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EXPERIMENTATION AND STRUCTURAL ANALYSIS OF OZ SAFEROOMS

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ABSTRACT

This project focuses on the structural analysis of OZ Saferooms. OZ Saferooms are continuously poured steel-reinforced concrete structures designed to withstand natural disasters. This project will assist Zagorski Forms Specialists, Inc. by providing them with structural analysis and experimental impact testing data to help validate the structural integrity of the OZ Saferoom product. The scope of the project will include the design of a sensor package which is capable of measuring the deflections associated with an experimental test of an OZ Saferoom. Furthermore, finite element analysis of an existing OZ Saferoom, as well as other specified structures will be delivered to analyze their stability after being subjected to tornado-like conditions.

INTRODUCTION

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 [1]. OZ Saferooms are monolithic concrete structures, built with no joints or seams, designed to withstand natural disasters. The OZ Saferoom shown in Fig. 1 is 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.

CONCRETE SAMPLE TESTING

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. 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.

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 [2]. The three-point bending concept and fixture is shown below in Fig. 2.

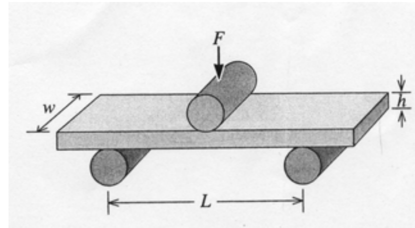

Figure 2: 3-Point Bending Setup

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 [3]. The averages of all the sample weights, maximum loads, and flexural strengths can be seen in Table 1.

$$\sigma_{\text{bend}} = \frac{3FL}{2wh^2} \quad (1)$$

	W (lb)	Load_{max} (lb)	σ_{bend} (psi)
AVG =	19.075	2528	711
STDDEV =	0.121	501	141

Table 1: 3-Point Bending Results

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. [4]

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

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 5 samples were tested at CME Associates, Inc. (located in Rochester, NY) and the results can be seen below. These test results in Table 2 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

Table 2: Compression Testing Results

Data Analysis

From the geometry and weight of the cylindrical concrete samples, the mass density, ρ, was calculated to be 141 lb/ft^3. According to MacGregor [5], for concrete with a density of 145 lb/ft^3, ACI (American Concrete Institute) Sec. 8.5.1 gives the modulus of elasticity as

$$E_c = 57{,}000\sqrt{f'_c} \qquad (3)$$

where f'_c is the compressive strength in psi. From the average compressive strength of 8,034 psi shown in Table 2, the modulus of elasticity of the concrete is 5.11 x 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.

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) is a numerical analysis method which calculates the response of a model by solving a set of simultaneous equations that represent the behavior of the structure under loading. FEA is used to analyze the performance of engineering designs. It is also used to find areas of maximum and minimum stresses and strains of the design being tested.

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.

Finite Element Failure Analysis

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 [5] defines the modulus of rupture for use in strength calculations as

$$f_r = 6\sqrt{f'_c} \qquad (4)$$

The resulting modulus of rupture or tensile strength was 538 psi. 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 psi ± 141 psi. The value calculated in equation 4 will be used in the FEA, as it corresponds to the worst case scenario found in the experimental analysis.

Figure 3 and 4 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 Table 3.

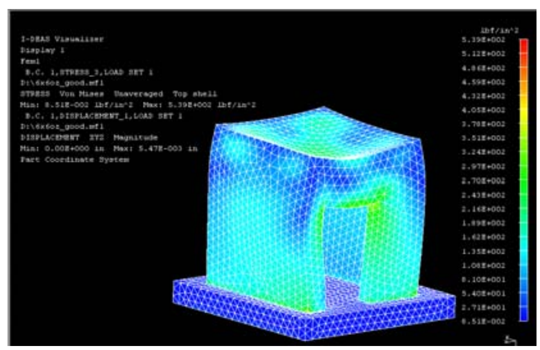

Figure 3: 38 psi load applied to the roof

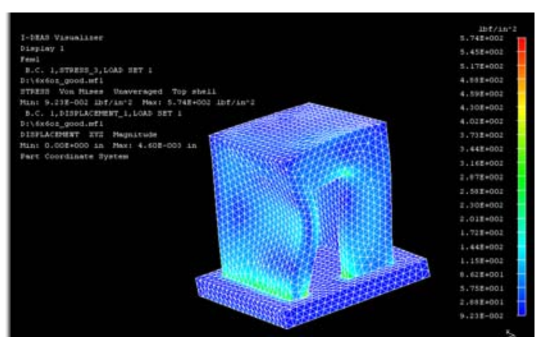

Figure 4: 5.5 psi load applied to the wall

Structure	Applied Pressure - Roof (psi)	Von Mises Stress (psi)	Applied Pressure - Wall (psi)	Von Mises Stress (psi)
78 in. x 78 in. x 92 in.	38	539	5.5	574
102 in. x 102 in. x 92 in.	21.5	545	6	610
126 in. x 126 in. x 92 in.	15.5	544	7	542
240 in. x 360 in. x 92 in.	2.8	540	19	538

Table 3: 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.

Simulated wind loads of 250 mph (F5 tornado) were also applied to the walls of each structure, and the resulting stresses are found in Table 4. As you can see, 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

Table 4: 250 mph wind pressure analysis

YIELD LINE ANALYSIS

An analysis was performed on the existing 78 in. cubic structure using Johansen's Yield Line Analysis [5]. 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.

$$\frac{wL^2\delta}{3} = 8m\delta \qquad (5)$$

where L is the length of the slab, w is the uniform distributed load, δ 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 lbs.).

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 tensile strength of 538 psi. The finite element model was not reinforced because of the limitations in available computing power. In comparing a slab with and without rebar, a difference of 15% in ultimate strength can be accepted.

IMPACT TESTING

Impact testing was performed on the existing 78 in. cubic structure in order to acquire its deflection and frequency response data. This data was then compared with finite element analysis to verify the models and results were correct.

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 Fig. 5, 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 uniform distributed load, is 0.00547 in. With rebar, the tensile strength of the structure is increased, yielding an even higher required impact load. The 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 Fig. 6.

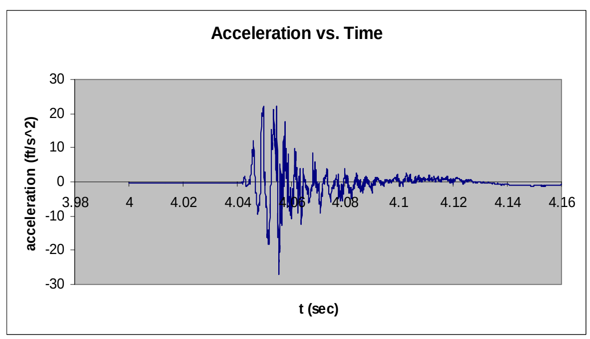

Figure 5: Acceleration signal from impact test

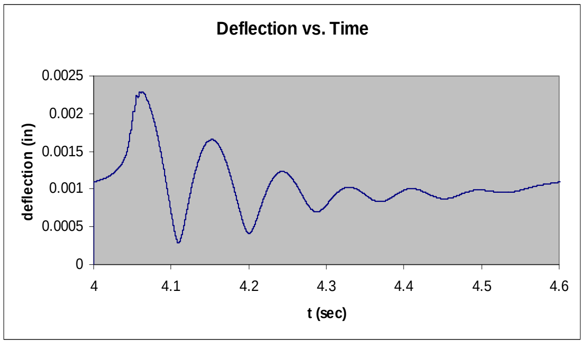

Figure 6: Roof's deflection

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 ft. x 3 ft. 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. The impulse-force equation

$$F = \frac{\Delta p}{\Delta t} \qquad (6)$$

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.

Frequency Analysis

In order to form another basis of comparison between the finite element model and the actual test results, the frequency responses were 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 315 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 315 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 Fig. 7 and 8, respectively.

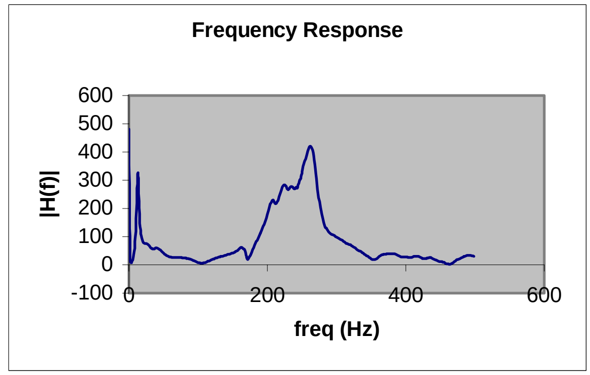

Figure 7: Frequency content of impact test

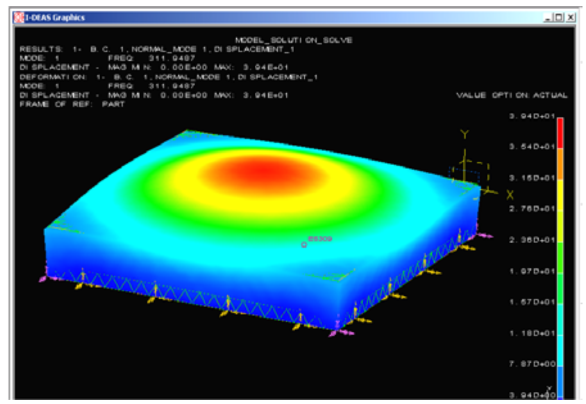

Figure 8: Frequency of the first mode shape

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.

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.

Following yield line analysis [5] 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 Fig 9. 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 shown below.

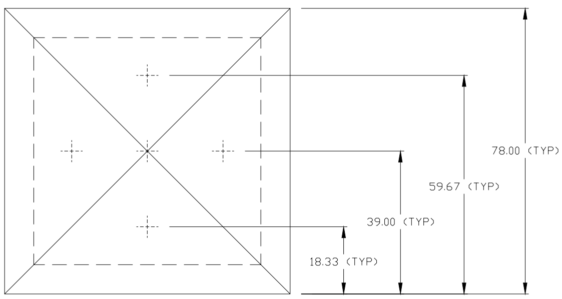

Figure 9: Accelerometer Locations (Note: all dimensions in inches)

Data Acquisition Equipment

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

P/N	Description	QTY	Supplier
353B03	Accelerometer	5	PCB
003EB100AC	Cable (100ft)	5	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
-	Computer	1	-
91592A205	Anchor Bolt	5	McMaster-Carr
-	Wire Tie	-	-

Table 5: Sensor package items

CONCLUSION

Both the FEA and impact test yielded results that were in agreement. The structure is able to withstand typical tornado debris and is capable of withstanding four times the impact of the most severe debris. Although the purpose of this project is not to advise the builders of OZ Saferooms in construction, it may be in their interest to reexamine the design of the structure and optimize its thickness. The sensor package designed will allow any structure to be examined and will be useful in measuring actual tornado impacts.

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- CME Associates, Inc.
- Prof. John Wellin
- Dr. Kevin Kochersberger
- Dr. Abi Aghayere

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