displacement between mesh sizes were calculated. The smallest mesh size was chosen in each case. This allowed for the most accurate calculations while still allowing the finite element analysis to run properly.

Mesh size (in ²)	Displacement (in)	Stress (psi)	% Difference displacement	% Difference Stress
4	2.02E-04	8.43	0.00	0.00
5	1.99E-04	8.35	1.49	0.95
7	1.95E-04	6.37	3.47	24.44
10	1.91E-04	6.26	5.45	25.74

Figure 13: 78 in. x 78 in. x 92 in. Structure Mesh Values

Mesh size (in ²)	Displacement (in)	Stress (psi)	% Difference displacement	% Difference Stress
5	1.49E-04	6.89	0.00	0.00
7	1.47E-04	5.28	1.34	23.37
10	1.44E-04	5.15	3.36	25.25
15	1.40E-04	4.30	6.04	37.59

Figure 14: 102 in. x 102 in. x 92 in. Structure Mesh Values

Mesh size (in ²)	Displacement (in)	Stress (psi)	% Difference displacement	% Difference Stress
5	2.08E-04	5.67	0.00	0.00
7	2.05E-04	4.92	1.44	13.23
10	2.01E-04	4.50	3.37	20.63
15	1.97E-04	4.10	5.29	27.69

Figure 15: 126 in. x 126 in. x 92 in. Structure Mesh Values

Mesh size (in ²)	Displacement (in)	Stress (psi)	% Difference displacement	% Difference Stress
10	2.08E-04	4.48	0.00	0.00
12	2.06E-04	4.34	0.96	3.13
15	2.04E-04	4.39	1.92	2.01
20	1.99E-04	3.76	4.33	16.07

Figure 16: 20 ft. x 30 ft. x 92 in. Structure Mesh Values

5.2.1 Analysis of Reinforced Concrete Slab

In order to properly model each safe room, rebar needed to be included within the concrete. To create the model of the reinforced concrete roof, a solid block was extruded, and the rows of rebar were partitioned within the roof. The model can be seen below in Figure 17. The next step was to mesh the rebar and roof as separate entities and materials. Boundary conditions were then applied to the roof. Constraints were placed on the bottom edges of the roof, and a distributed pressure load was applied to the top. Numerous simulations were run to analyze the reinforced concrete roof. However, the simulation started but never yielded results because the mesh applied to the rebar created such a complex model that the machine was unable to run the simulation. Several mesh density sizes from 0.25 to 30 were applied, but none yielded results. An antisymmetric shell mesh was also applied to the reinforced concrete roof, but the machine continued to struggle with the complexity of the model. There were so many elements and nodes generated that the computer could not manage the number of equations. To correctly model the safe rooms with rebar, the team would need more powerful computers. Therefore, for failure analysis, the team modeled the safe rooms without reinforcement.

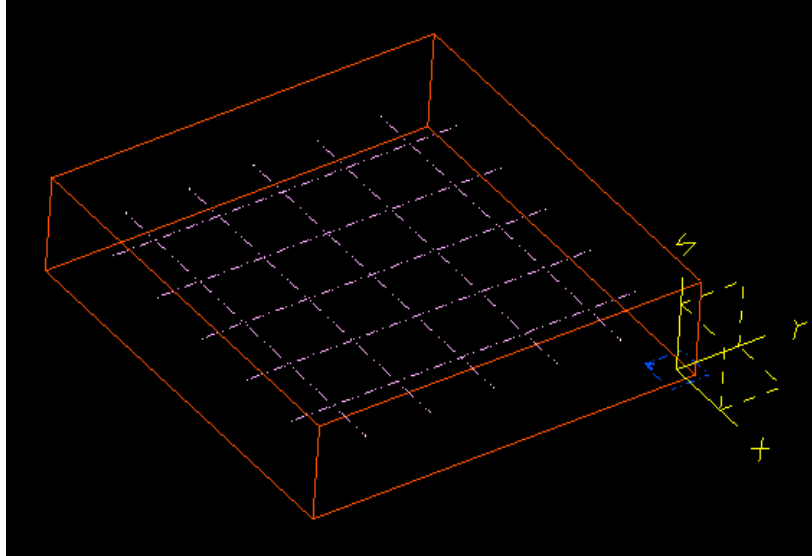


Figure 17: Reinforced concrete roof

5.2.2 Structural Integrity of OZ Saferooms

Finite element analysis was conducted on four OZ Saferoom structures to determine the maximum load each structure could withstand before failure. These forces were applied to the roof and wall of the structure and the Von Mises stress and maximum deflection were found. After ASTM concrete sample testing for 3-point bending and compression were completed, the material properties of the concrete used in the construction of OZ Saferooms were found and applied to the finite element model. The properties that were most vital for the analysis were the Modulus of Elasticity and the material density. The Modulus of Elasticity was determined experimentally and the material density was calculated from the geometry of the samples.

In order to determine the survivability (maximum load before cracking) of each structure, the finite element models were loaded until failure. By comparing the stresses observed to the yield strength of the structure, one can determine the load which causes the structure to fail. Concrete is strong in compression and weak in tension. As a result,

cracks develop whenever loads induce tensile stresses in excess of the tensile strength.

ACI Sec. 11.4.2.1 defines the modulus of rupture for use in strength calculations as

$$f_r = 6\sqrt{f'_c}$$

The resulting modulus of rupture or tensile strength was 538 psi (MacGregor, 47-55).

Therefore, in order to take the structures to failure, the pressure applied to the roof and wall of each structure had to yield a maximum Von Mises stress that was larger than 538 psi. From experimental analysis, the modulus of rupture was determined to be $711 \text{ psi} \pm 141 \text{ psi}$. The value of 538 psi calculated in the equation above will be used in the FEA, as it corresponds to the worst case scenario found in the experimental analysis.

Figure 18 and 19 display contour plots of the Von Mises stresses associated with the given loads applied for the 78 in. cubic structure without rebar. A 38 psi (231,192 lbs.) distributed load yielded a maximum stress value of 539 psi, which was greater than the tensile strength of 538 psi. In addition, a 5.5 psi (39,468 lbs.) distributed load applied to the wall yielded a maximum stress of 574 psi, which was also greater than the tensile strength. The failure loads and stress outputs of all simulations can be seen below in Figure 20.

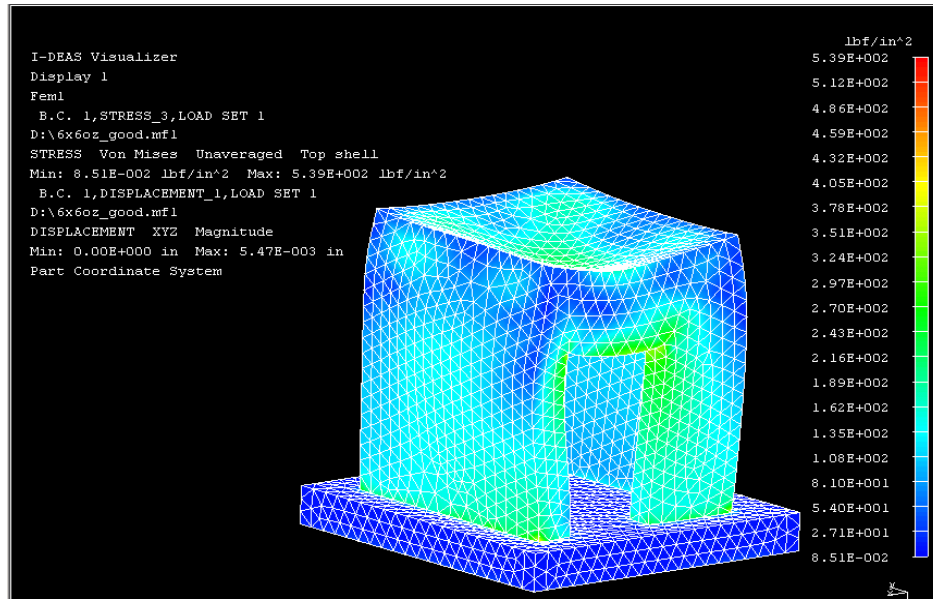


Figure 18: 38 psi distributed pressure applied to the roof

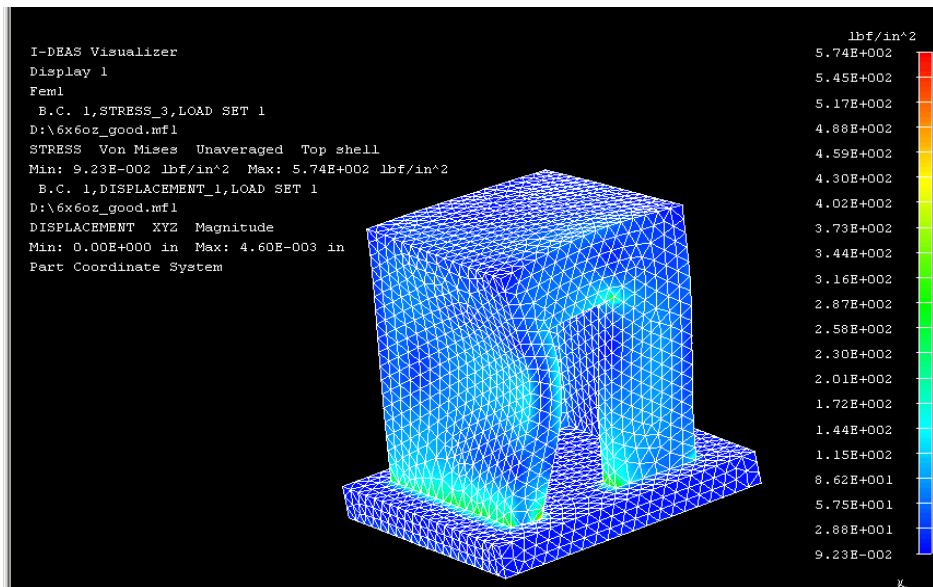


Figure 19: 5.5 psi distributed pressure applied to the wall

Structure	Applied Pressure - Roof (psi)	Equivalent Applied Load - Roof (lbs.)	Von Mises Stress (psi)	Applied Pressure - Wall (psi)	Equivalent Applied Load - Wall (lbs.)	Von Mises Stress (psi)
78 in. x 78 in. x 92 in.	38	231192	539	5.5	39468	574
102 in. x 102 in. x 92 in.	21.5	223686	545	6	56304	610
126 in. x 126 in. x 92 in.	15.5	246078	544	7	81144	542
240 in. x 360 in. x 92 in.	2.8	241920	540	19	629280	538

Figure 20: FEA failure analysis

The maximum Von Mises stresses for the 78 in., 102 in., and 126 in. cubic structures were located on the inside edges of the door and ceiling nearest to the applied load. For the 240 in. x 360 in. structure, the max stress was located on the inside edge of the center support member nearest to the applied load. All simulations and failure analysis in I-DEAS can be seen in Appendix B.

5.2.3 Wind Load Analysis

Wind loads depend on many factors such as wind speed, topography, building geometry, and type of exposure and enclosure. According to the guidelines given by FEMA 361, storm shelters should be designed for 250 mph wind speeds and corresponding debris impacts. The effects of topography on tornado wind fields are not known. Therefore, the Topographic Factor $K_{zt} = 1$ is used, which assumes flat, open terrain. In addition, an Exposure C is assumed as though the surrounding space is open. A tornado inflicts wind gusts from more than one direction, so FEMA 361 specifies the Wind Directional Factor $K_d = 1$. The Importance Factor I , which is assumed equal to 1,

reflects the probability that the structure will experience winds exceeding the design wind speed during the structure's expected life. Furthermore, the Wind Directional Factor ($K_d = 1$) considers the fact that it is unlikely that the maximum wind from any direction will impact the structure in the direction of its greatest vulnerability. A Wind Gust Factor of 0.85 and an External Pressure Coefficient of 0.8 are also assumed for this analysis.

Finally, the Internal Pressure Coefficient $GC_{pi} = \pm 0.18$ may be used for small shelters with internal volumes less than 500 ft^3 , which is the case for the 78 in. x 78 in. x 92 in. and 102 in. x 102 in. x 92 in. (outside dimensions) structures. For intermediate size structures with volumes between 500 and $1,000 \text{ ft}^3$, as in the case for the 126 in. x 126 in. x 92 in. (outside dimension) structure, GC_{pi} may be scaled linearly, i.e.:

$$GC_{pi} = \pm [(0.74)(10^{-3})\text{Volume} - 0.19]$$

	Structures			
	78 in. x 78 in. x 92 in.	102 in. x 102 in. x 92 in.	126 in. x 126 in. x 92 in.	20 ft. x 30 ft. x 92 in.
$GC_{pi} (\pm) =$	0.18	0.18	0.29	0.55

Figure 21: Internal Pressure Coefficients

An analysis is shown below to determine the highest pressure a wind load can inflict on an OZ Saferoom. All equations, coefficients and values were found using FEMA 361 guidelines, which are directly obtained from ASCE 7-98 (American Society of Civil Engineers).

Coefficient Values

$$I = 1$$

$$V = 250 \text{ mph}$$

$$K_z = 0.85$$

$$K_{zt} = 1$$

$$K_d = 1$$

$$G = 0.85$$

$$C_p = 0.8$$

$$GC_{pi} = +/- 0.18$$

I = importance factor
V = wind speed in mph (F-5 tornado)
K_z = velocity pressure exposure
K_{zt} = topographic factor
K_d = directional factor
G = gust effect factor
C_p = external pressure coefficient
GC_{pi} = internal pressure coefficient

Analysis

$$q = (0.00256)(K_z)(K_{zt})(K_d)(V^2)(I)$$

$$q = (0.00256)(0.85)(1)(1)(250 \text{ mph})^2(1)$$

$$q = 136 \text{ psf}$$

$$p = (q)(G)(C_p) - (q_i)(GC_{pi})$$

$$p = (136 \text{ psf})(0.85)(0.8) - (136 \text{ psf})(+/- 0.18)$$

$$p = 68 \text{ psf}, 117 \text{ psf}$$

p (Design Pressure) = equivalent static pressure in psf acting perpendicular to the surface in question

q (Velocity Pressure) = pressure exerted by the wind on a flat plate suspended in the wind stream

Calculating loads using the internal pressure coefficient shows a maximum pressure of 117 psf and a minimum pressure of 68 psf. Due to the fact that a vacuum will be created inside the structure due to the vents, the maximum pressure of 117 psf will be used in finite element analysis. Figure 22 below shows the wind pressures inflicted on each structure. The finite element simulations of all the determined wind pressures for each structure can be seen in Appendix B.

	Structures			
	78 in. x 78 in. x 92 in.	102 in. x 102 in. x 92 in.	126 in. x 126 in. x 92 in.	20 ft. x 30 ft. x 92 in.
q (psf) =	136	136	136	136
p_{Low} (psf) =	68	68	54	18
p_{high} (psf) =	117	117	131	167

Figure 22: Wind Load Determination

Simulated wind loads of 250 mph (F5 tornado) were also applied to the walls of each structure, and the resulting stresses are found in Figure 23. As shown below, the induced stresses from a tornado wind load are much less than an impact load.

Structure	Wind Pressure (psi)	Von Mises Stress (psi)
78 in. x 78 in.	0.8125	54.9
102 in. x 102 in.	0.8125	33.3
126 in. x 126 in.	0.9097	34.5
240 in. x 360 in.	1.1597	32.1

Figure 23: 250 mph wind pressure analysis

5.3 *Experimental Impact Testing*

The impact testing is divided into two areas of focus: properly loading the structure and obtaining reliable data from the acquisition system. A detailed explanation of the team's approach and final decision is discussed in the following section.

5.3.1 Determination of Load

To properly simulate tornado debris, many parameters are involved. A projectile's mass, volume, effective stiffness, velocity and angle of impact are crucial factors to accurately determine an applied load. For this project, the focus will lie in the projectile's mass, stiffness and velocity.

The team's initial testing concept was to load the roof of the structure statically and correlate this with a dynamic force. This would provide measurable deflections and allow calculations of the stress induced on the structure. After researching the concept, this idea was abandoned since the structure will respond differently under dynamic loading.

The final design included loading the roof with a uniform wooden pallet stacked with sandbags, from a specified height. Such a weight was chosen so that it would absorb some energy transferred during impact, and prevent the structure from cracking. The weight was hoisted by a crane and released onto the structure. The response was measured with an accelerometer mounted in the center of the structure's ceiling. Collected data allowed for calculations of the deflections and frequency response of the structure.

5.3.2 Data Acquisition

The initial design concept involved a data acquisition system, utilizing data loggers, to read data from strain gauges mounted to the roof. A laptop would be used to extract the data from the data logger. Upon further review, this design was proved unfeasible. The necessary strain gauges and data loggers exceed the team's budget. Also, strain gauges are not suitable for dynamic loading.

The final design utilized a PCB Piezotronics shock accelerometer, model 353B03. Due to budget limitations, the mechanical engineering department at the Rochester Institute of Technology allowed the team to use its data acquisition system and Labview software.

The response of the structure was measured with an accelerometer mounted in the structure's ceiling using a fixture designed by the team. The mounting device for the accelerometer consisted of a 0.5 in. diameter steel rod of 3 in. length with a 10-32 female thread (for the accelerometer stud). In order to install this device, a hole needed to be drilled in the structure's roof. The accelerometer screwed onto a mounting stud, which was screw into a metal rod. The rod was embedded into the structures ceiling using a special epoxy to keep the fixture in place.



Figure 24: Mounted accelerometer

Labview software was used for data acquisition and data analysis. The data acquisition system provided two arrays: time and acceleration. From the data recorded, the frequency response of the structure and the deflection of the roof's center were determined.

Because the DAQ system was provided by the Rochester Institute of Technology, equipment safety was a major concern. As a result, a one-hundred foot cable was used to connect the accelerometer to the DAQ to ensure there was enough distance between the DAQ equipment and the testing area. The cable from the accelerometer exited the structure through air vents in the wall.

5.3.3 Impact Testing Analysis

An analysis was performed on the existing 78 in. cubic structure based on the theory developed in MacGregor [1]. This theory addresses the Yield Line Criterion used for the elasto-plastic behavior of a reinforced concrete slab. The internal work of the slab was calculated from its moment capacity. The external work was found through the

deflection and the applied pressure. The internal work and external work were then equated to find the maximum applied load using the following equation.

$$\frac{wL^2\delta}{3} = 8m\delta$$

where L is the length of the slab, w is the uniform distributed load, d is the deflection, and m is the maximum moment per unit width. Using this method, the maximum theoretical distributed load was calculated at 14.5 psi (88,218 lb).

In an impact test of a reinforced concrete slab, the concrete will fail in tension before compression. When a uniform distributed load of 14.5 psi was applied to the finite element model with no rebar, the resulting stress was 615 psi. This is about 15% higher than the theoretical result of 538 psi. The finite element model was not reinforced because of the limitations in available computing power. Comparing a slab with and without rebar, a difference of 15% in ultimate strength can be accepted.

To simulate tornado debris, a 485 lb weight was dropped on the structure's roof from a height of 20 ft. The acceleration signal, shown in Figure 25, was analyzed through which a deflection of 0.00197 in. was calculated. This value is below the deflection required to cause the structure to fail. According to the FEA, the required deflection to crack the structure without rebar, using a static load, is 0.00547 in. With rebar, the tensile strength of the structure is increased, yielding an even higher required impact load. Discrepancy between the calculated load and the impact test results lies in the static vs. dynamic loading. Also, the internal energy cannot be directly equated with the external energy since the concrete dissipates a percentage of it. This percentage is difficult to measure, and is partly the reason for variations between the FEA and theoretical results. In the FEA, a static load was applied which results in a lower

deflection than that of an “equivalent” dynamic load. The deflection data from the impact test is shown in Figure 26.

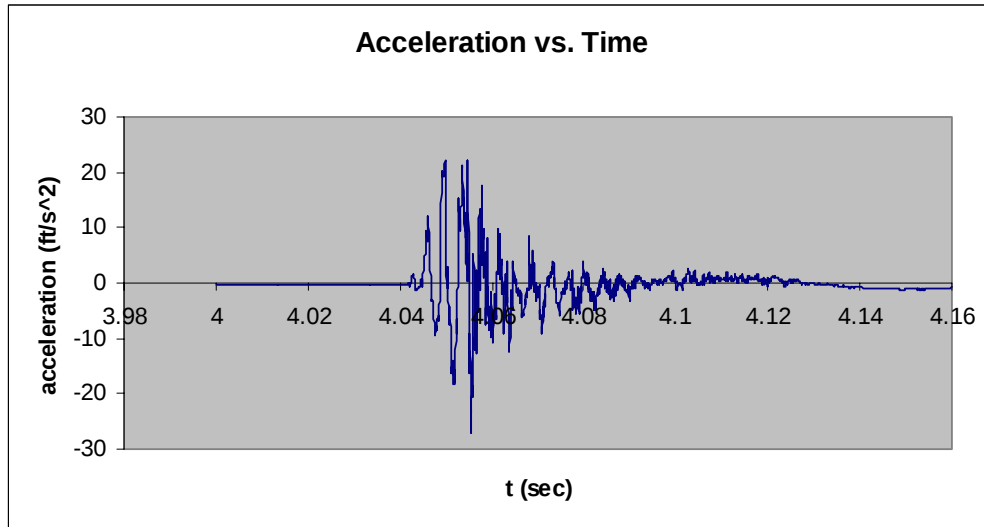


Figure 25: Acceleration signal from impact test

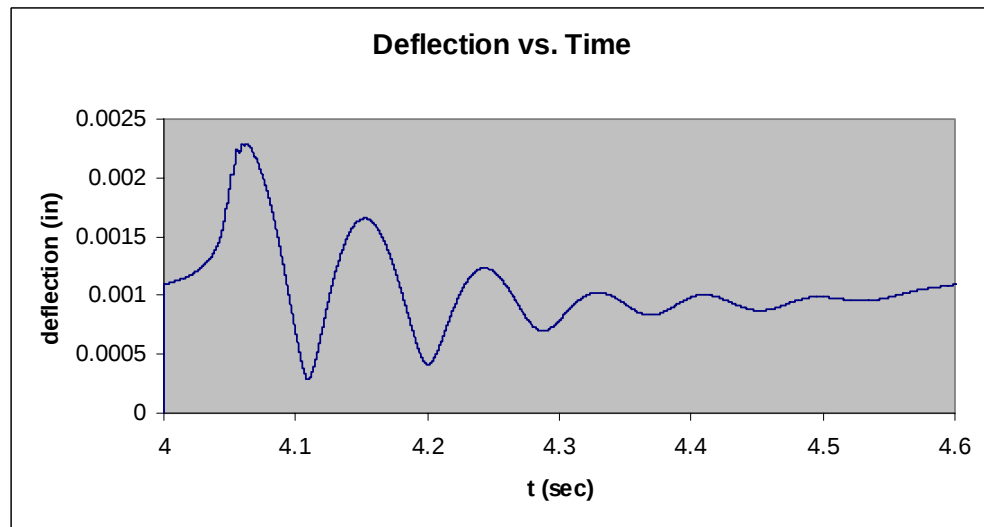


Figure 26: Roof's deflection

The 485 lb weight falling from a height of 20 ft has an associated potential energy of 70 KJ. This weight, a pallet full of sand bags, distributed across a 3' x 3' area, has a much higher density (and stiffness) than that of a vehicle or other typical tornado debris. From the deflection data, the duration of impact was about 0.1 second. Using the

impulse-force equation, where, p is the loads momentum, F is the resulting force and t is time,

$$F = \frac{\Delta p}{\Delta t}$$

resulted in an impact force of 5,600 lb distributed over nine square feet, resulting in a pressure of 4 psi on the structure. This is about 1/10 of the pressure applied in the FEA which caused the structure to fail. In comparing a vehicle falling on the structure to the test load, the mass would be about ten times as great, distributed over an area about twice as large. For a worst case scenario, the time duration will be assumed the same. Using these parameters to achieve the required maximum stress found in the FEA, it would require the energy of about 4 cars (4000 KJ) falling on the structure at the same time. Again, this would be higher if the FEA were built with rebar. While the purpose of this paper is not to endorse OZ Saferooms, it is worth mentioning that such debris is not common in the most severe tornados.

5.3.3.1 Frequency Analysis

In order to form another basis of comparison between the FEA model and the actual test results, the frequency responses are compared. From the test data, the first resonant frequency was found to be around 15 Hz and the second at 260 Hz. The first natural frequency of the finite element model was 312 Hz. Since this involved free vibration with no applied load, it did not account for the compliance of the impact load frequency of 15 Hz. Therefore, the second resonant frequency of the test data can be compared with the first natural frequency of the finite element model. The difference between the 260 and 312 Hz is likely due to the model lacking rebar. The frequency

content of the impact test and the finite element model can be seen in Figure 27 and 28, respectively.

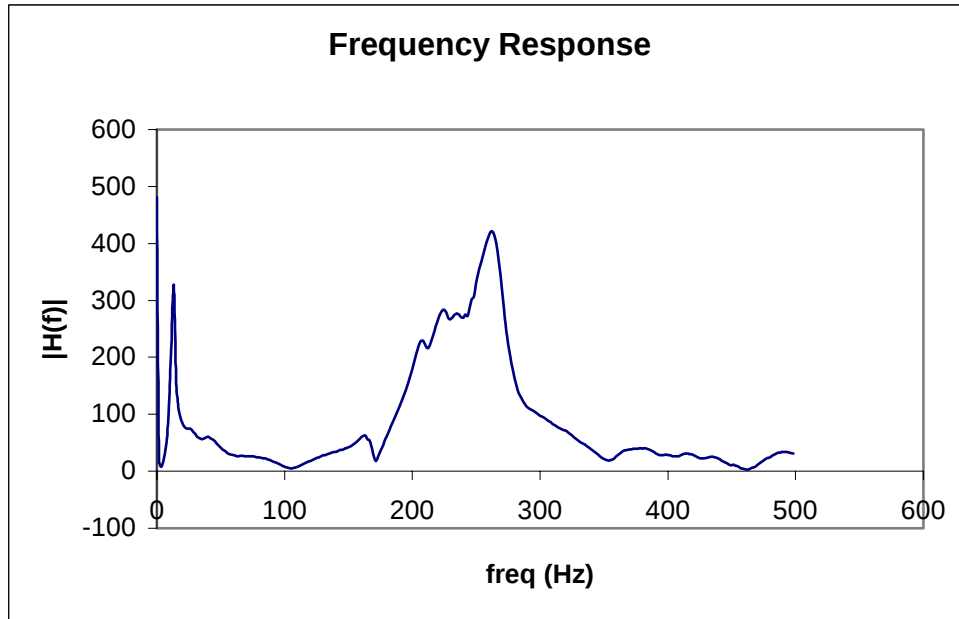


Figure 27: Frequency content of impact test

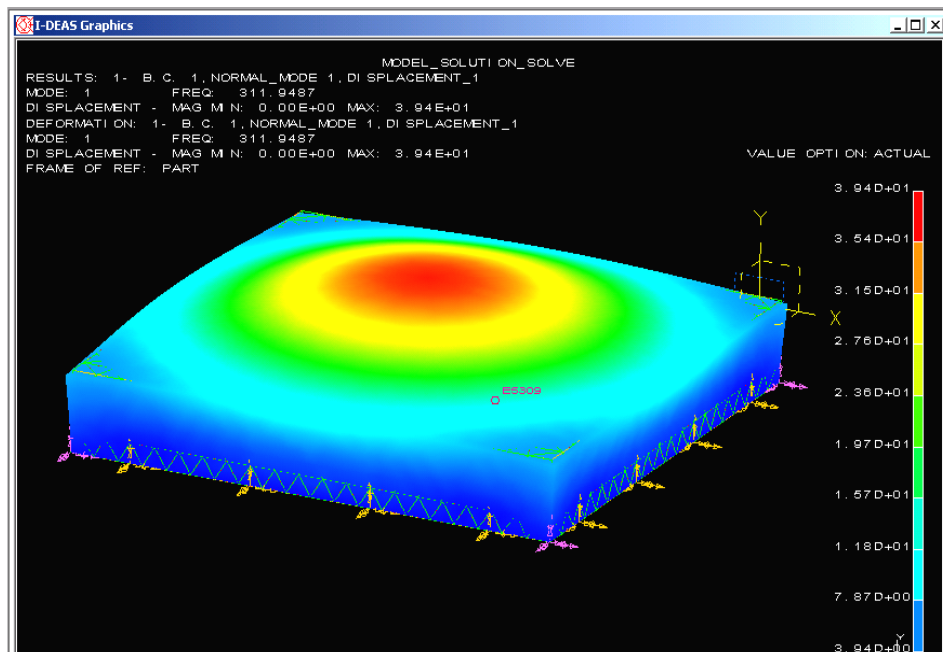


Figure 28: First mode frequency of 312 Hz

6 Sensor Package Design

In order to analyze future OZ Saferooms subjected to impact tests, a sensor package design is needed. With the success of the actual impact testing of the existing OZ Saferoom structure, the senior design team utilized its initial sensor package design and expanded for the future.

6.1 Accelerometer Mounting

The initial mounting device for the accelerometer consisted of a 0.5 in. diameter steel rod of 3 in. length with a 10-32 female thread (for the accelerometer stud). In order to install this device, a hole needed to be drilled in the structure's roof. For convenience, it is desired that all future accelerometer mounting fixtures be installed when constructing the structure. In order to account for this, commercial steel L-style anchor bolts, with 7 in. length and female 10-32 thread on one end, can be utilized. These anchor bolts can be wire tied to the 5 x 5 grid of rebar which is located in the center of the 12 in. thick roof. The length of 7 in. allows for the anchor bolt to extend beyond the bottom of the roof so the accelerometers can be mounted using a 10-32 stud.

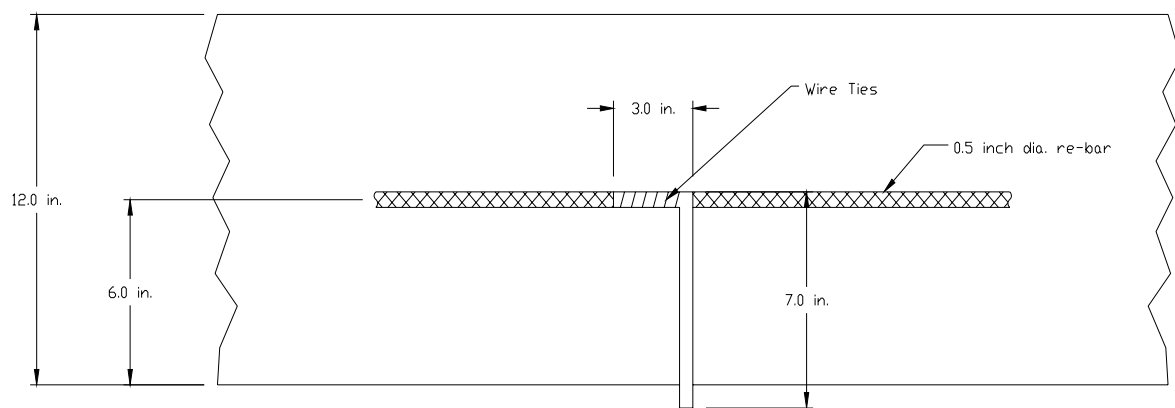


Figure 29: Cross-section of roof, rebar, and anchor bolt

Following yield line analysis for the 78 in. cubic structure, the accelerometers will be mounted in the center of the triangles created by the solid, diagonal yield lines in Figure 30 and 31. An additional accelerometer will be placed in the center of the roof, which is assumed to have the greatest deflection. The anchor bolts will be strategically placed so the accelerometers are mounted at the locations on the roof and wall shown below.

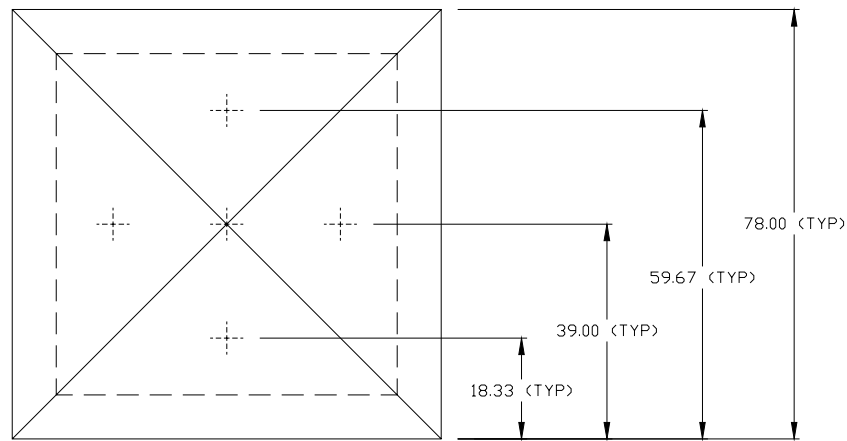


Figure 30: Accelerometer locations – roof

Note: All dimensions in inches

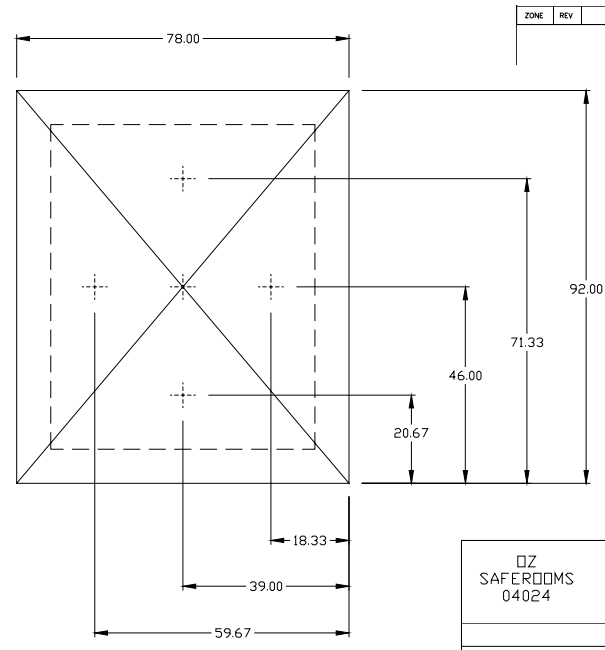


Figure 31: Accelerometer locations – wall

Note: All dimensions in inches

6.2 Data Acquisition Equipment

The following equipment will be needed in order to conduct future impact testing analysis.

P/N	Description	QTY	\$/per	Cost	Supplier
353B03	Accelerometer	5	\$256.50	\$1,282.50	PCB
003EB100AC	Cable (100ft)	5	\$153.90	\$769.50	PCB
6052E	PC Interface Card	1	\$1,595.00	\$1,595.00	National Instruments
SCXI 1531	Signal Conditioner	1	\$2,295.00	\$2,295.00	National Instruments
-	SCXI Chassis	1	\$695.00	\$695.00	National Instruments
-	Labview Software	1	\$995.00	\$995.00	National Instruments
-	Computer	1	-	-	-
91592A205	Anchor Bolt	5	\$2.86	\$14.30	McMaster-Carr
-	Wire Tie	-	-	-	-

Total Cost: \$7,646.30

Figure 32: Sensor package items

7 Future Suggestions and Opportunities

At this point, the team has completed all of the deliverables for the OZ Saferoom senior design project. The following sections focus on future suggestions and opportunities for further analysis of OZ Saferooms.

7.1 Finite Element Analysis

Future projects affiliated with OZ Saferooms involving finite element analysis could include simulating the safe room with rebar. Modeling the safe room as a

reinforced structure would more accurately depict the stress and displacement results found in an actual reinforced OZ Saferoom. To simulate this complex model, a more powerful computer or workstation is needed.

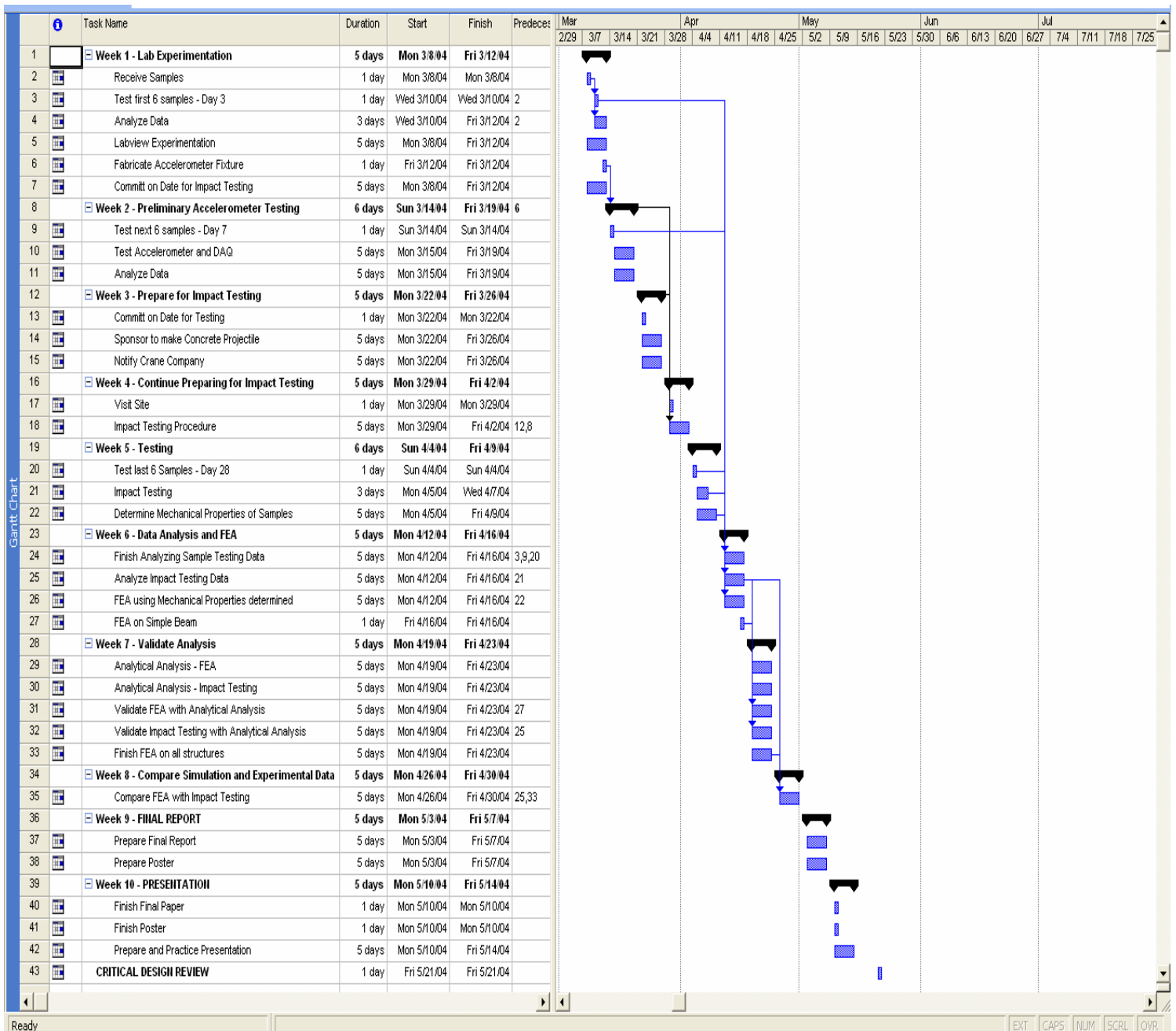
The second opportunity or suggestion that would involve FEA would be to subject the safe room to dynamic loads. With dynamic loading, it would be easier to portray debris such as trees, cars or parts of buildings striking the safe room. Dynamic loading would also yield more precise impact test result for stress and displacement.

7.2 Impact Testing

This project has successfully demonstrated the durability of the existing OZ Saferoom, yet there are many opportunities for further projects relating to impact testing. Due to resource constraints, the team was only able to dynamically load the structure's roof. It may also be worthwhile to consider an impact test to the structure's walls and door. This may be accomplished through the use of a swinging projectile or other innovative methods. It may be in Zagorski Forms' best interest to load a structure to failure, in order to realize its true ultimate strength. Also, further projects could be initiated using a strain gage on the structure's rebar during an impact test. This would provide experimental data for the stress seen by the rebar. From all of these possible concepts, Zagorski Forms could alter the design of the structure as needed.

8 Project Schedule

A schedule was developed for the spring quarter which helped keep the team focused and on track to finish the project on time. The schedule, shown below, was designed to give the team an idea of what work should be done and when it should be completed on a week-to-week basis.



9 Budget

The team's final budget is shown below.

	P/N	Description	\$/per	Qty	Total	Supplier
Impact Testing	353B03	Accelerometer	\$256.50	3	\$769.50	PCB
	003EB100AC	Cable (100ft)	\$153.90	1	\$153.90	PCB
	-	Freight Charge	\$25.00	1	\$25.00	PCB
	6052E	PC Interface Card	-	1	-	National Instruments
	SCXI 1531	Signal Conditioner	-	1	-	National Instruments
	-	SCXI Chassis	-	1	-	National Instruments
	-	Labview Software	-	1	-	National Instruments
	081B05	10-32 Mounting Stud	-	1	-	PCB
	-	Accelerometer Fixture	-	1	-	RIT Machine Shop
	-	Crane	-	1	-	Sponsor
	-	Impact Load	-	1	-	Sponsor
	-	Misc. Supplies	-	1	\$13.45	Home Depot
	-	Misc. Supplies	-	1	\$19.85	Keystone Builders
	-	Tinius Olsen machine	-	1	-	RIT Mechanics Lab
Sample Testing	-	Computer	-	1	-	RIT Mechanics Lab
	-	6" diameter x 12" height cylindrical concrete samples	-	9	-	Sponsor
	-	14"x4"x4" concrete beam samples	-	9	-	Sponsor
	-	3 steel rods for three-point bending fixture	-	1	-	RIT Machine Shop
	-	Base Plate for three-point bending fixture	-	1	-	RIT Machine Shop

Total Cost: \$981.70

10 References

- “Design and Construction Guidance for Community Shelters,” Federal Emergency Management Agency, FEMA 361, First Edition, July 2000.
- “Taking Shelter from the Storm,” Federal Emergency Management Agency, FEMA 320, 2nd Edition, August 1999.
- “Association Standards for the Design, Construction, and Performance of Storm Shelters,” National Storm Shelter Association, First Edition, April 2001.
- ASCE 7-98, (1999), “Minimum Design Loads for Buildings and Other Structures,” American Society of Civil Engineers.
- ASTM C78-02, (2003), “Standard Test Method for Flexural Strength of Concrete,” American Society for Testing and Materials, Volume 4.
- ASTM C39, (2003), “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” American Society for Testing and Materials, Volume 4.
- MacGregor, J. G., 1992, “Reinforced Concrete Mechanics and Design,” 2nd edition, Prentice Hall, pp. 47-55, 659-672.
- Askeland, D. R. and Phule, P. P., 2003, "The Science and Engineering of Materials," 4th edition, Brooks/Cole, p. 255.
- OZ Saferooms. 5 Dec. 2003 <<http://www.ozsaferooms.com/>>.

11 Appendix A

11.1 Feasibility Assessment

11.1.1 Weighted Method

ESTIMATION OF RELATIVE IMPORTANCE OF ATTRIBUTES

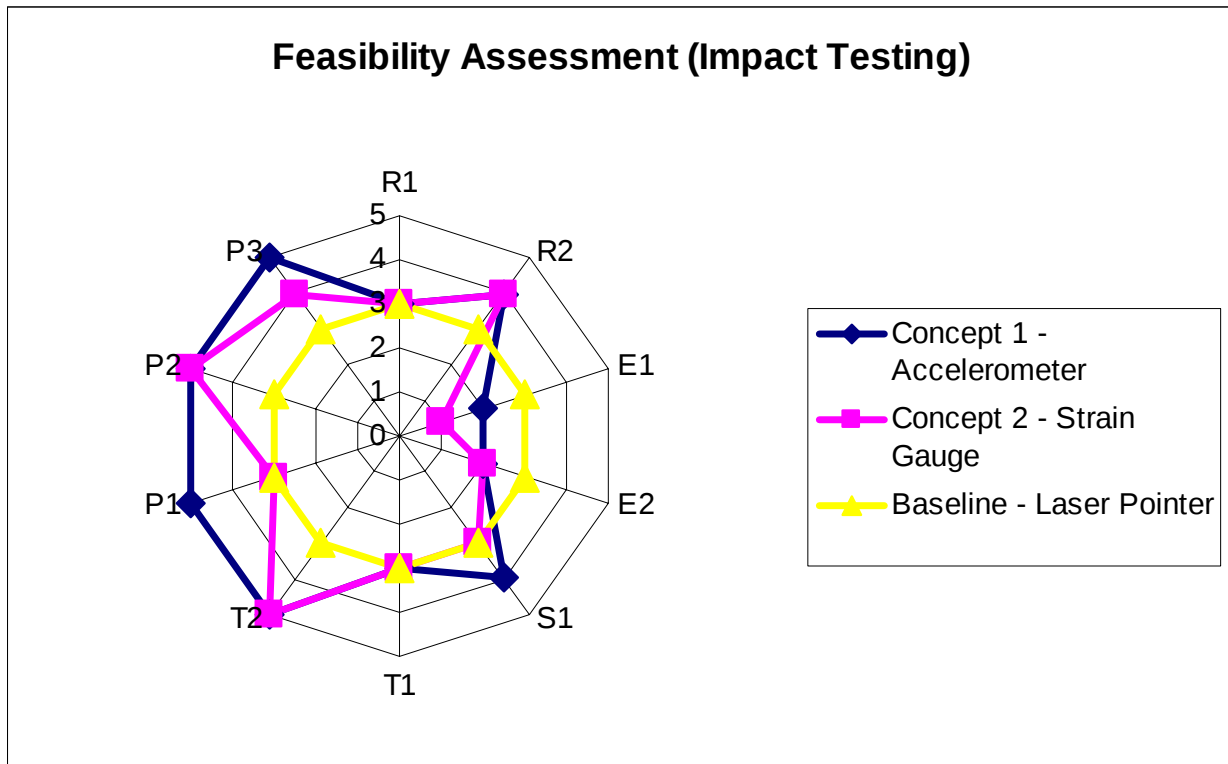
	ATTRIBUTES	ROW TOTAL	COLUMN TOTAL	ROW + COLUMN	RELATIVE WEIGHT
R1	Sufficient Skills	6	3.5	9.5	0.173
R2	Sufficient Equipment to launch projectiles	3.5	3.5	7	0.127
E1	Total Cost	4.5	0	4.5	0.082
E2	Cost of Assembly	2	0	2	0.036
S1	Meeting Milestones	0	7.5	7.5	0.136
T1	Ability to Implement	6	3	9	0.164
T2	Documentation/Standards	1	2	3	0.055
P1	Dynamic Loading	4.5	0	4.5	0.082
P2	Projectiles	2	0.5	2.5	0.045
P3	Data Acquisition	2	3.5	5.5	0.100
			COLUMN TOTAL	55	1

ASSESSING THE LEVEL OF ATTAINMENT AND SCORING THE ALTERNATIVES

	ATTRIBUTES	RELATIVE WEIGHT	CONCEPT 1 (Accelerometer)	CONCEPT 2 (Strain Gauge)	BASELINE CONCEPT (Laser Pointer)
R1	Sufficient Skills	0.173	3	3	3
R2	Sufficient Equipment to launch projectiles	0.127	4	4	3
E1	Total Cost	0.082	2	1	3
E2	Cost of Assembly	0.036	2	2	3
S1	Meeting Milestones	0.136	4	3	3
T1	Ability to Implement	0.164	3	3	3
T2	Documentation/Standards	0.055	5	5	3
P1	Dynamic Loading	0.082	5	3	3
P2	Projectiles	0.045	5	5	3
P3	Data Acquisition	0.100	5	4	3
		RAW SCORE	3.71	3.23	3.00
		NORMALIZED SCORE	1.24	1.08	1.00

CONCLUSION:	ACCELEROMETER
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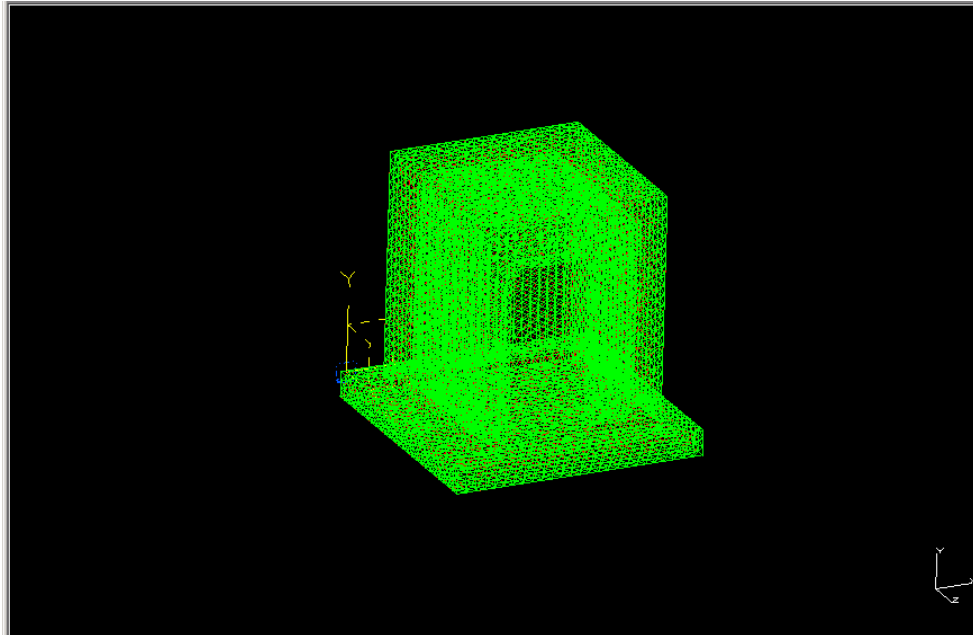
11.1.2 Radar Chart



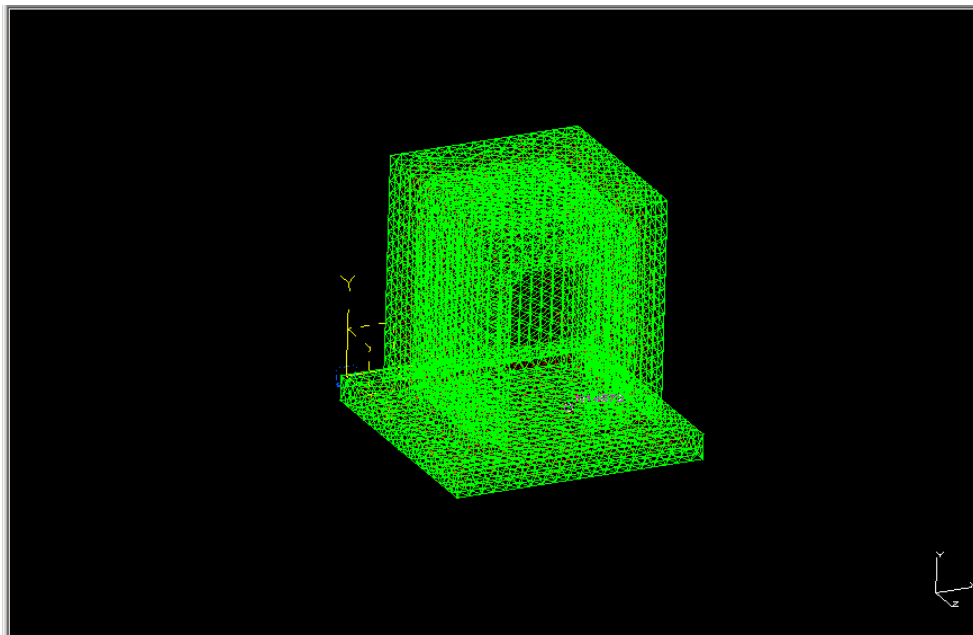
12 Appendix B

12.1 78 in. x 78 in. x 92 in. Structure Finite Element Model

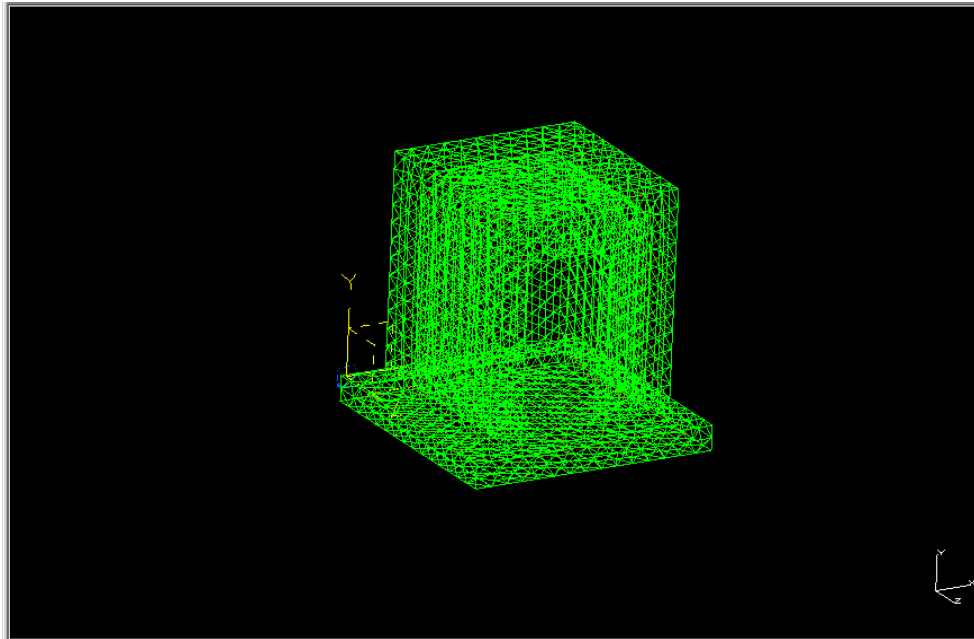
12.1.1 Mesh



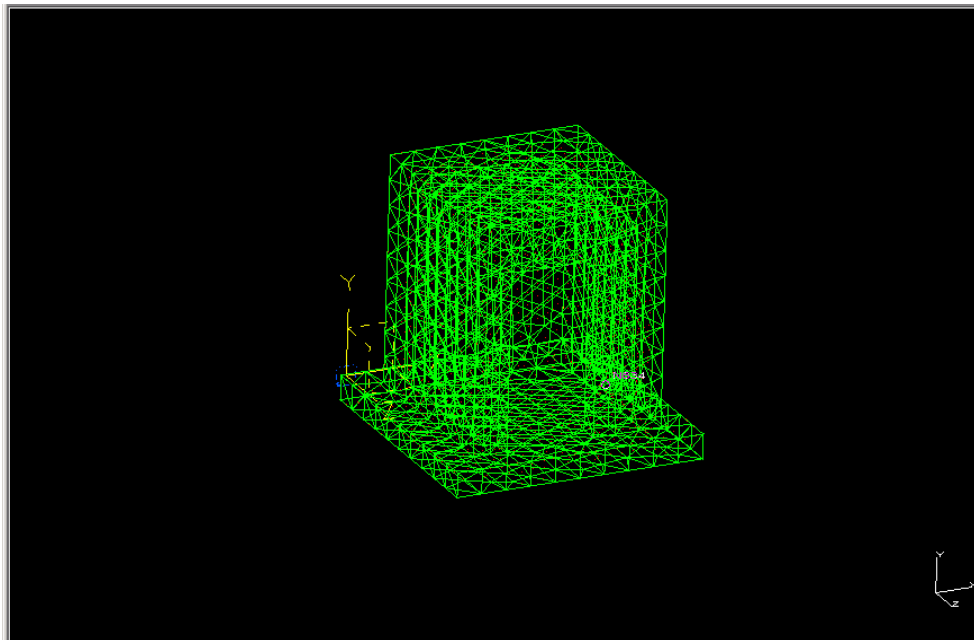
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Mesh = 5

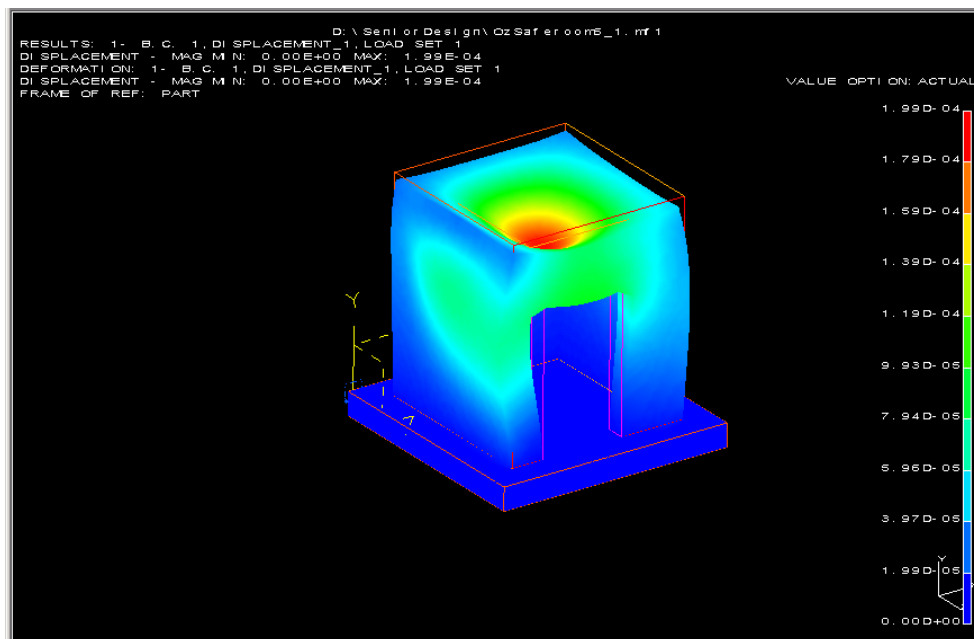


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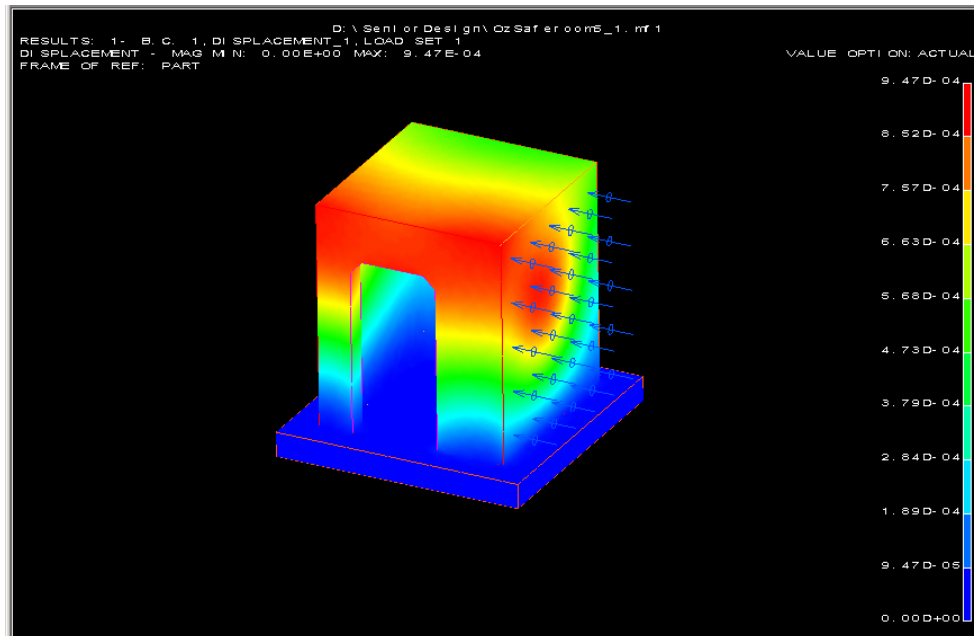


Mesh = 10

12.1.2 Preliminary Deflection Results

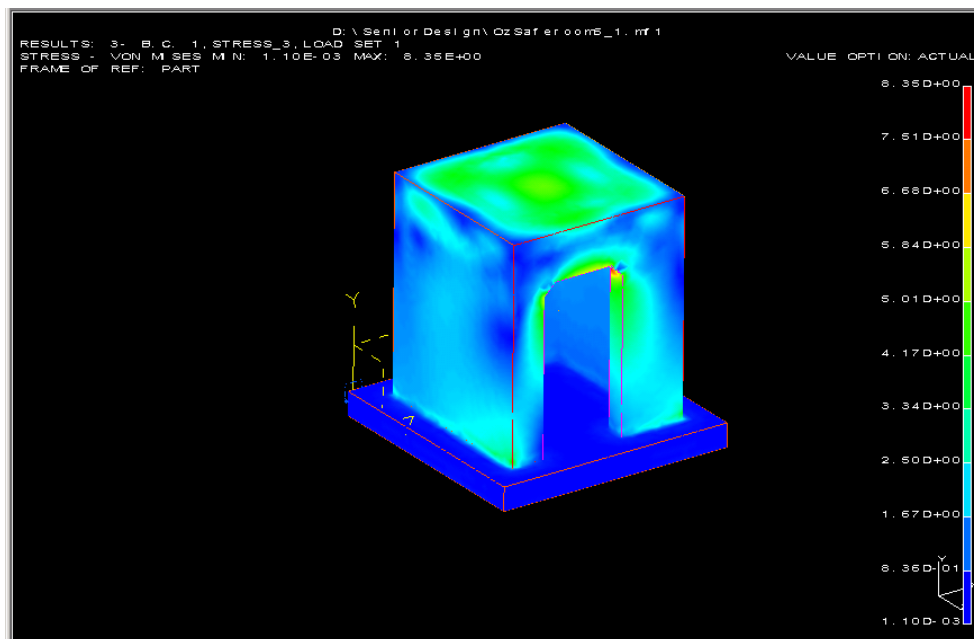


2500 lb Distributed Load (Static)
Maximum deflection = 0.000199 inches

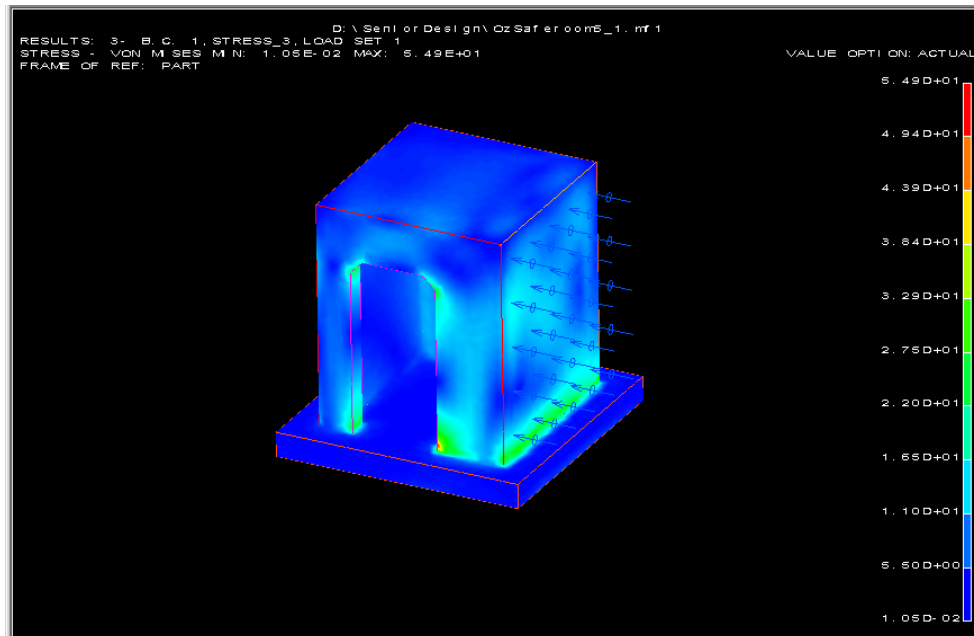


117 psf (0.8125 psi) Wind pressure
Maximum deflection = 9.47×10^{-4} inches

12.1.3 Preliminary Stress Results

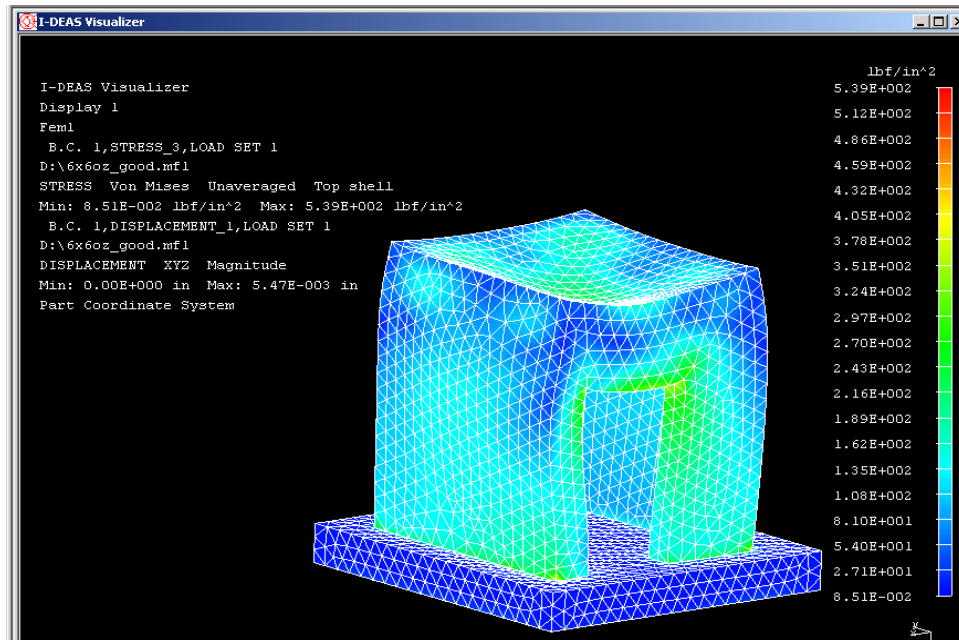


2500 lb Distributed Load (Static)
Maximum Von Mises Stress = 8.35 psi

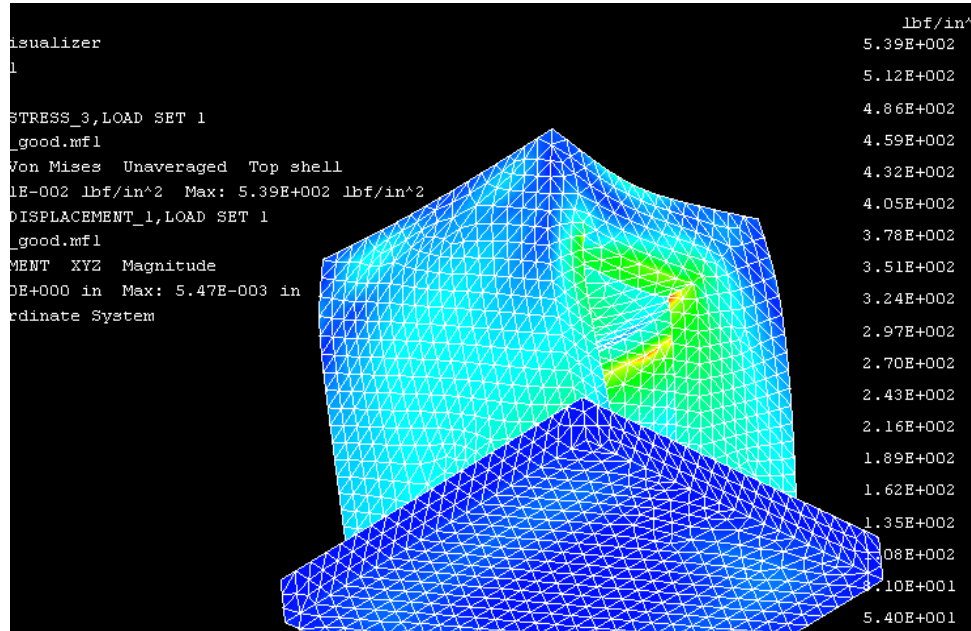


117 psf (0.8125 psi) Wind pressure
Maximum Von Mises Stress = 54.9 psi

12.1.4 Failure Analysis – Roof

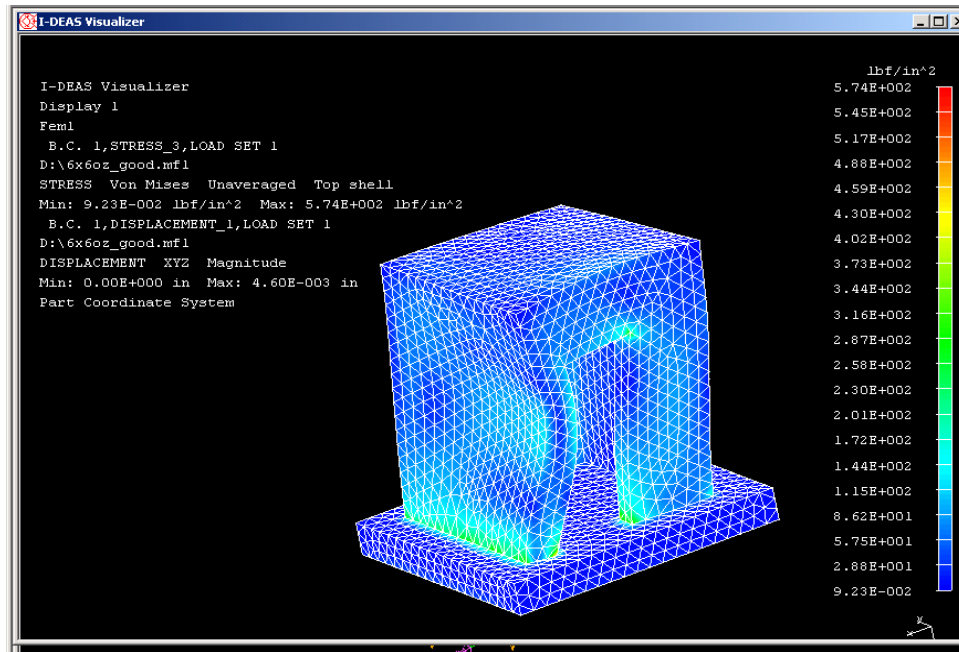


38 psi distributed pressure
Max stress = 539 psi

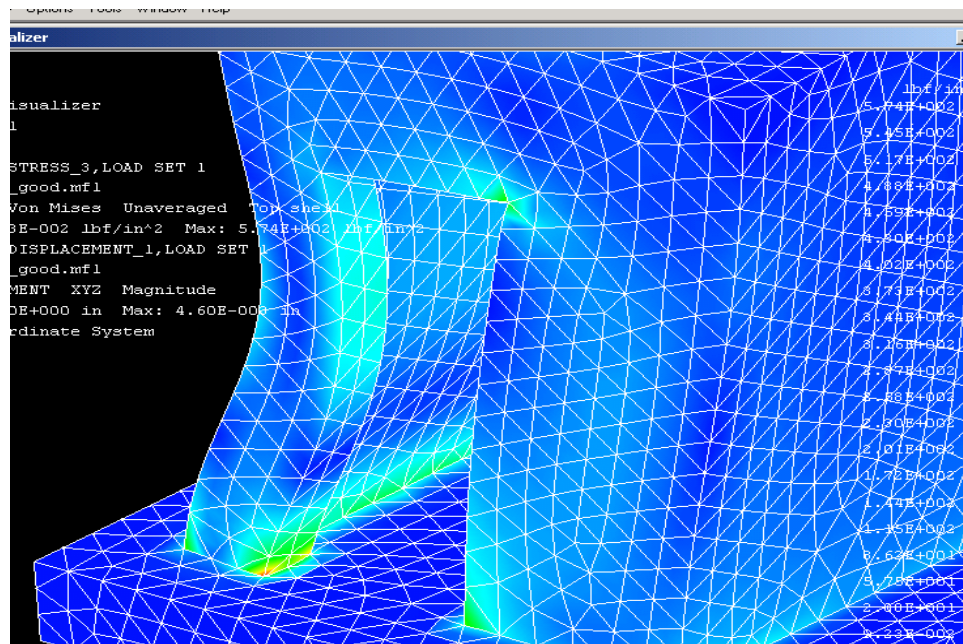


Max stress location

12.1.5 Failure Analysis – Wall



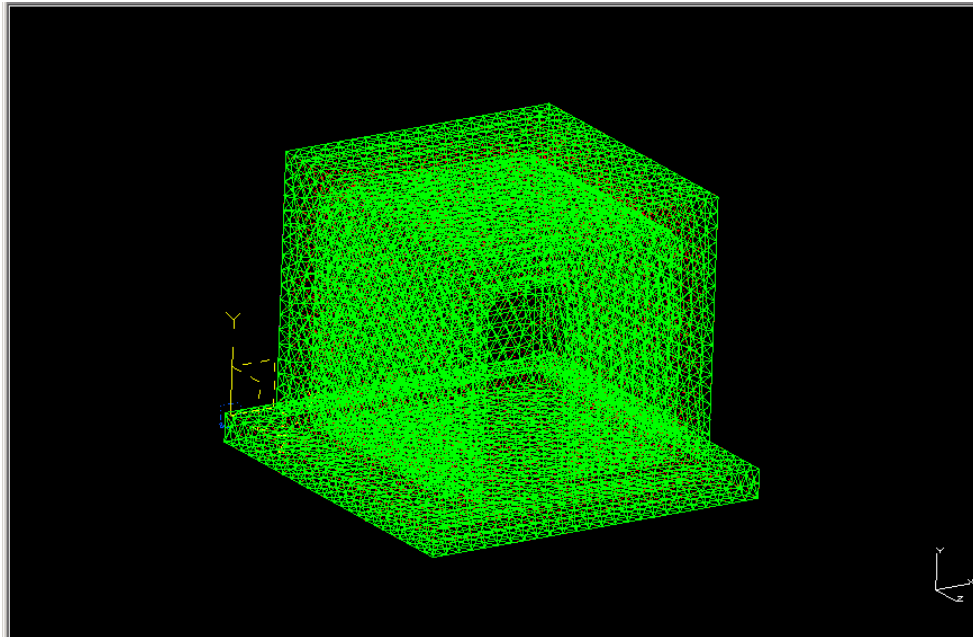
5.5 psi distributed pressure
Max stress = 574 psi



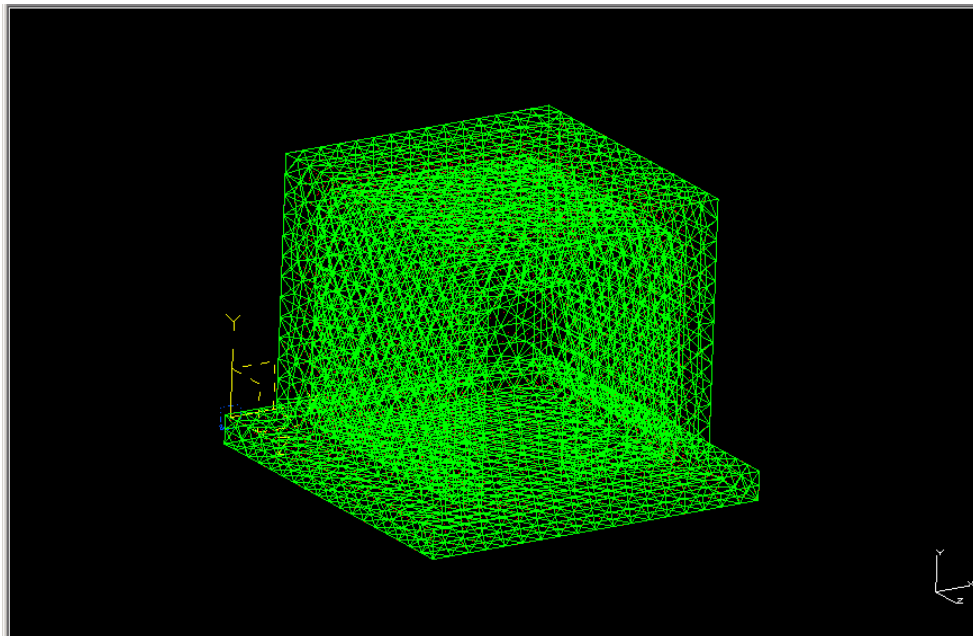
Max stress location

12.2 102 in. x 102 in. x 92 in. Structure Finite Element Model

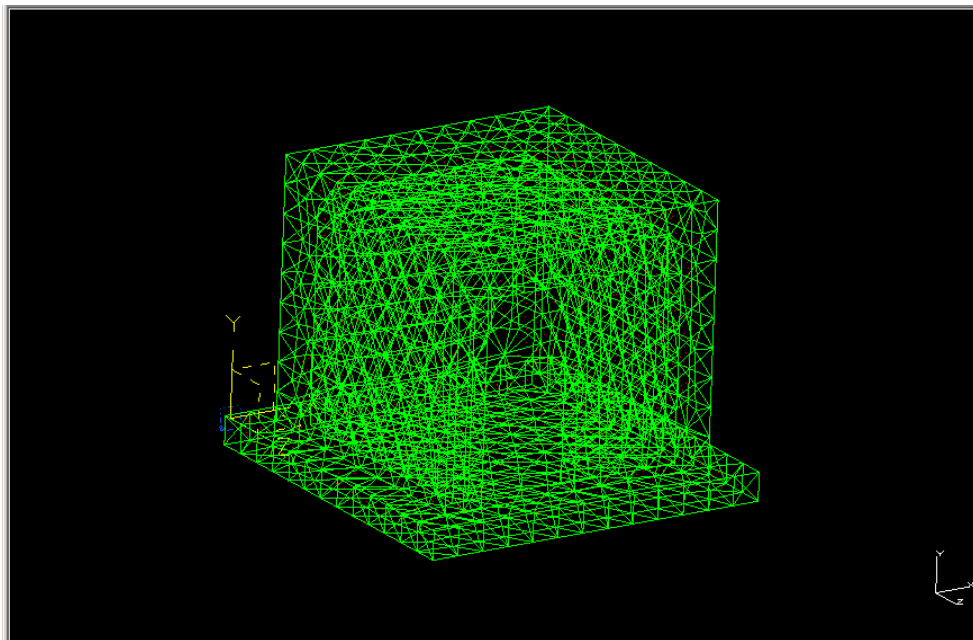
12.2.1 Mesh



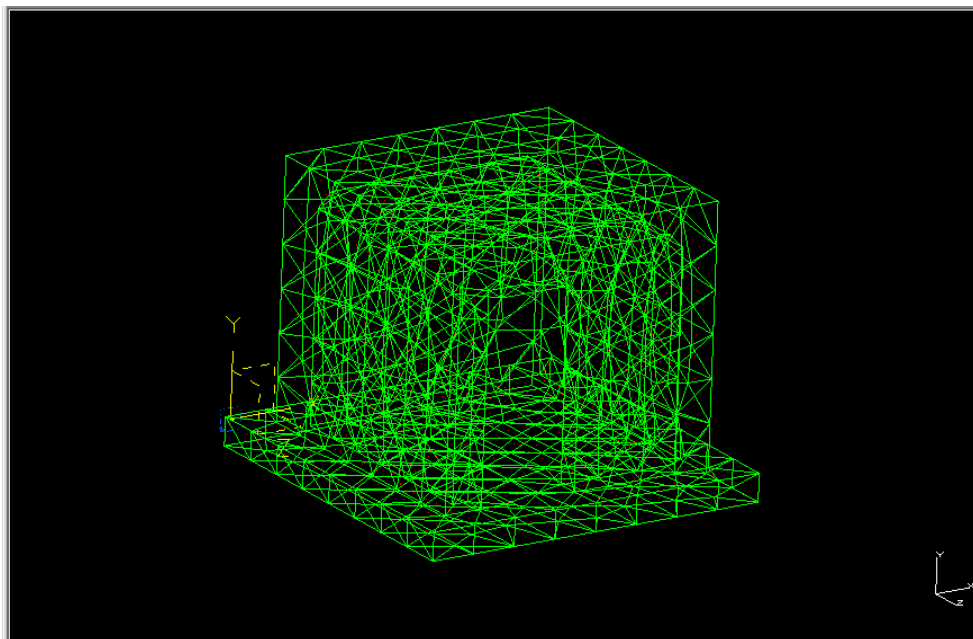
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Mesh = 7

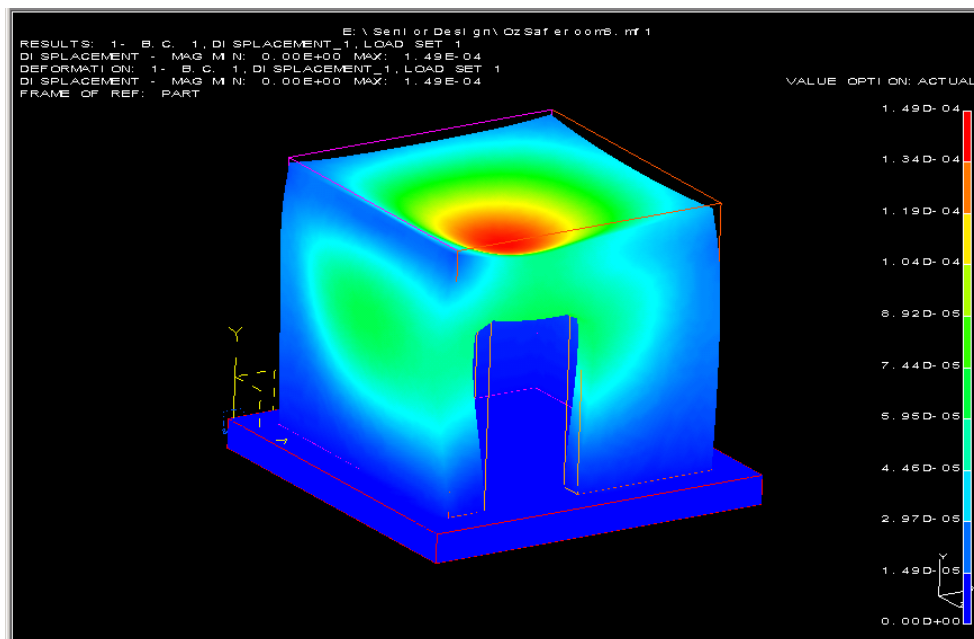


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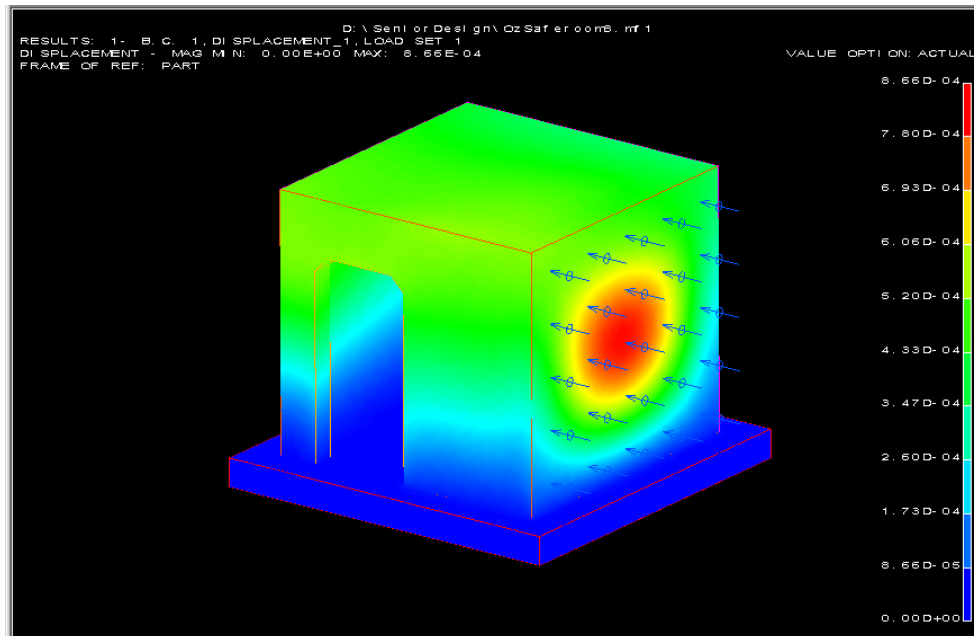


Mesh = 15

12.2.2 Preliminary Deflection Results

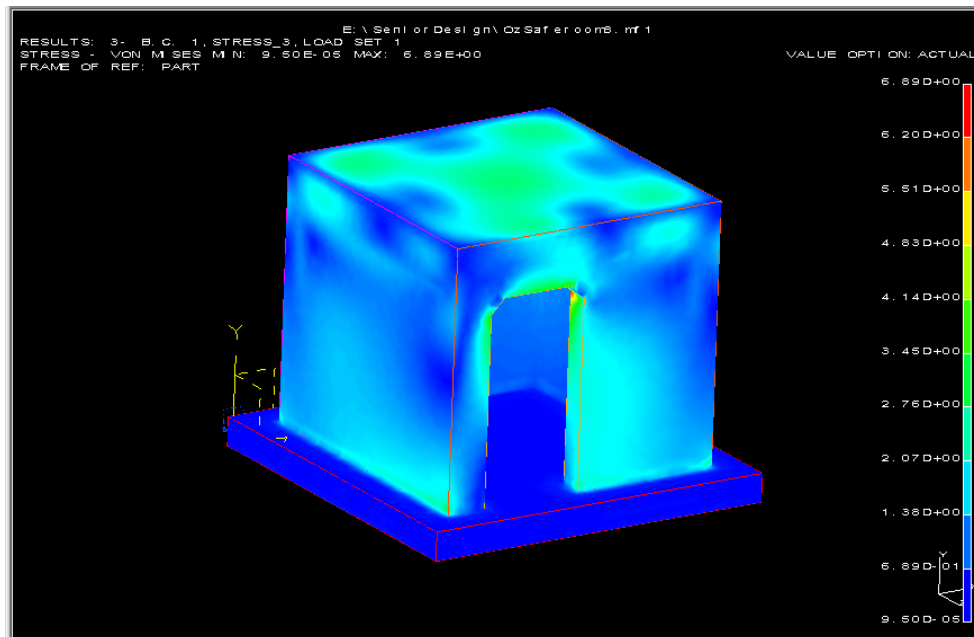


2500 lb Distributed Load (Static)
Maximum deflection = 0.000149 inches

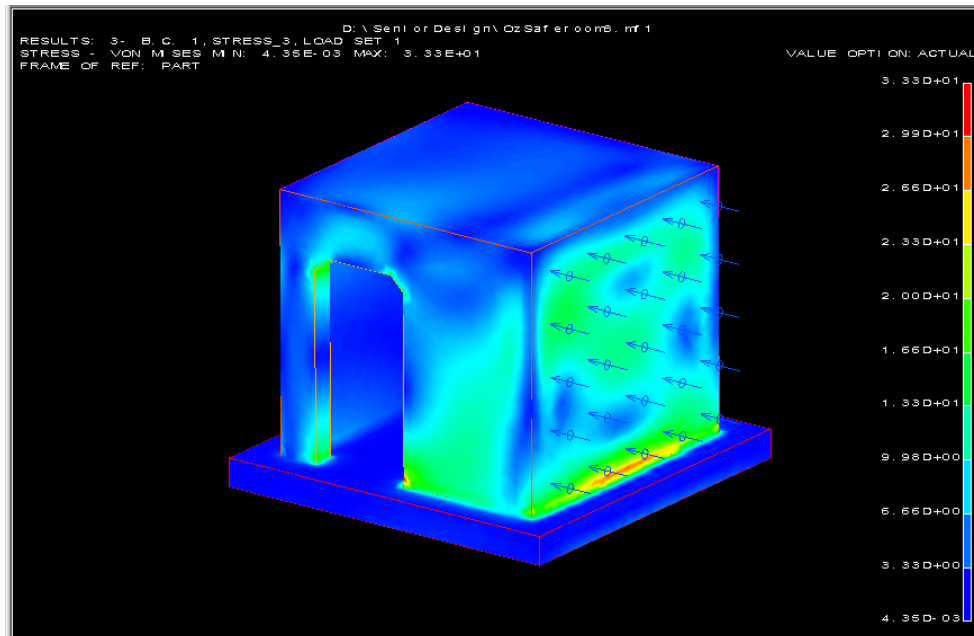


117 psf (0.8125 psi) Wind pressure
Maximum deflection = 8.66×10^{-4} inches

12.2.3 Preliminary Stress Results

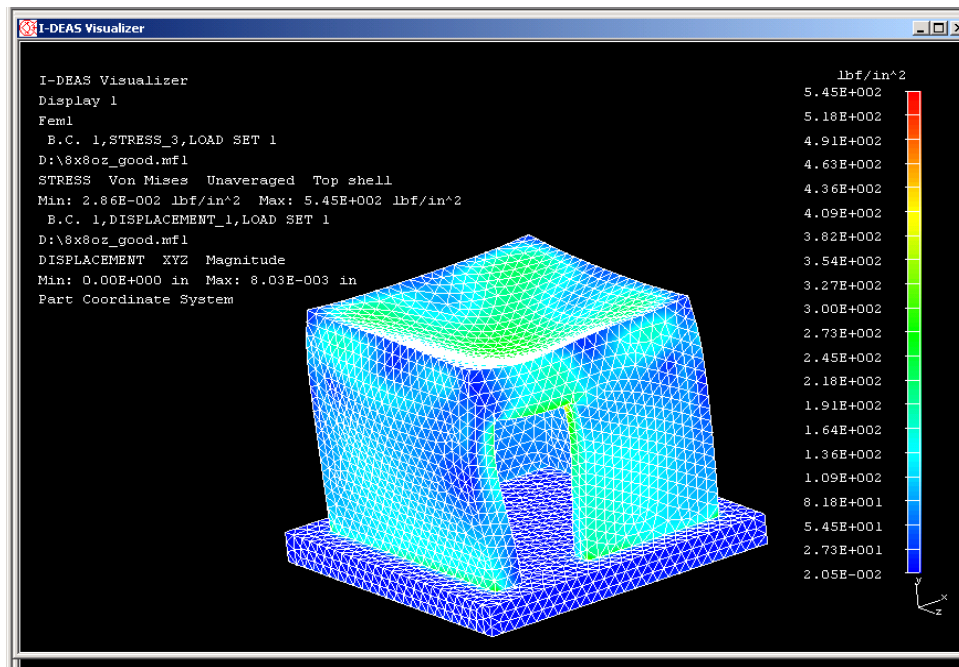


2500 lb Distributed Load (Static)
Maximum Von Mises Stress = 6.89 psi

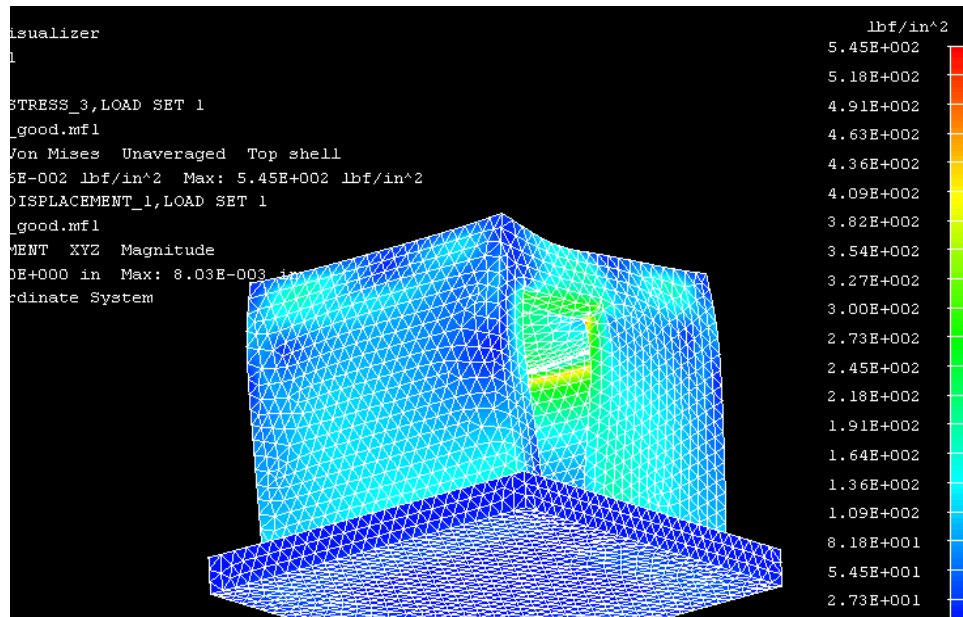


117 psf (0.8125 psi) Wind pressure
Maximum Von Mises Stress = 33.3 psi

12.2.4 Failure Analysis – Roof

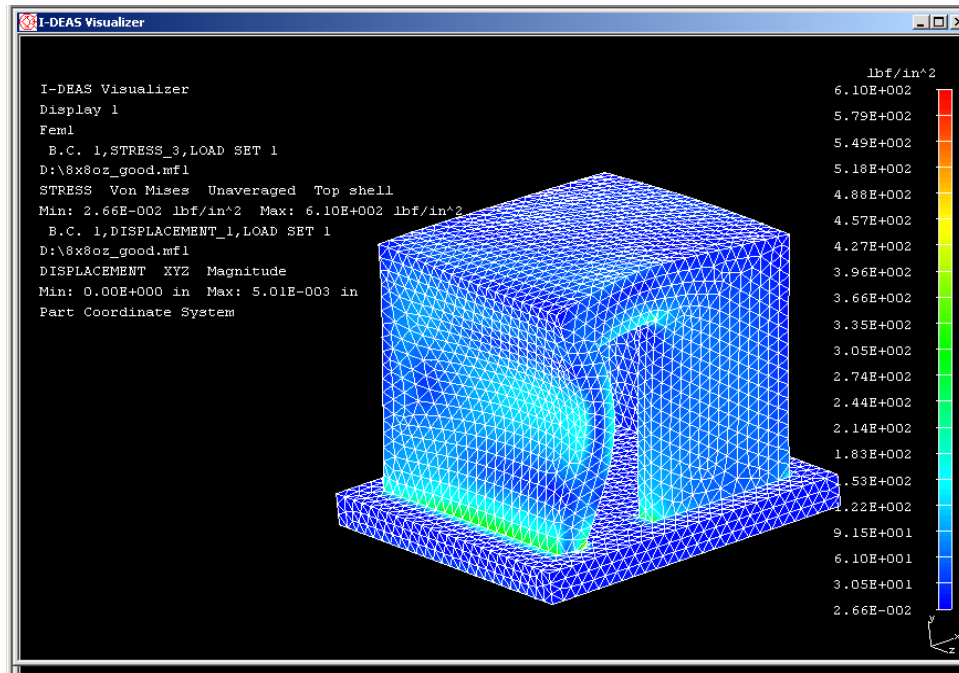


21.5 psi distributed pressure
Max stress = 545 psi

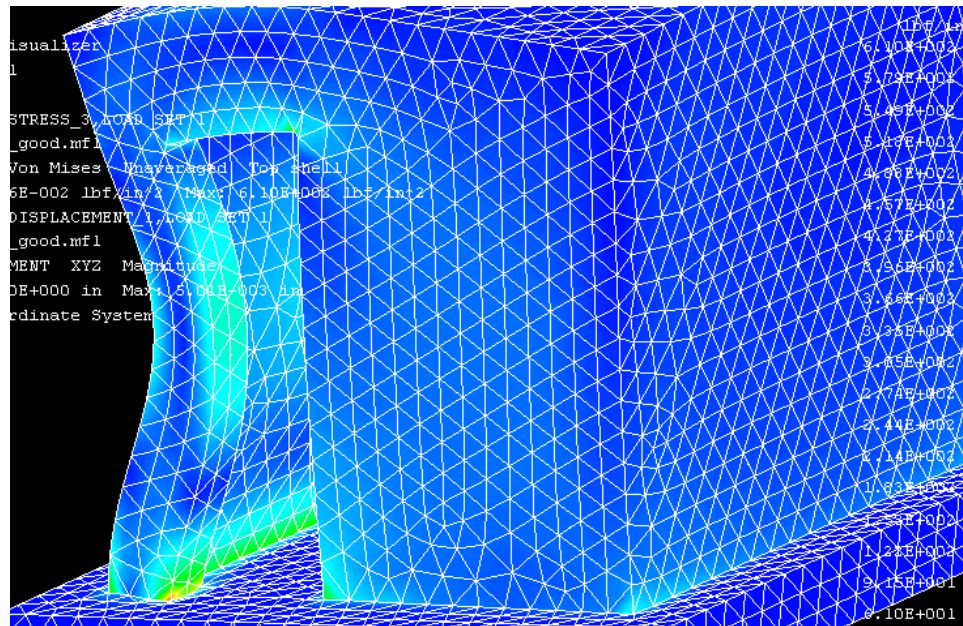


Max stress location

12.2.5 Failure Analysis - Wall



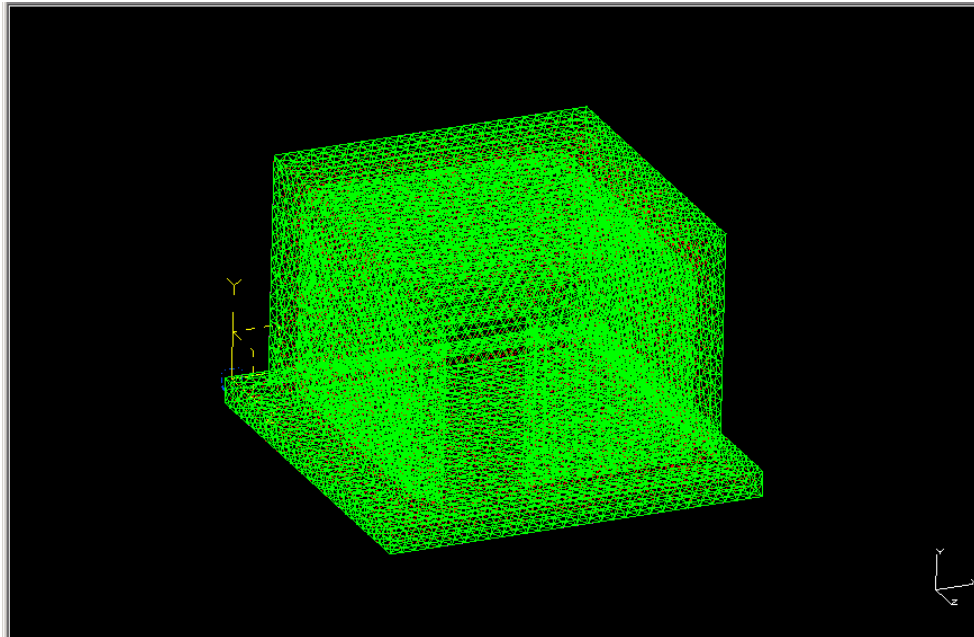
6 psi distributed pressure
Max stress = 610 psi



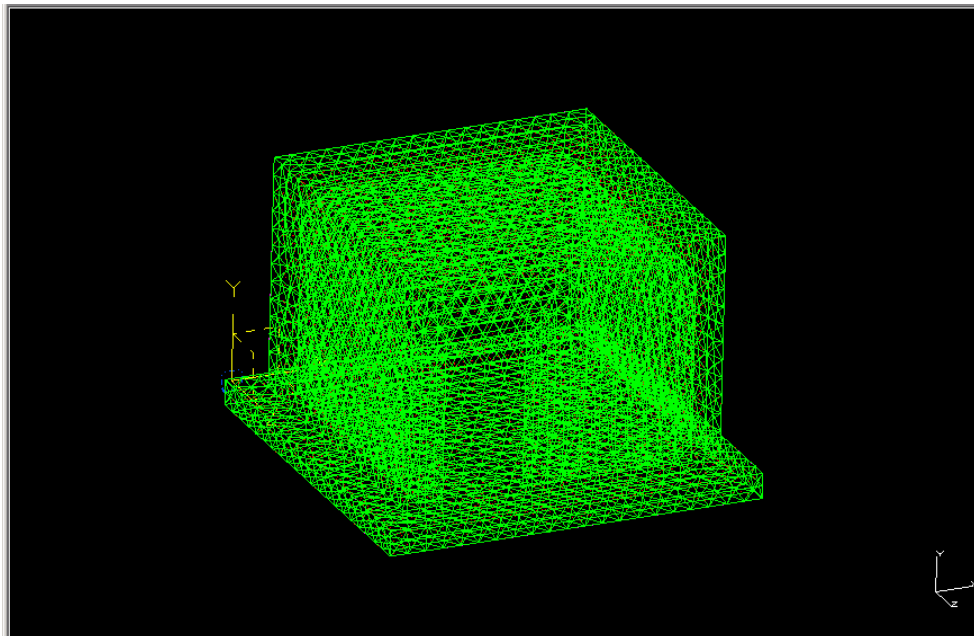
Max stress location

12.3 126 in. x 126 in. x 92 in. Structure Finite Element Model

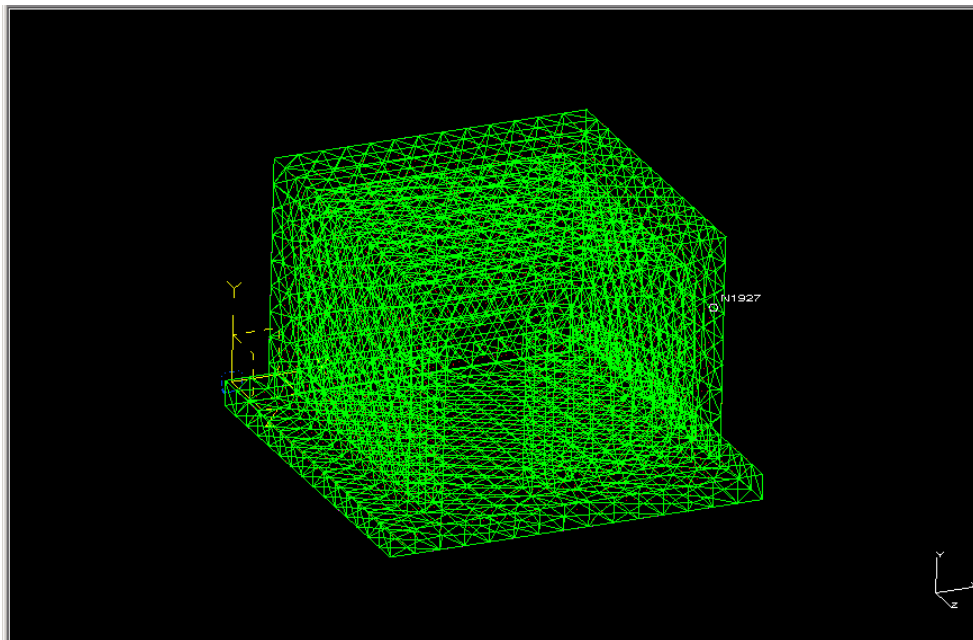
12.3.1 Mesh



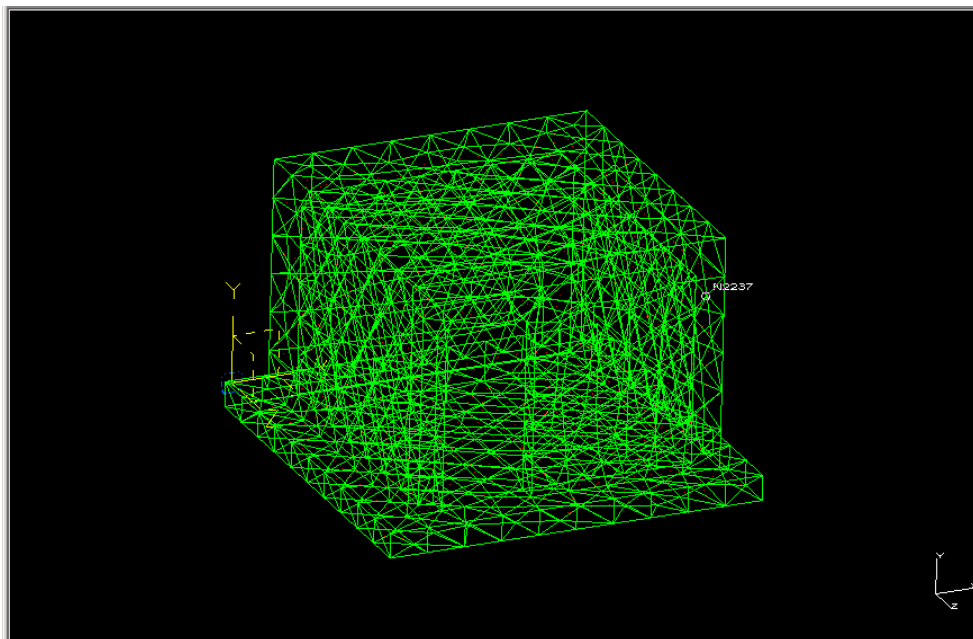
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Mesh = 7

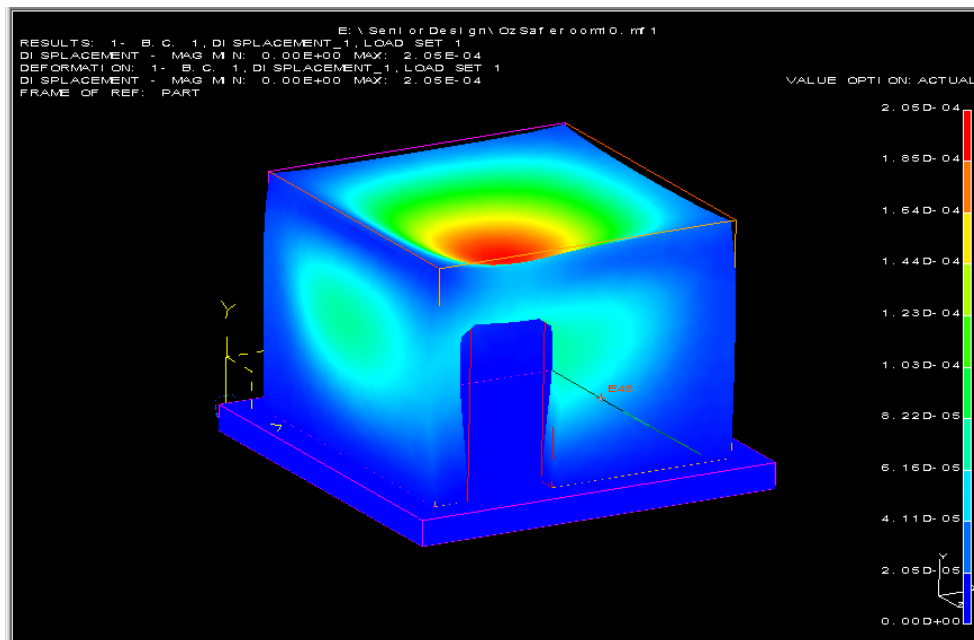


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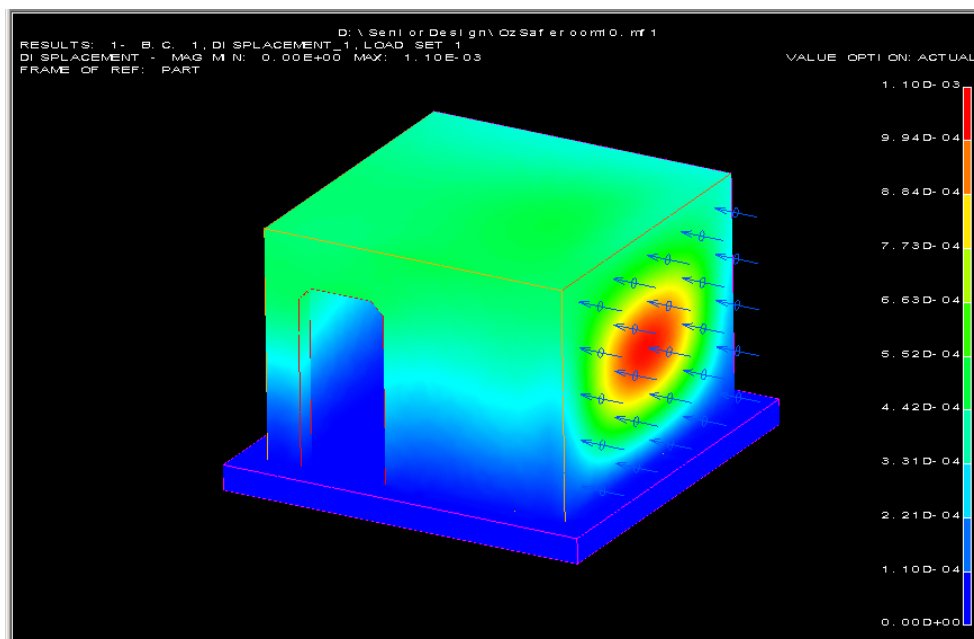


Mesh = 15

12.3.2 Preliminary Deflection Results

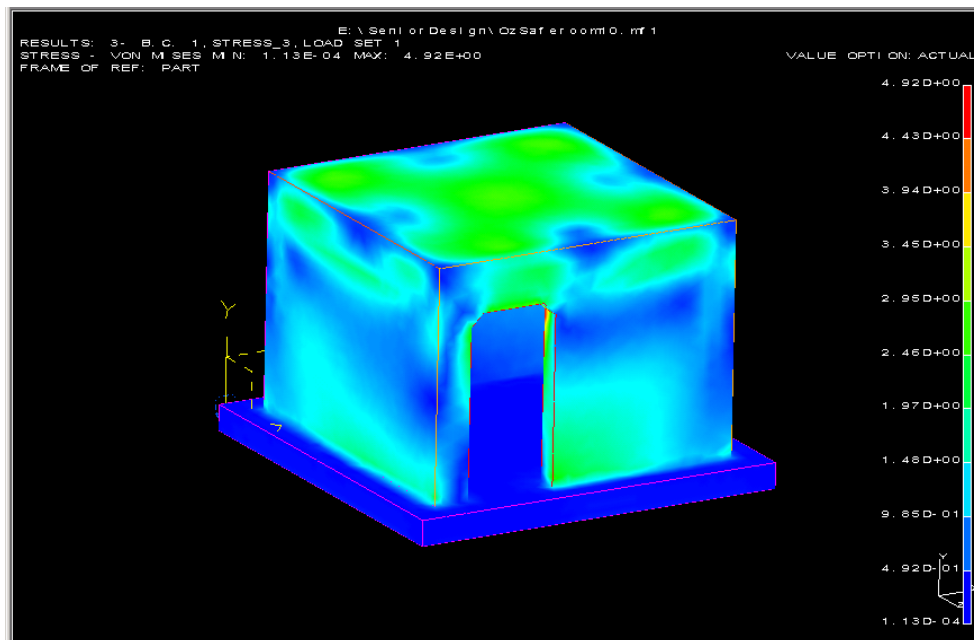


2500 lb Distributed Load (Static)
Maximum deflection = 0.000205 inches

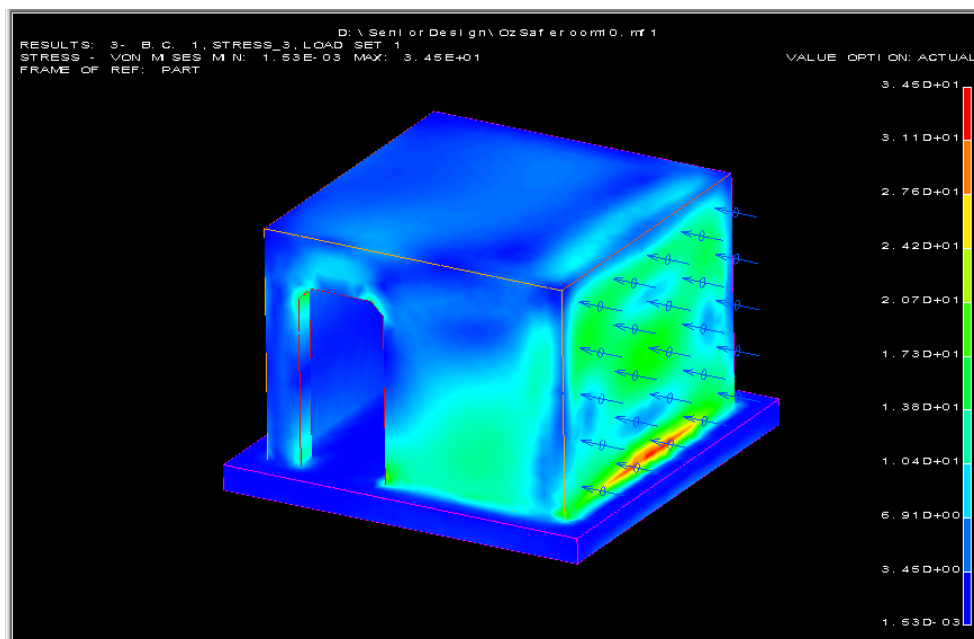


131 psf (0.9097 psi) Wind pressure
Maximum deflection = 1.1×10^{-3} inches

12.3.3 Preliminary Stress Results

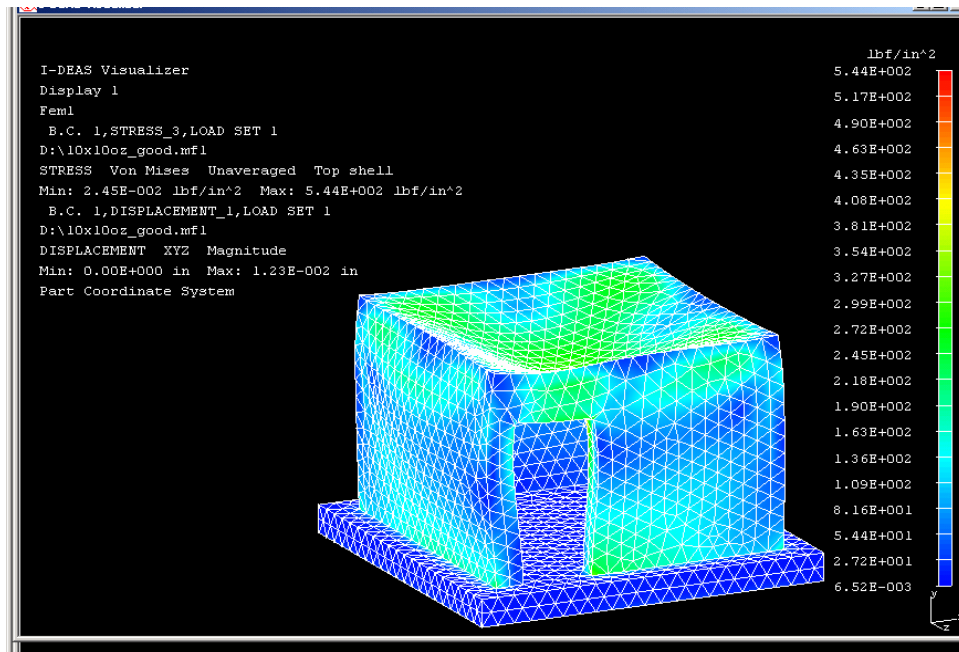


2500 lb Distributed Load (Static)
The maximum Von Mises Stress is 4.92 psi

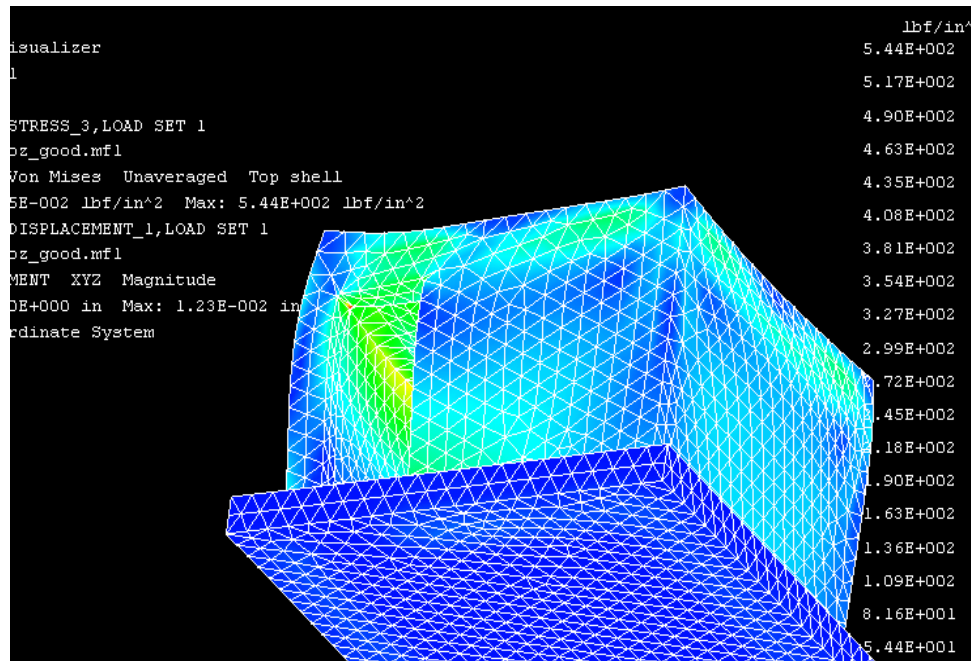


131 psf (0.9097 psi) Wind pressure
Maximum Von Mises Stress = 34.5 psi

12.3.4 Failure Analysis – Roof

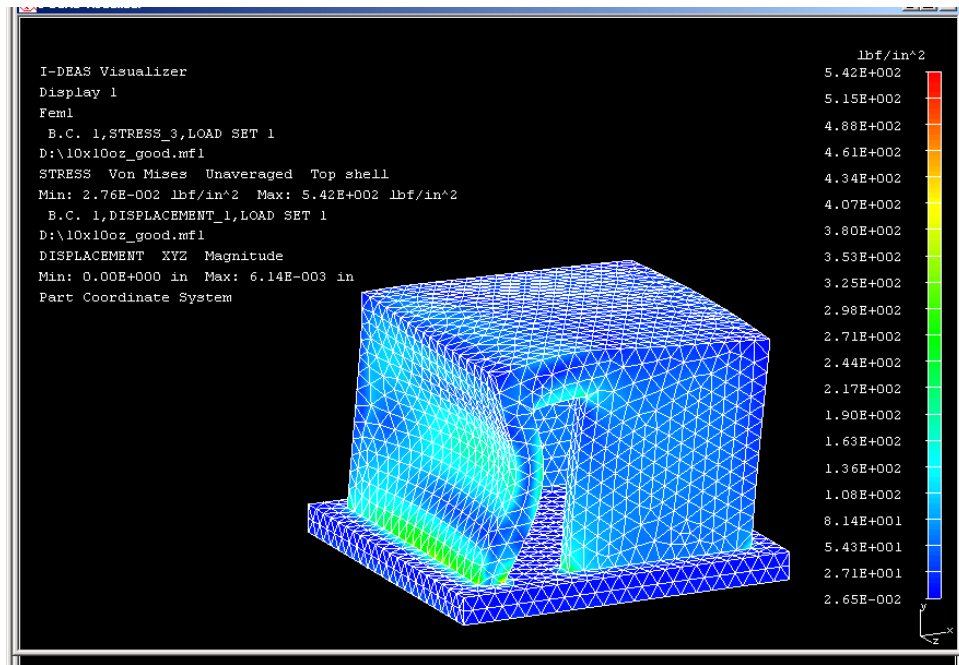


15.5 psi distributed pressure
Max stress = 544 psi

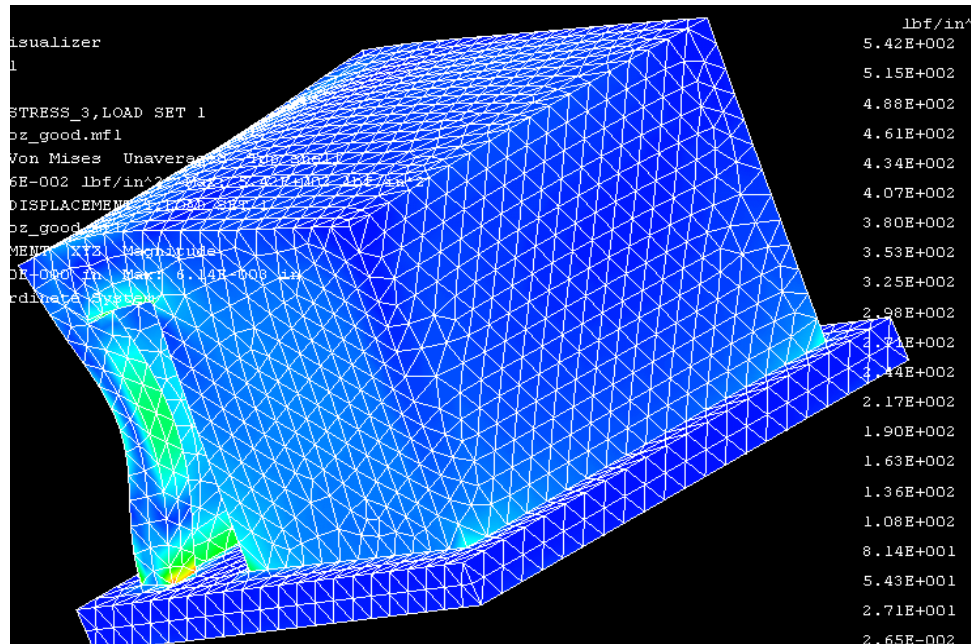


Max stress location

12.3.5 Failure Analysis - Wall



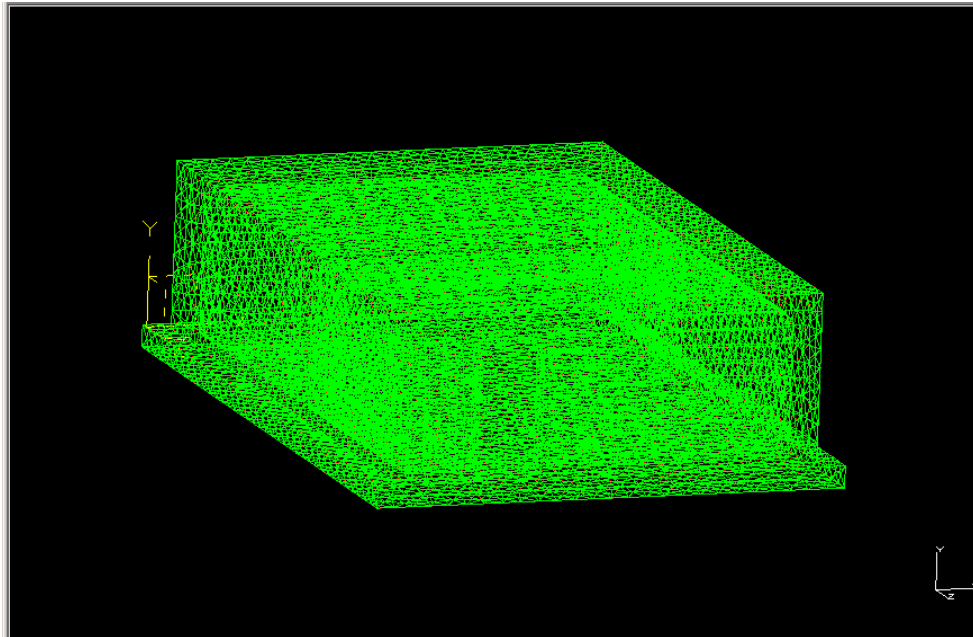
7 psi distributed pressure
 Max stress = 542 psi



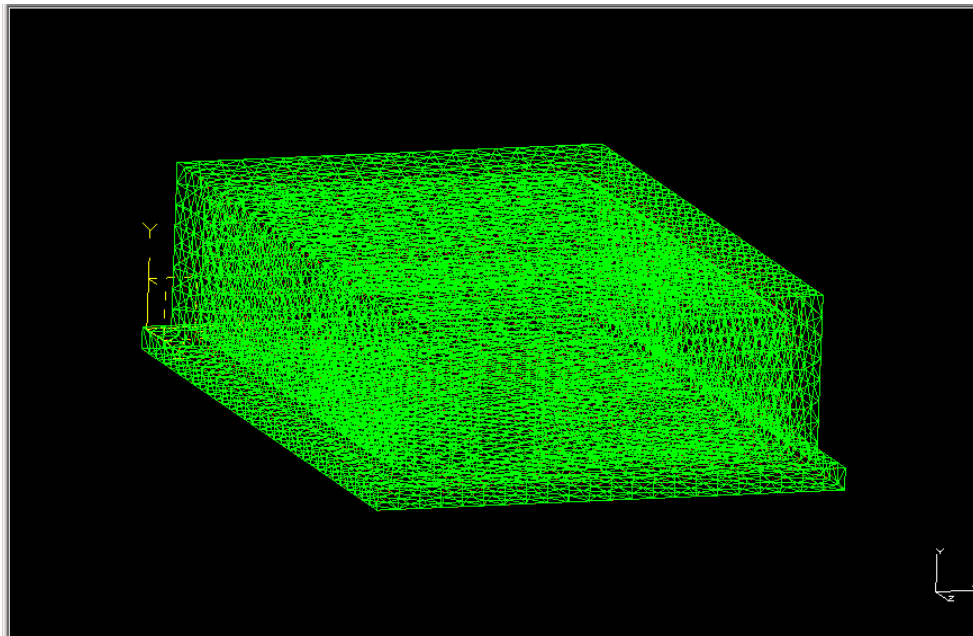
Max stress location

12.4 20 ft. x 30 ft. x 92 in. Structure Finite Element Model

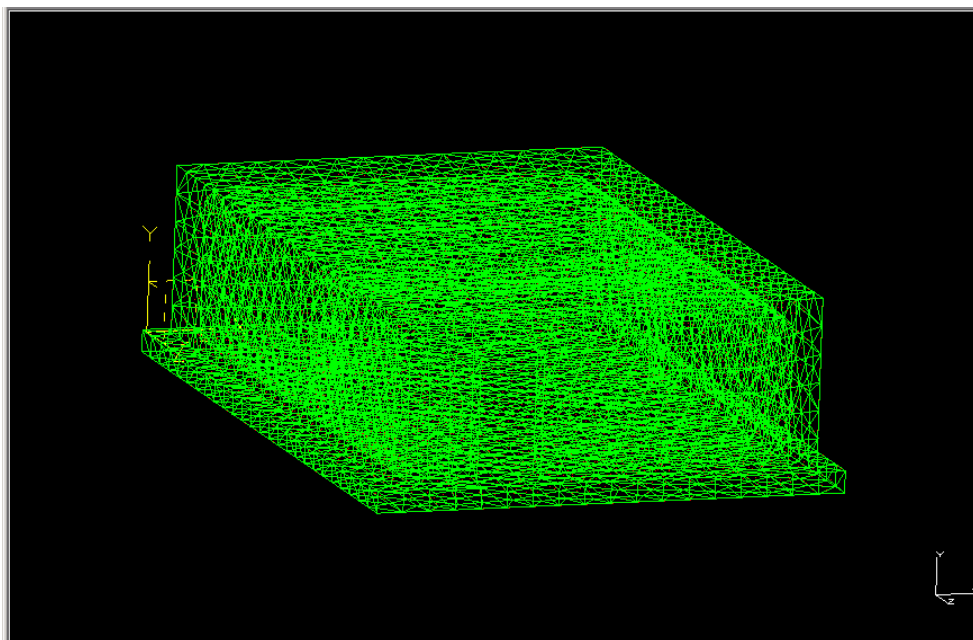
12.4.1 Mesh



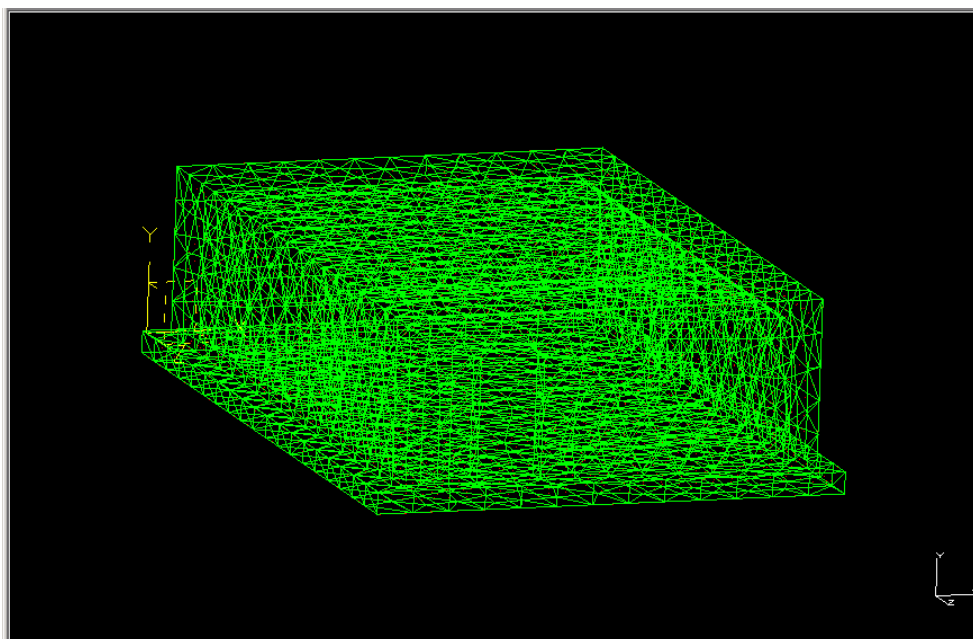
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Mesh = 12

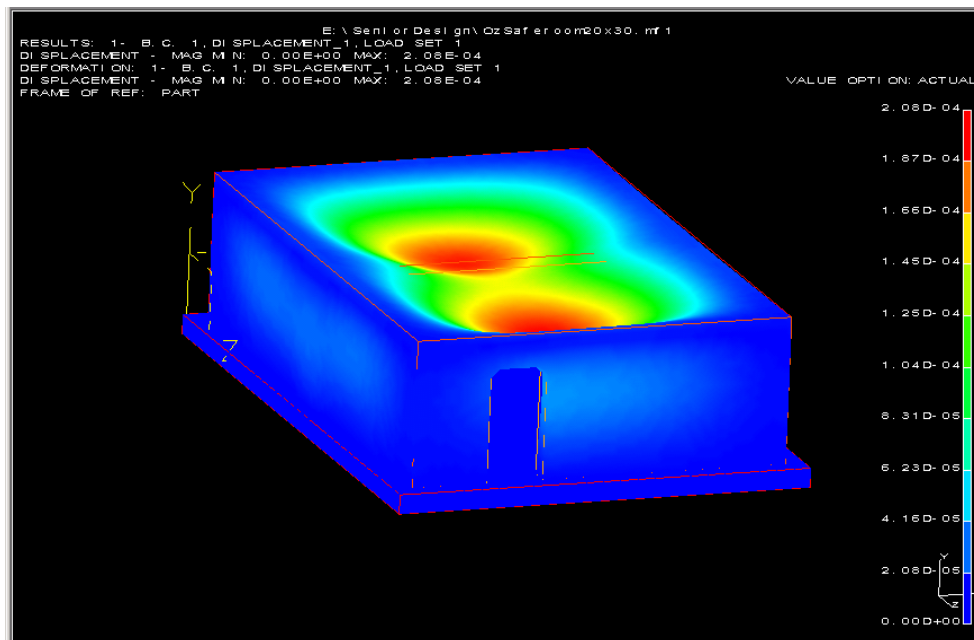


Mesh = 15

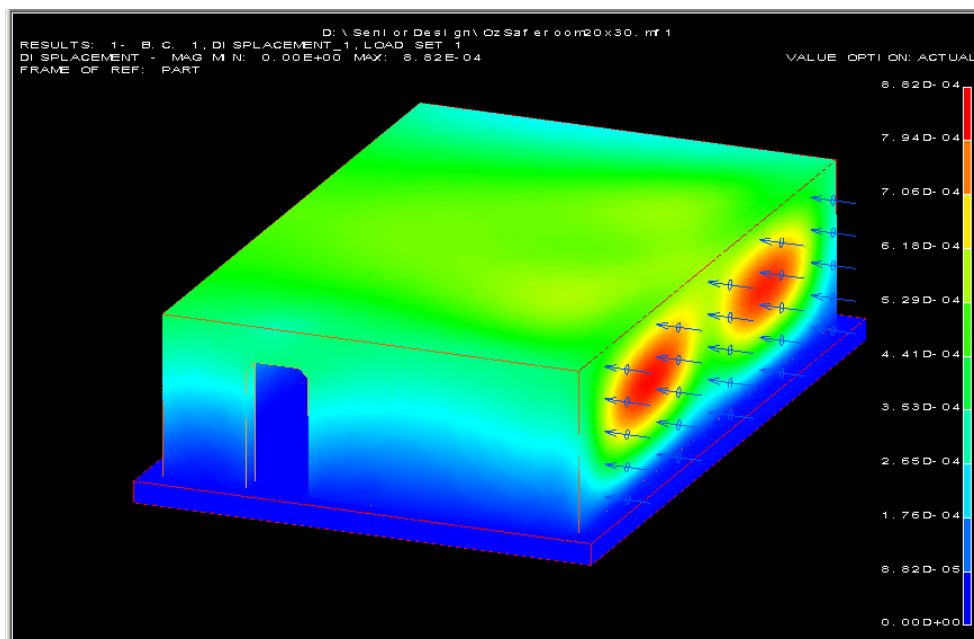


Mesh = 20

12.4.2 Preliminary Deflection Results

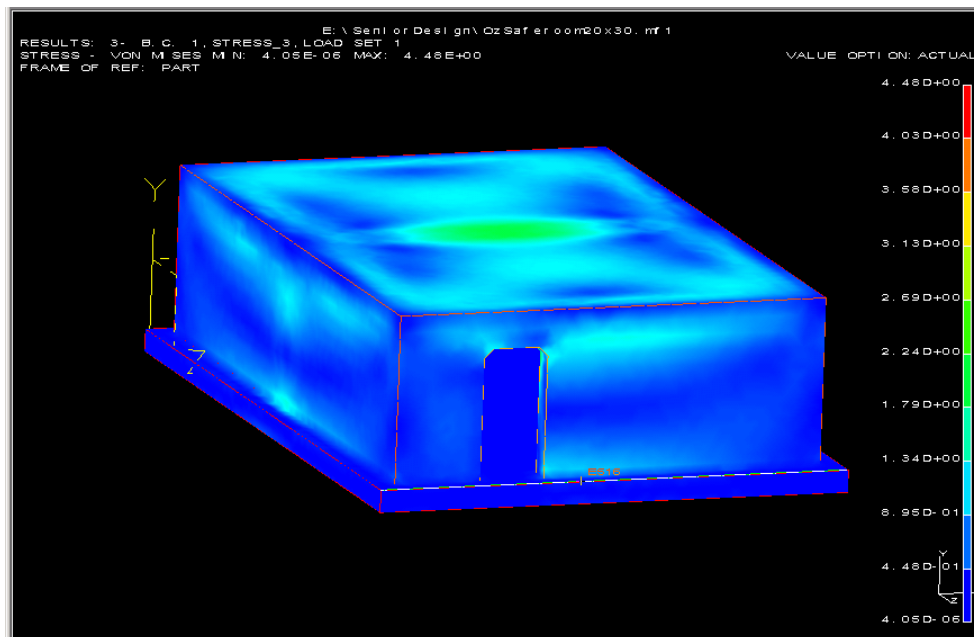


2500 lb Distributed Load (Static)
Maximum deflection = 0.000208 inches

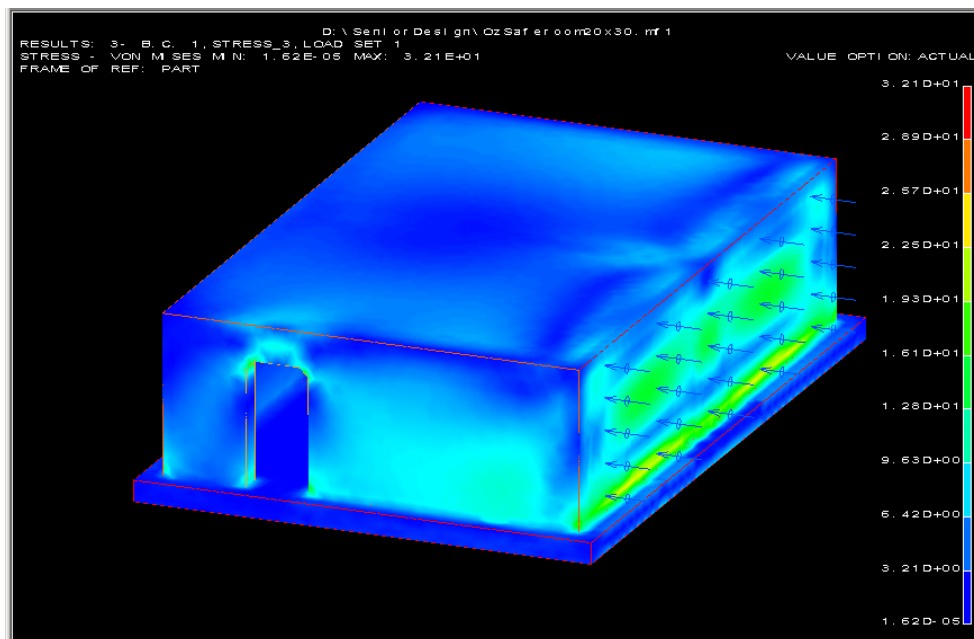


167 psf (1.1597 psi) Wind Pressure
Maximum deflection = 8.82×10^{-4} inches

12.4.3 Preliminary Stress Results

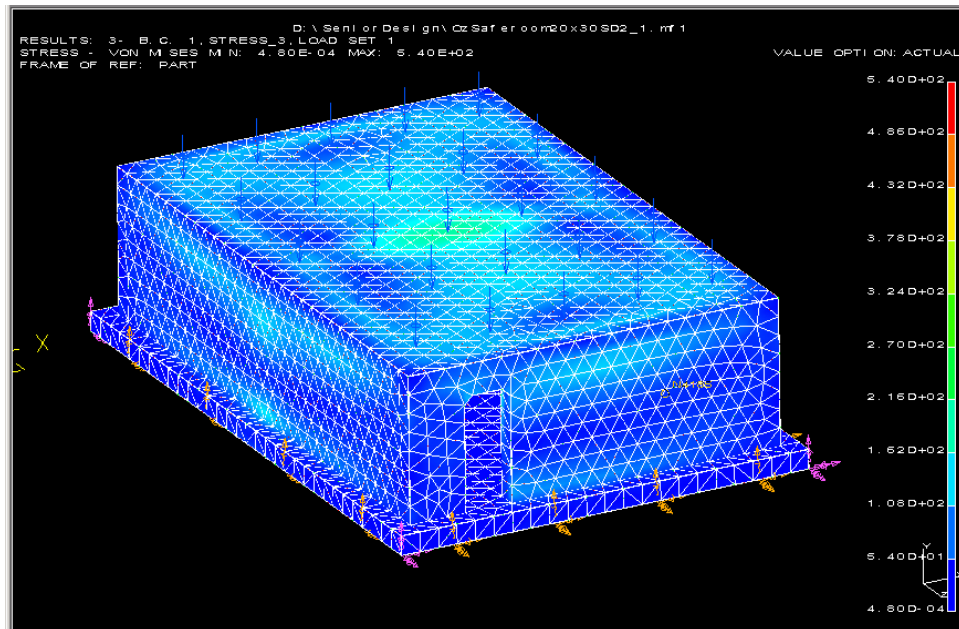


2500 lb Distributed Load (Static)
Maximum Von Mises Stress = 4.48 psi

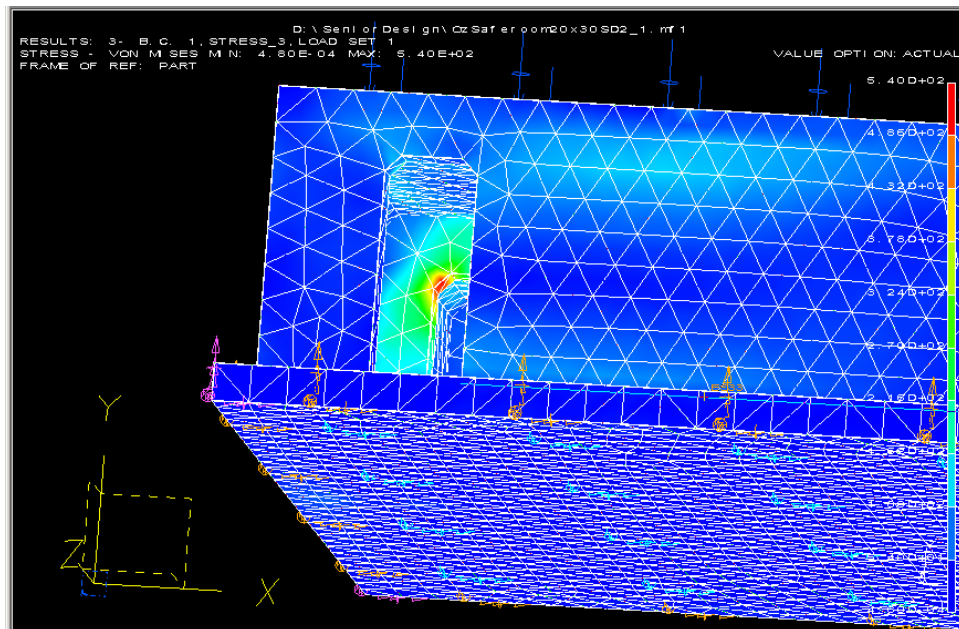


167 psf (1.1597 psi) Wind Pressure
Maximum Von Mises Stress = 32.1 psi

12.4.4 Failure Analysis – Roof

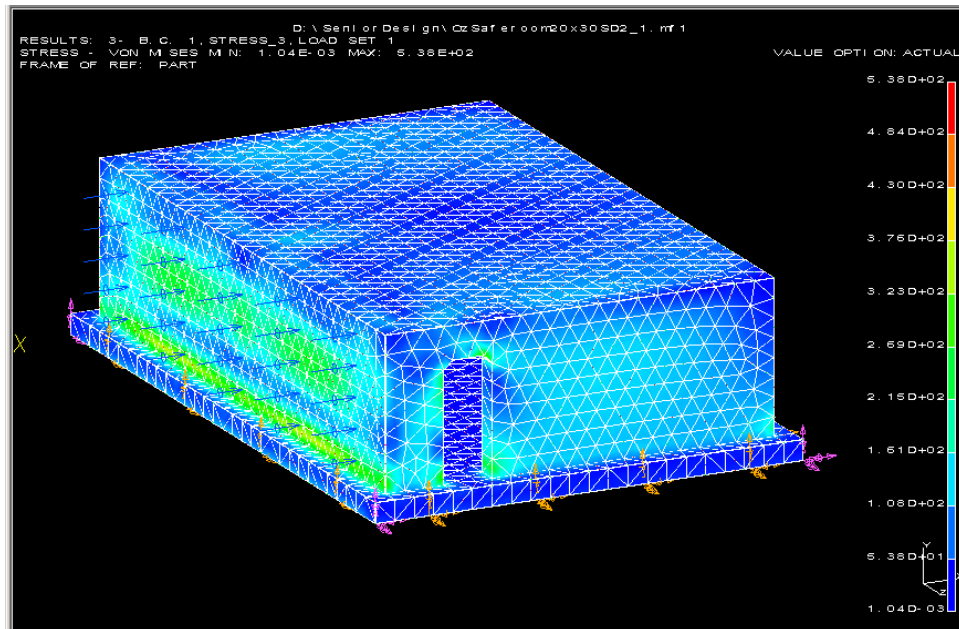


2.8 psi distributed pressure
Max stress = 540 psi

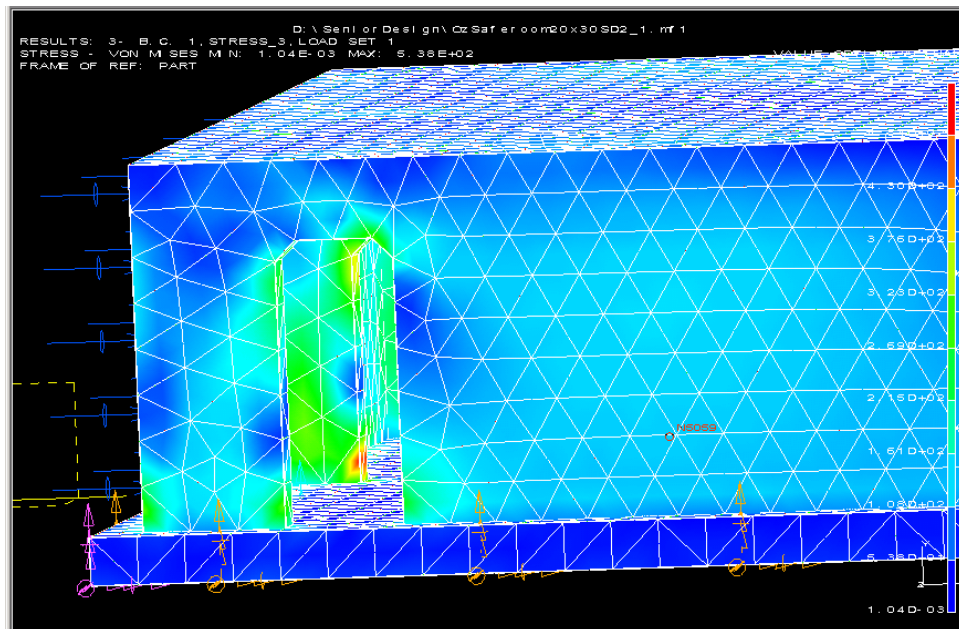


Max stress location (inner support members)

12.4.5 Failure Analysis - Wall



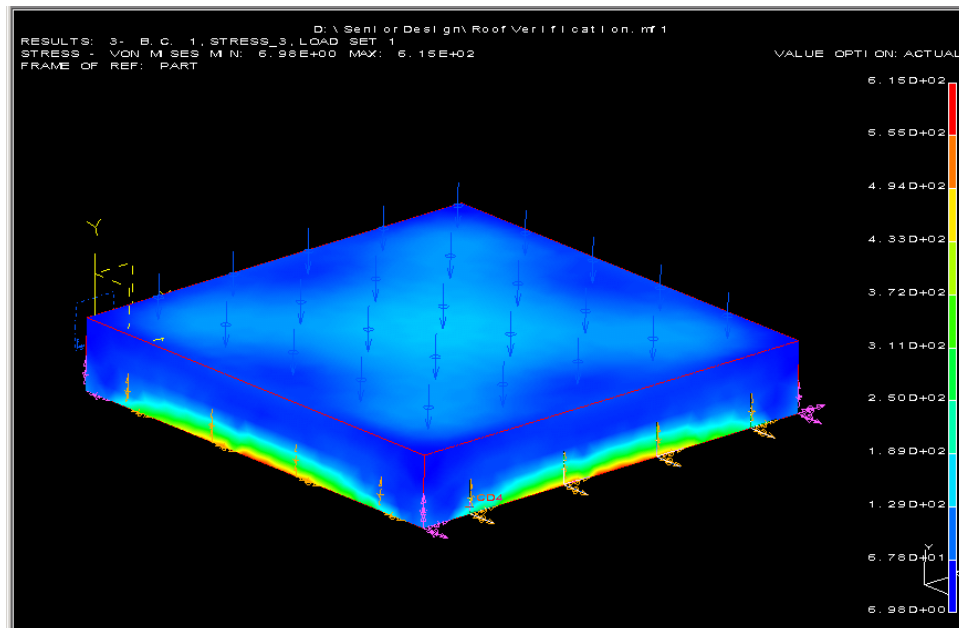
19 psi distributed pressure
Max stress = 540 psi



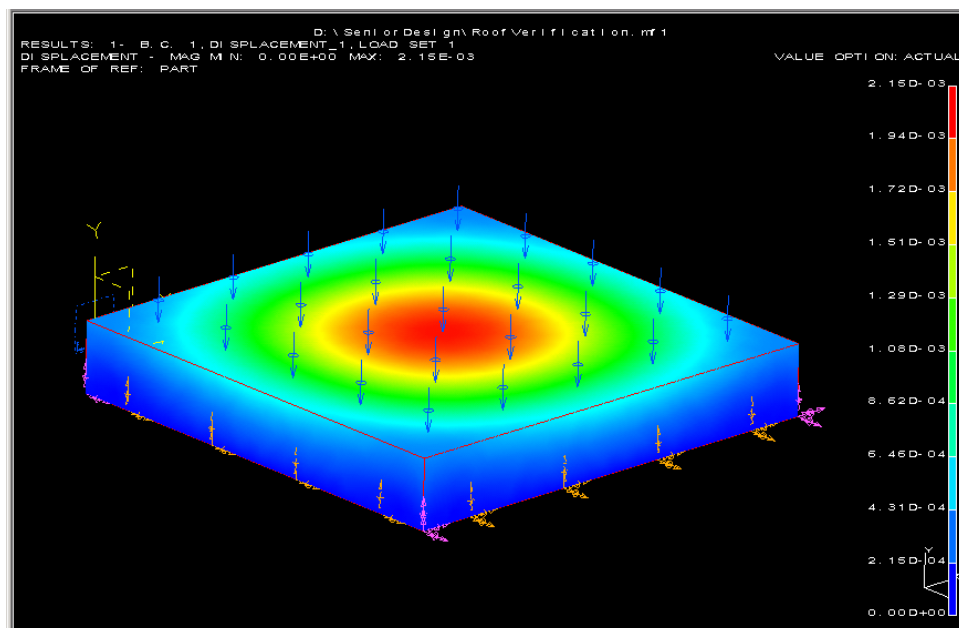
Max stress location (inner support members)

13 Appendix C

13.1 Finite Element Analysis – Roof Slab



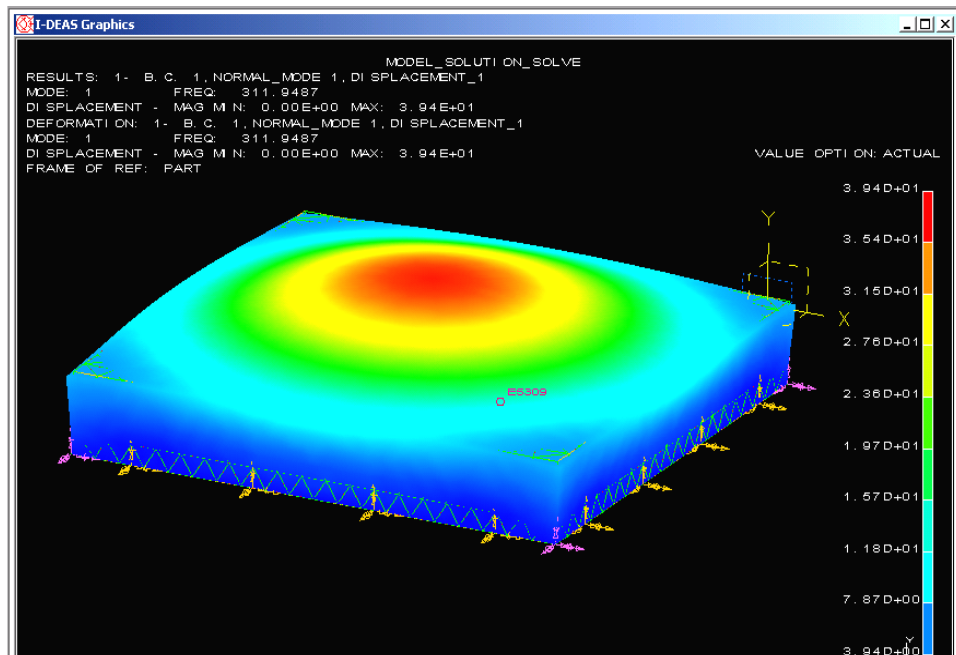
14.5 psi distributed pressure
Max stress = 615 psi



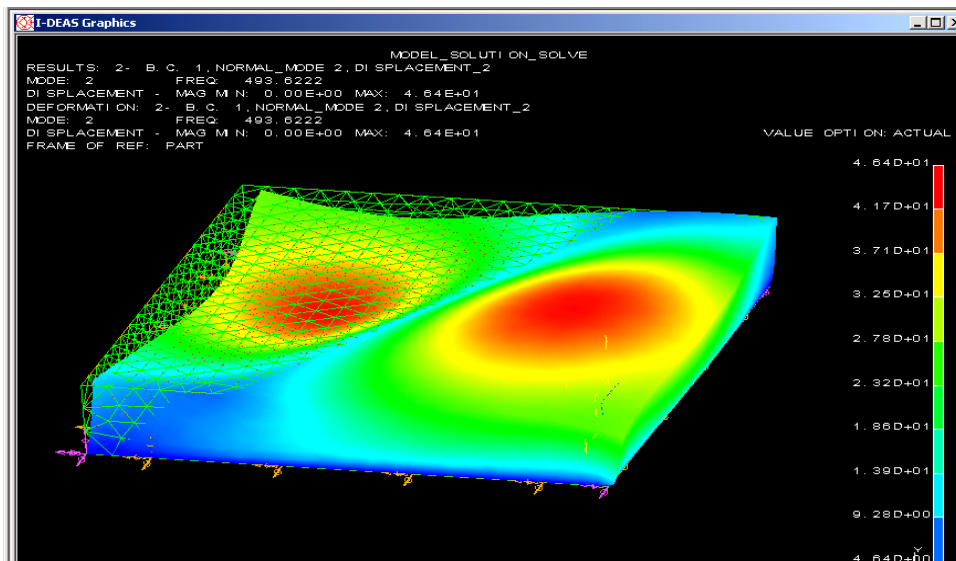
14.5 psi distributed pressure
Max deflection = .00215 in.

14 Appendix D

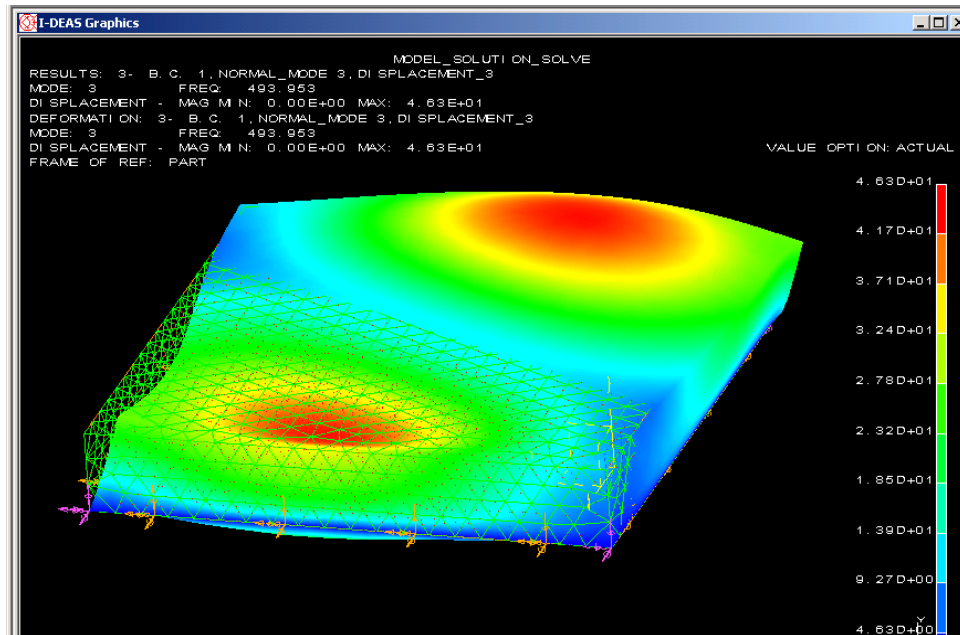
14.1 Modal Analysis of Roof using I-DEAS



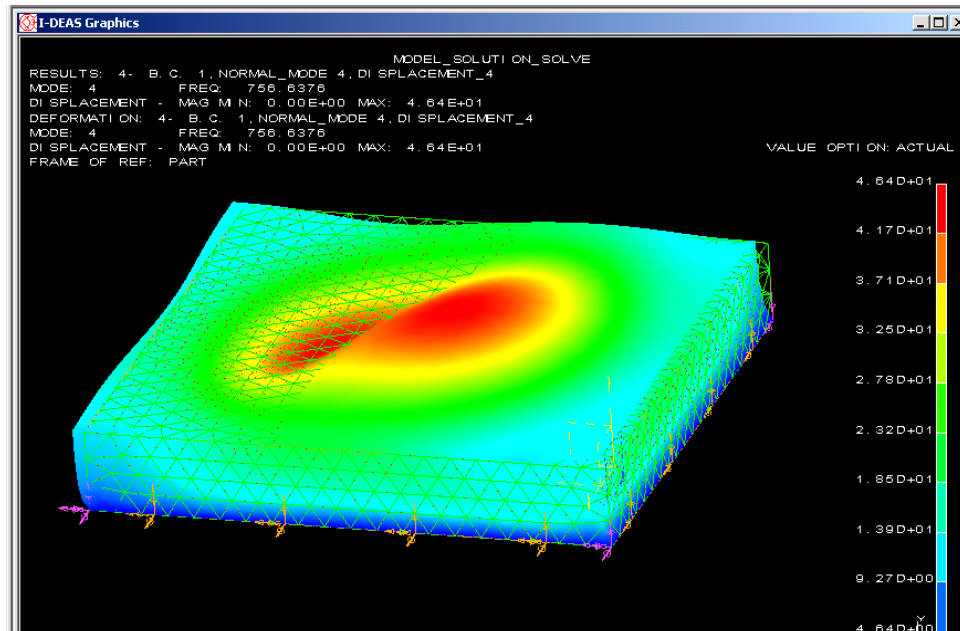
First mode frequency of 311.95 Hz



Second mode frequency of 493.62 Hz



Third mode frequency of 493.95 Hz



Fourth mode frequency of 756.64 Hz

15 Appendix E

15.1 MATLAB Code for Impact Testing Analysis

```
%%%% Finding frequency response and displacement

%load file1.txt
%t=file1(:,1);
%a=file1(:,2);
%fa=1/6000*fft(a(1:6000));

% determine frequencies

    fa = fft(a(1:6000));
for k = 1:6000;
    f(k) = k/(6000*.0001);
    frad(k) = 2*pi*(f(k));
    fv(k) = fa(k)/(i*frad(k));
    fx(k) = fa(k)/(i*frad(k))^2;
end;

%Displacement (m)
xx = ifft(fx(1:6000));
figure(1),plot(t(1:6000),real(xx)),xlabel('t (sec)'),ylabel('displacement (m)'),title('displacement')
figure(2),semilogy(f(1:300),abs(fa(1:300))),xlabel('freq (Hz)'),ylabel('|H(f)|')
figure(3),plot(t(1:2000),a(1:2000)),xlabel('t (sec) '),ylabel('accel (m/s)^2'),axis([4 4.2 -10 8])
```

15.2 Theoretical Hand Calculations

16 Appendix F

16.1 Concrete Sample Testing Procedure

Lab Procedure for Bending and Compression Tests

The purpose of this lab procedure is to lay out the necessary steps to test concrete samples for both compressive and bending strength. While there are two separate independent tests being conducted, the procedures for running them are similar. The only difference will be the fixture needed to mount the sample.

Powering Up

1. Start up the equipment by switching breaker panels #20-22-24 located near the door. Wait one minute for Tinius Olsen equipment to power up.
2. Turn on the computer switch on the main power strip located underneath the tower. Start Windows up as usual.
3. Once the apparatus is powered up, double click the “Tension” icon located in the top right of the screen.
4. In the Data Logger window, click on *File->Restore Logger Setup->c:\My Documents\vinnie.wlg*. Change the filename from *group1.WL* to an appropriate name for the experiment being conducted. Store the file in My Documents. The *Record* button will start collecting the data when the experiment is ready.

Equipment Setup

The model 398 DAQ System collects the data from the experiments. The control unit for the DAQ is placed next to the Tinius Olsen machine.

1. Clear out all previous test results by pressing the key sequence *menu 5-2-1-1*.

2. The DAQ has a series of pre-defined tests already stored in memory. The test needed for this experiment is test number 6. To access test number 6 press *menu-1-1-6-enter*.
3. Once the test program is entered, press *Clear* to reset the DAQ system (green button on it will light up), and the Test Status will display *Ready* mode. If the test status is *Idle*, press *Step* to go in *Ready* mode.
4. Zero out the DAQ by pressing *7-4-1-0* to reset all channels. The load and strain values should be zeroed out. There will be some noise that will cause a very small fluctuation in the reading even though nothing is happening.

Sample Setup and Test

Two separate tests will be run: 3-point bending and compression testing. The only setup difference between the two tests is the manner in which the samples are mounted in the machine. To test a sample:

1. Place specimen in the appropriate fixture.
2. On the Tinius Olsen control panel there is a dial control that varies the speed in which the top of the machine comes down. Bring the top down slowly until it is just beginning to apply a load to the sample.
3. Once the load has started, press start on the DAQ control panel and then quickly press record on the computer program to begin recording data.
4. Continue applying pressure until the specimen fails.
5. When the test is complete press stop on the computer screen.
6. Bring the top back up by reversing the directing lever on the Tinius Olsen machine.

7. Clean out the debris from the test and set up for the next sample.
8. Save the file from the previous run in *MyDocuments* and create a new file.
9. Repeat this procedure for all samples.

Data Analysis

The data acquired by the logger will be in hexadecimal format. This will be converted and implemented in Microsoft Excel.

1. To convert the data, open Excel and on the toolbar select *Data-Import Data-My Documents (file)*.
2. When the import text wizard appears, click on line seven and click next. Then select import as text to bring in the data. This is necessary since hexadecimal format is a series of letters and numbers.
3. Convert the data into a useful format by calling a function called “g.” To find the *g- function*, select *Tools-Macro-VB Editor*. This will bring up the Visual Basic editor.
4. Select *File-Import-My Documents/Tinius.bas*. This brings the g-converter into Excel.
5. To convert the data, make a column next to the data using the function g in each cell (i.e. Cell = g(A1)).

17 Appendix G

17.1 Mechanical Drawings

17.2 Spec Sheets

18 Appendix H

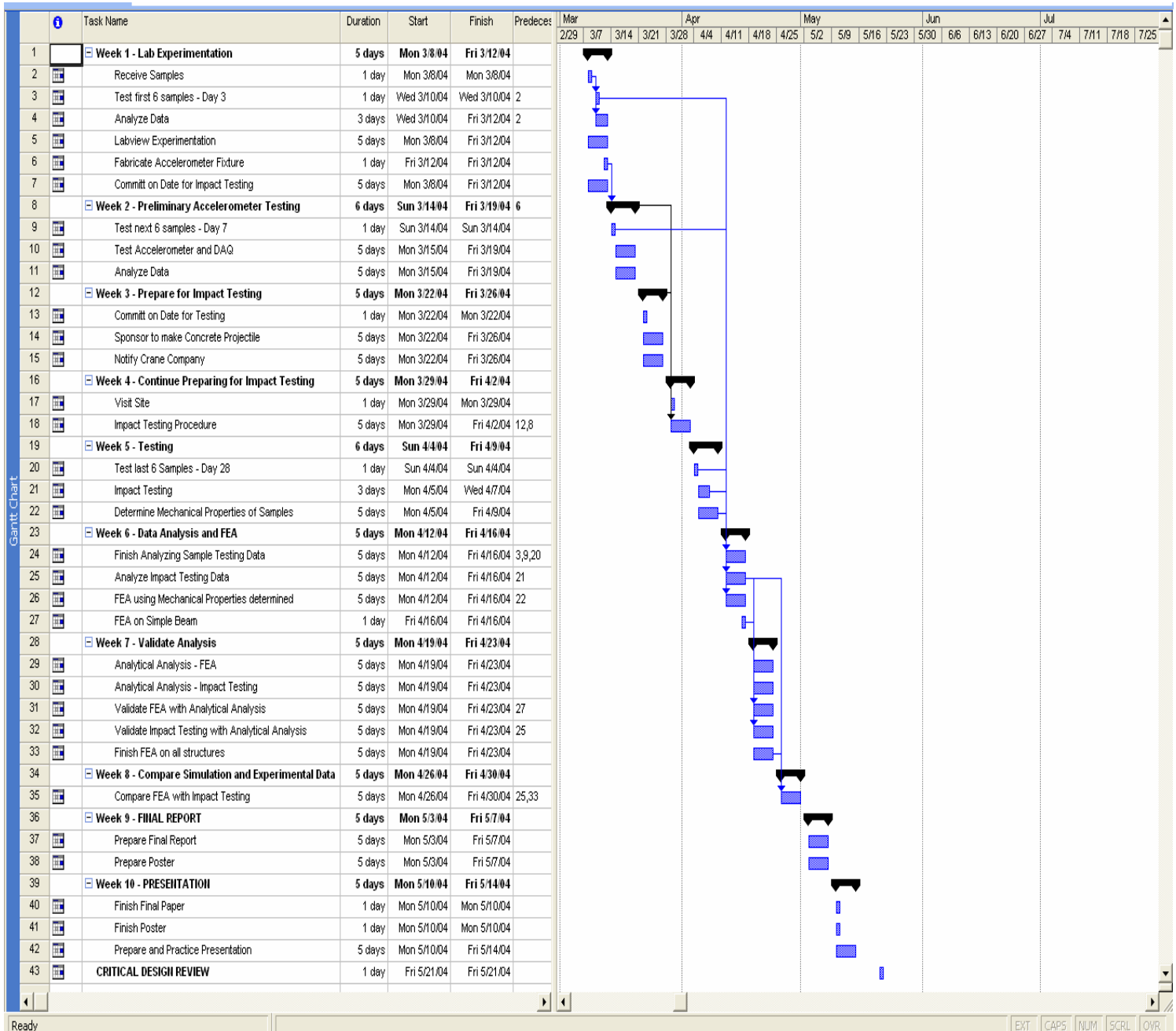
18.1 Bill of Materials

	P/N	Description	\$/per	Qty	Total	Supplier
Impact Testing	353B03	Accelerometer	\$256.50	3	\$769.50	PCB
	003EB100AC	Cable (100ft)	\$153.90	1	\$153.90	PCB
	-	Freight Charge	\$25.00	1	\$25.00	PCB
	6052E	PC Interface Card	-	1	-	National Instruments
	SCXI 1531	Signal Conditioner	-	1	-	National Instruments
	-	SCXI Chassis	-	1	-	National Instruments
	-	Labview Software	-	1	-	National Instruments
	081B05	10-32 Mounting Stud	-	1	-	PCB
	-	Accelerometer Fixture	-	1	-	RIT Machine Shop
	-	Crane	-	1	-	Sponsor
	-	Impact Load	-	1	-	Sponsor
		Misc. Supplies	-	1	\$13.45	Home Depot
	-	Misc. Supplies	-	1	\$19.85	Keystone Builders
Sample Testing	-	Tinius Olsen machine	-	1	-	RIT Mechanics Lab
	-	Computer	-	1	-	RIT Mechanics Lab
	-	6" diameter x 12" height cylindrical concrete samples	-	9	-	Sponsor
	-	14"x4"x4" concrete beam samples	-	9	-	Sponsor
	-	3 steel rods for three-point bending fixture	-	1	-	RIT Machine Shop
	-	Base Plate for three-point bending fixture	-	1	-	RIT Machine Shop

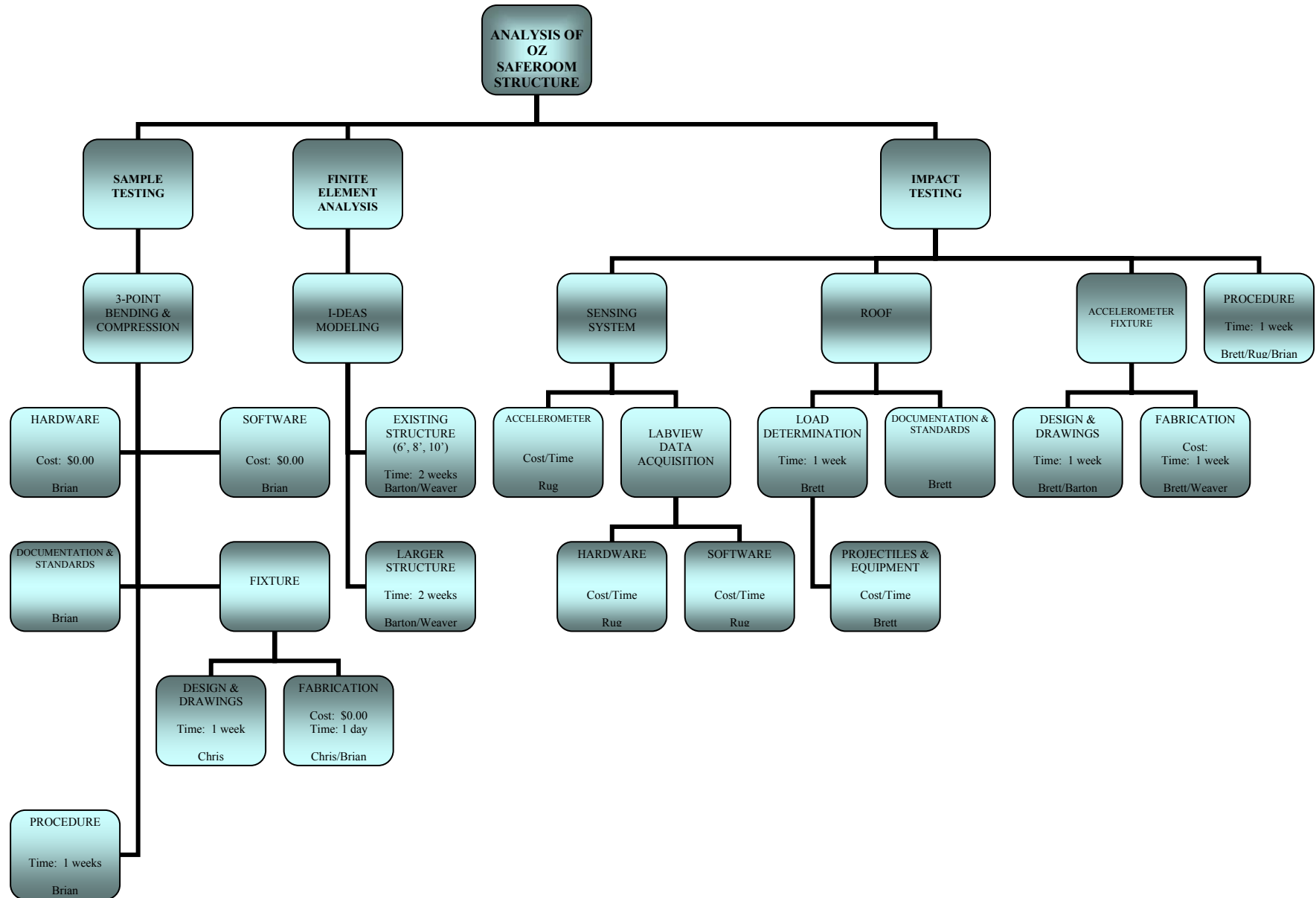
Total Cost: \$981.70

19 Appendix I

19.1 Gant Chart



19.2 Work Breakdown Structure



19.3 Design Structure Matrix

		1	4	5	7	8	10	2	3	9	21	22	23	24	6	18	11	12	13	14	17	19	20	15	16
Concrete Samples	1	1																							
Bending Fixture	4		4																						
Accelerometer	5			5																					
Load Determination	7				7	1																			
Projectile weight and height	8					8	1																		
Crane	10				1		10																		
3-Point Bending	2	1	1					2																	
Compression Testing	3	1							3																
Accelerometer mounting	9			1						9															
FEA - 6x6 structure with standard Prop.	21				1						21														
FEA - 8x8 structure with standard Prop.	22				1							22													
FEA - 10x10 structure with standard Prop.	23				1								23												
FEA - 20x30 structure with standard Prop.	24				1									24											
DAQ, Connections, etc.	6			1						1					6										
Determination of Mechanical Properties	18	1						1	1							18									
FEA - 6x6 structure with Mech. Prop.	11				1											1	11								
FEA - 8x8 structure with Mech. Prop.	12				1											1		12							
FEA - 10x10 structure with Mech. Prop.	13				1											1			13						
FEA - 20x30 structure with Mech. Prop.	14				1											1				14					
Preliminary Testing of Accelerometer	17			1						1					1						17				
Analytical Analysis	19				1											1						19			
Impact Testing Procedure	20			1	1	1	1			1					1								20		
Validate FEA	15																					1		15	
Validate Impact Testing	16														1							1			16

