Finite Element Analysis of Slope Face Storm Shelter

Technical Report Submitted to
OZ Saferooms, Del City, OK.
By

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October 2017

Abstract

Abandoned vehicles sent into projectile motion are potential threats to saferooms during a tornado. The main goal of this dynamic Finite Element Analysis is to better understand how well a slope face storm shelter can withstand damage from a vehicular impact and compare the results to an OZ saferoom of different geometry. The analysis would determine whether the concrete-based structures could withstand the collision under the testing requirements of the NCAC/CCSA.

This report analyzes the slope face shelter with two unique internal rebar structures, one measuring 12” between rebar straights, and the other measuring 14” between them. The slope face shelters maintained a roof thickness of 4” while the OZ saferoom had a roof thickness of 18”. All simulations tested the impact of a Chevrolet C2500 pickup truck with an initial velocity of 35 mph dropped vertically overtop the shelter. The truck was given a tilt angle of 20° from the vertical axis to emulate a more realistic drop scenario. A secondary lateral simulation was run to provide further insight on the shelter’s effectiveness.

The slope face shelter was first modeled in Solidworks and exported to ANSYS simulation software. In ANSYS, body interaction characteristics, contact parameters, boundary conditions, and meshes were defined. The model was then exported to LS-DYNA, where the simulation was given initial conditions and tested.

The simulations show that both slope face shelter models were unable to withstand the impact of the airborne truck without collapsing. The roofs suffered heavy damage in their centers and cracks propagated outward towards the corners of the shelters. Such a structural collapse could potentially cause harm to persons inside. Conversely, the OZ saferoom withstood the vehicular impact. Similar results were seen in the lateral tests. However, the maximum displacement was not as great in the lateral simulations since the truck’s impact area on the roof was increased and the forces associated with the impact were more dispersed.

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1. Numerical Methods

The numerical material models simulated in this report track the time history of damages and displacements for individual elements and global geometries. Through these simulations, one can compare the impact damages visually and quantifiably for a greater understanding of how the shelters perform in real-world conditions. These models were run in industrial standard software ANSYS release 17.2 and LS-DYNA PrePost 4.3-x64, according to parameters published in the scientific literature. Simulations take many hours to accurately capture data on element-by-element relationships and other material-based properties over finite, discrete time intervals. Stringing the static data together, it is possible to visualize the impact dynamically.

All simulations employ the Riedel-Hiermaier-Thoma model built into ANSYS for the concrete material properties (MAT-272). For the rebar structure encased within the shelter, the default steel properties from ANSYS were selected (MAT-001). These ANSYS-generated materials apply the properties for compressive, shear, and tensile stresses into the model for an accurate representation of the system response.

LS-DYNA was used to run the simulation as well as process the results in post-simulation. The program is comprised of LS-PrePost and LS-PostProcessor, which analyze the model at different phases of the simulation process. An analysis of the post-processed damage results, including graphics of the slope face shelter and comparisons to the OZ saferoom simulation, is included in the Results section of this report.

2. SolidWorks 2015

A SolidWorks 3D model was constructed for the 6' x 8' Slope face shelter according to specifications provided by OZ Saferooms Technologies. Dimensional drawings are shown in **Figure 2.1** below. For the purpose of displaying the shelter's general size and shape, some dimensions were omitted. Notice that there is a taper angle to the base's vertical walls of 2.14° and another taper angle to the top's vertical faces of 1.9°. The ventilation holes on the shelter roof have diameters of 8" and 6" respectively [1]. Soil was modeled to add soft compression to the contact between the ground and shelter, increasing the accuracy of the dynamic simulation.

The model is comprised of three separate components. The top of the shelter is glued and bolted to the recessed bottom structure at a seal joint [1]. The door was modeled as a steel plate and rests in the opening at the top of the shelter. For additional details, an exploded view of the assembly can be seen in Appendix 1.

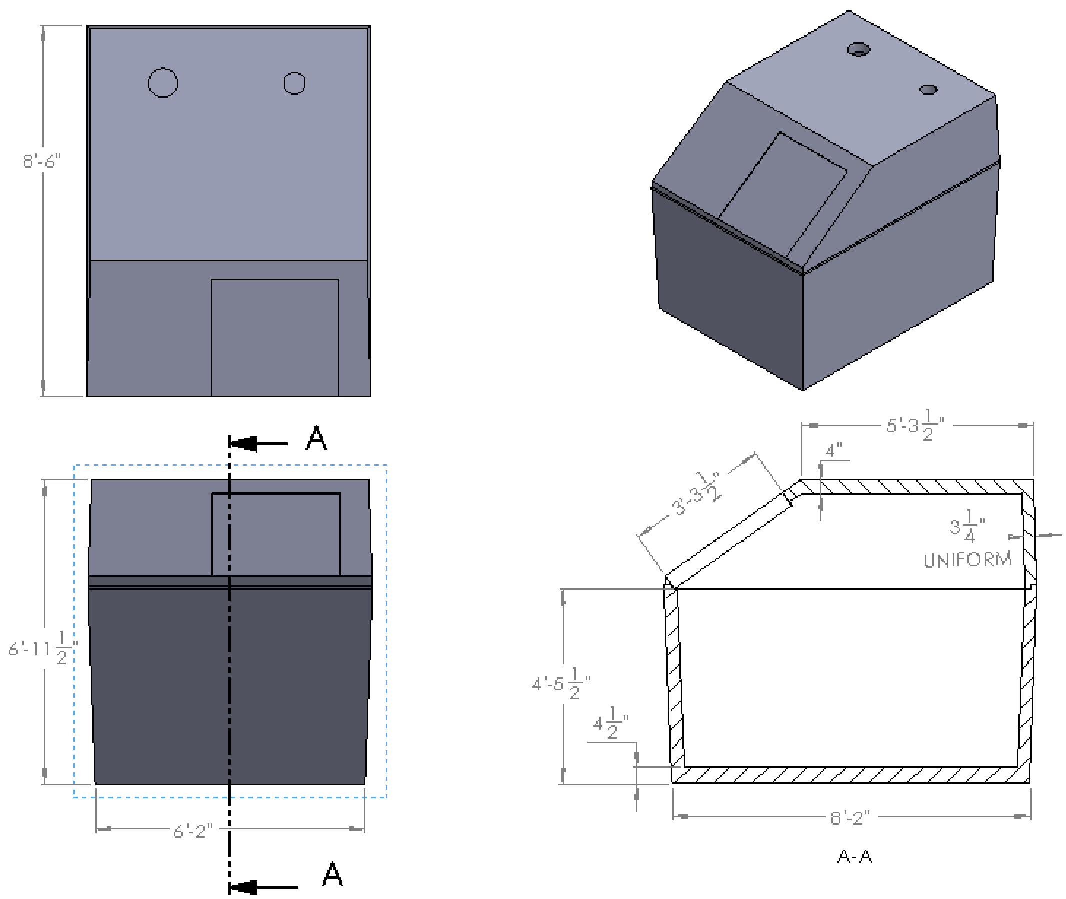


Figure 2.1: SolidWorks model for the slope face tornado shelter. Rebar is not included in this model. The base of the design is submerged below ground during implementation. The soil is not included in this image for clarity. General dimensions are provided for an understanding of the design scale.

3. ANSYS MODEL

Once the SolidWorks model was created, it was imported in ANSYS 17.2 and meshed to create the elements and nodes that would be analyzed in LS-DYNA. **Figures 3.1.1** and **3.1.2** show the ANSYS model without and with meshing.

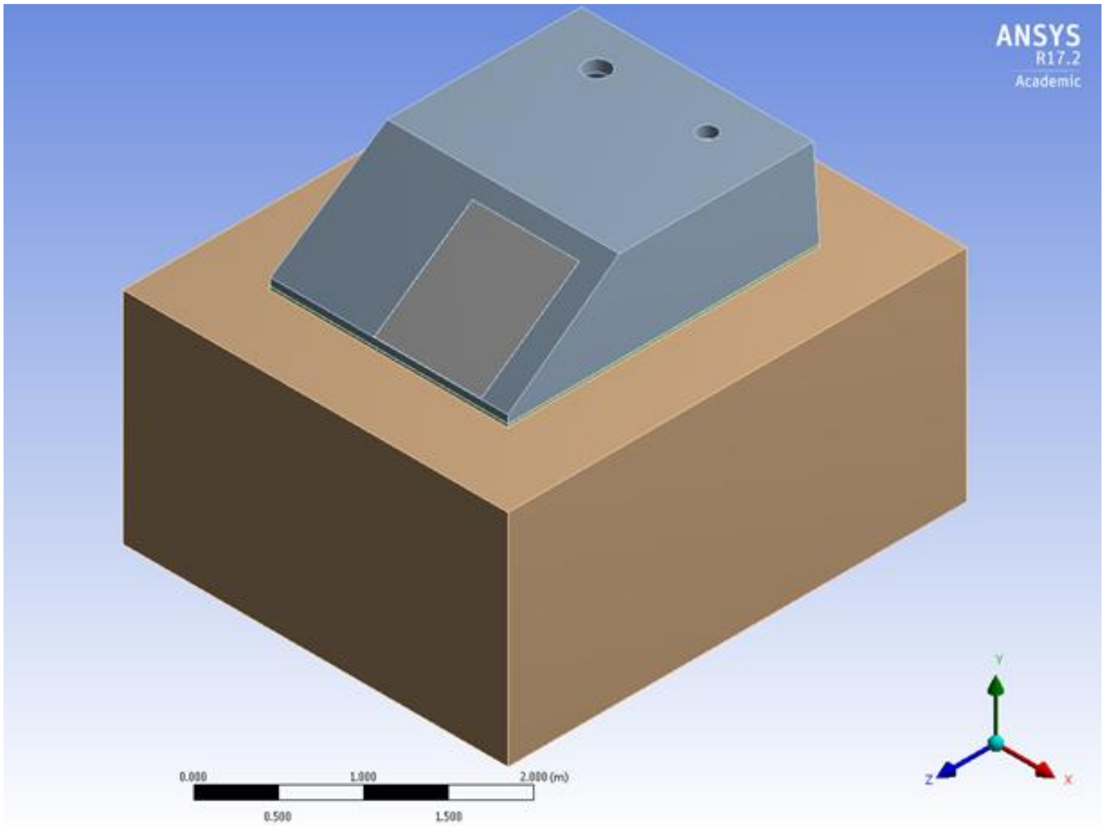


Figure 3.1.1: ANSYS model for the slope face shelter. Meshing not shown in this visual.

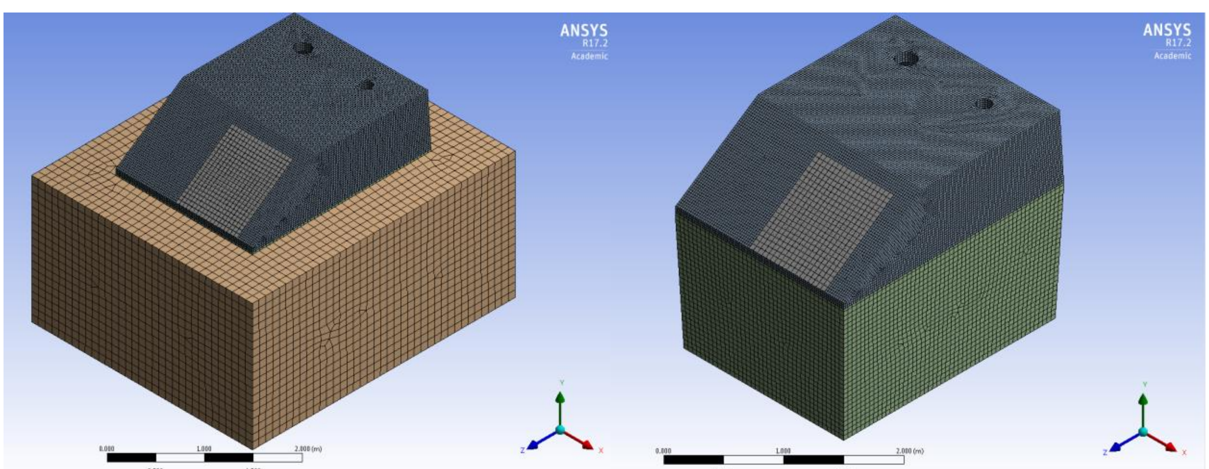


Figure 3.1.2: ANSYS model for the meshed slope face shelter. The model is shown with soil (left) and without (right).

In ANSYS, a mesh that provided clean hexahedral elements and minimal lattice imperfections on the top surface was required. **Figure 3.3.1** and **Figure 3.3.2**, shown on the following page, display the cross-sectional lattice and top surface lattice of the shelter, respectively. **Table 3.2** presents the parameters used to mesh the respective shelter components along with the corresponding element quantities. Notice that the soil, door, and base were assigned meshes of larger lattices since they were less critical to the impact analysis. This translates to more accurate results in the impact zone while reducing computational time.

Body interaction characteristics were then assigned to the different interfaces of the shelter. The base interfaces with both the top and soil through frictional contact, whereas the door and top interface through bonding contact. A value of 0.2 was applied for both frictional and dynamic coefficients. The simulation was assigned a run time of 0.15 seconds and a program-controlled time step. For boundary conditions, a no displacement condition was applied to all faces of the soil and standard Earth gravity (-9.8066m/s^2) was applied to the center of the shelter.

Table 3.2: ANSYS Meshing Parameters

Component	Element Size [mm]	Number of Elements
Top	23	114008
Door	50	1363
Bottom	50	17961
Soil	100	18424
	Total	151756

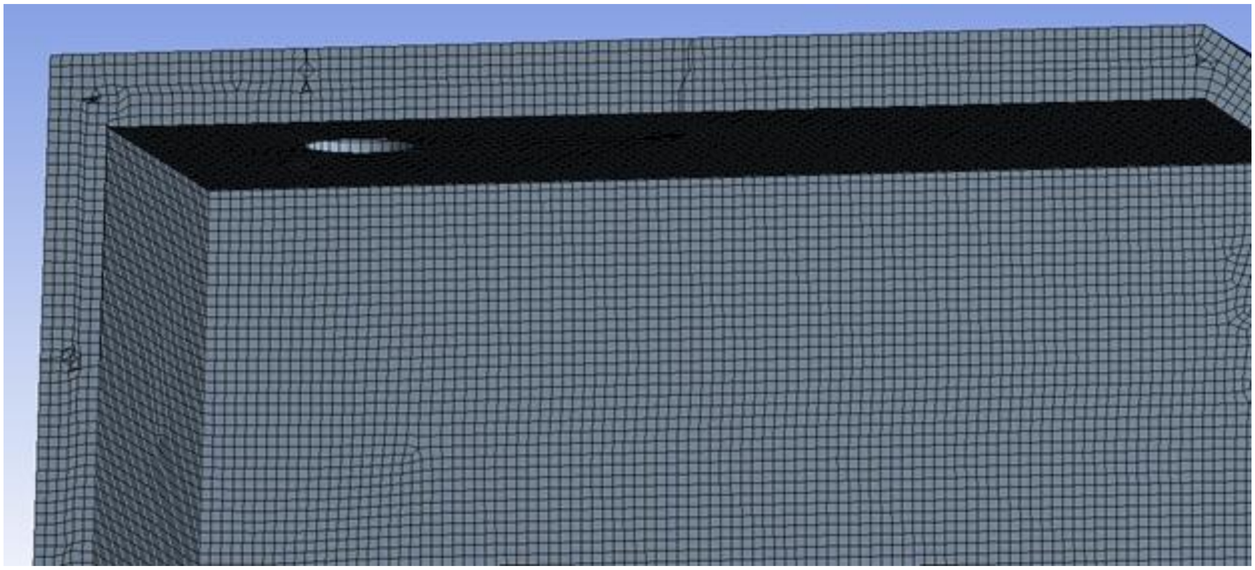


Figure 3.3.1: Cross-sectional view of the meshed lattice, positioned at the inside corner of the roof of the Slope face shelter . Note that it is predominantly hexahedral with few lattice imperfections.

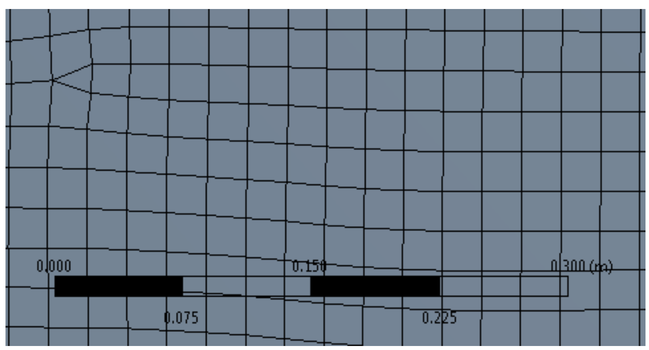


Figure 3.3.2: View of the meshed lattice on the top surface of the Slope face shelter. Note that the mesh is predominantly hexahedral with few lattice imperfections.

4. LS-DYNA MODEL

The ANSYS-meshed model was imported into LS-PrePost 4.3-x64 where the internal rebar was constructed within the geometry. One of the Slope face shelter models was created with 12" gaps between peripheral rebar straights and the other with 14" gaps between them. The rebar elements followed the specifications from the slope face shelter datasheet, indicating that the bars were to lie within a ½" tolerance of their identified locations. The rebar elements were also constrained to be 1" from the outer vertical walls, 2 ¼" from the outer bottom surface, and 1" from all inside surfaces [1]. The #4 rebar was given a diameter of 0.5" and conformed to the ASTM A615 [2] standard for reinforcing steel. The rebar was constructed in a cage-like fashion, with all peripheral straights connected, including at each corner. Additional properties were assigned according to **Table 4.1** below.

Table 4.1: Slope face shelter Simulation Parameters of Vehicle Drop Simulation

Group	Name	Value	Unit	Notes
Top	Width (X)	76	in	eqv. 1930 mm
Top	Length (Z)	63.5	in	eqv. 1612 mm
Top	Thickness (Y)	4	in	eqv. 102 mm
Bottom	Width (X)	74	in	eqv. 1880 mm
Bottom	Length (Z)	98	in	eqv. 2489 mm
Bottom	Thickness (Y)	4.5	in	eqv. 114 mm
Rebar	Diameter	#4	Gauge	eqv. 0.5" OD
Rebar	Grade	40	ksi	eqv. 276 MPa
Door	Thickness	12	Gauge	eqv. 2.66 mm
Door	Strength	>36	ksi	eqv. 276 MPa
Concrete	Compressive Strength	>6000	psi	at 28 days

Note that the Top only includes the unsloped surface area.

A Chevrolet C2500 model, developed by the NCAC/CCSA [3], was then imported and aligned in the model for crash impact analysis. **Figure 4.2** illustrates the detailed vehicle model tested in this report. The detailed model contains internal design structures such as the vehicle's seats, as well as an accurate weight balance for impact testing.

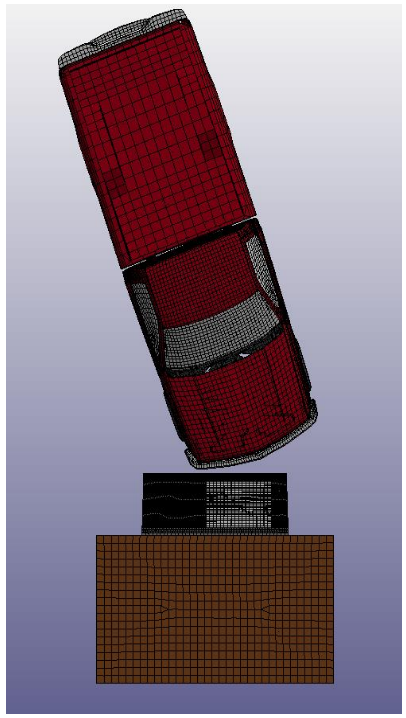


Figure 4.2: Chevrolet C2500 detailed design model provided by the NCAC/CCSA [3]. The truck was given a 20° tilt angle from the vertical axis.

The vehicle was positioned 2.16" above the top surface of the Hausner shelter in ANSYS. The truck's center of mass was located overtop the shelter roof and the vehicle was assigned a 20° tilt from the vertical axis to emulate a realistic impact scenario.

Initial conditions and various material and testing parameters were assigned to the combined model. An initial velocity of 35 mph was given to the truck, as though it had been launched by the heavy winds of an EF5 tornado. It was determined that acceleration would have negligible impact on the speed of the vehicle over such a small distance, so gravity was ignored to speed up the time of computation.

The shelter roof contained 114,000 elements for both the 12" and 14" models. The effective volume of the horizontal slab of the roof was consequently 0.317 m^3. This slab would be the surface most directly affected by the impact. **Table 4.3** defines the distribution of system elements along with the material properties assigned to the shelter, soil, rebar, and door. LS-DYNA's Mechanical Solver was used to run the simulation and write the output binary files for post-processing. The files created were approximately 11.6 MB in size and the simulations took roughly 100 hours to run each.

Table 4.3: Initial Conditions and Material Properties of Vehicle Drop Simulation

Group	Name	Value	Unit	Source	Notes
Vehicle	Mass	1923	kg	NCA/CCSA	eqv. 4,250lb
	Initial Velocity	15646	mm/s	NCA/CCSA	eqv. 35mph
Concrete	Compressive Stress	34.5	MPa	LS-DYNA	RHT concrete
	Relative Shear Strength	0.18	-	LS-DYNA	RHT concrete
	Tensile Force	0.18	MPa	LS-DYNA	RHT concrete
	Shear Elastic Modulus	0.7	GPa	LS-DYNA	RHT concrete
	Density	2.3	Mg/m^3	LS-DYNA	RHT concrete
Soil	Density	2.35	Mg/m^3	FHWA [5]	FHWA Nebraskan soil
Truck FE Model	Detailed Truck Model	58313	No. Elements		
12” FE Model	12" Top Only	114008	No. Elements		
	12" Shelter (no soil)	134382	No. Elements		
	Entire 12" Model	210656	No. Elements		
14” FE Model	14" Top Only	114008	No. Elements		
	14" Shelter (no soil)	141836	No. Elements		
	Entire 14" Model	218573	No. Elements		
Simulation	Runtime	100	h		Approximate

5. RESULTS

A total of 24 simulations were run in LS-DYNA to achieve consistent and reasonable results and to evaluate whether there was a slight possibility that the Hausner shelter could withstand the impact. The 12-inch and 14-inch rebar models were also compared to examine whether there were any large discrepancies between the two models. RHT model History Variable #4 tracks the accumulation of plastic strains and corresponds to zones where model elements are failing. In this section, a summary of these simulations is presented and History Variable #4 is shown on the right hand side of each figure. A History Variable #4 value of 1 indicates failure of an element, while a value of 0 indicates no damage.

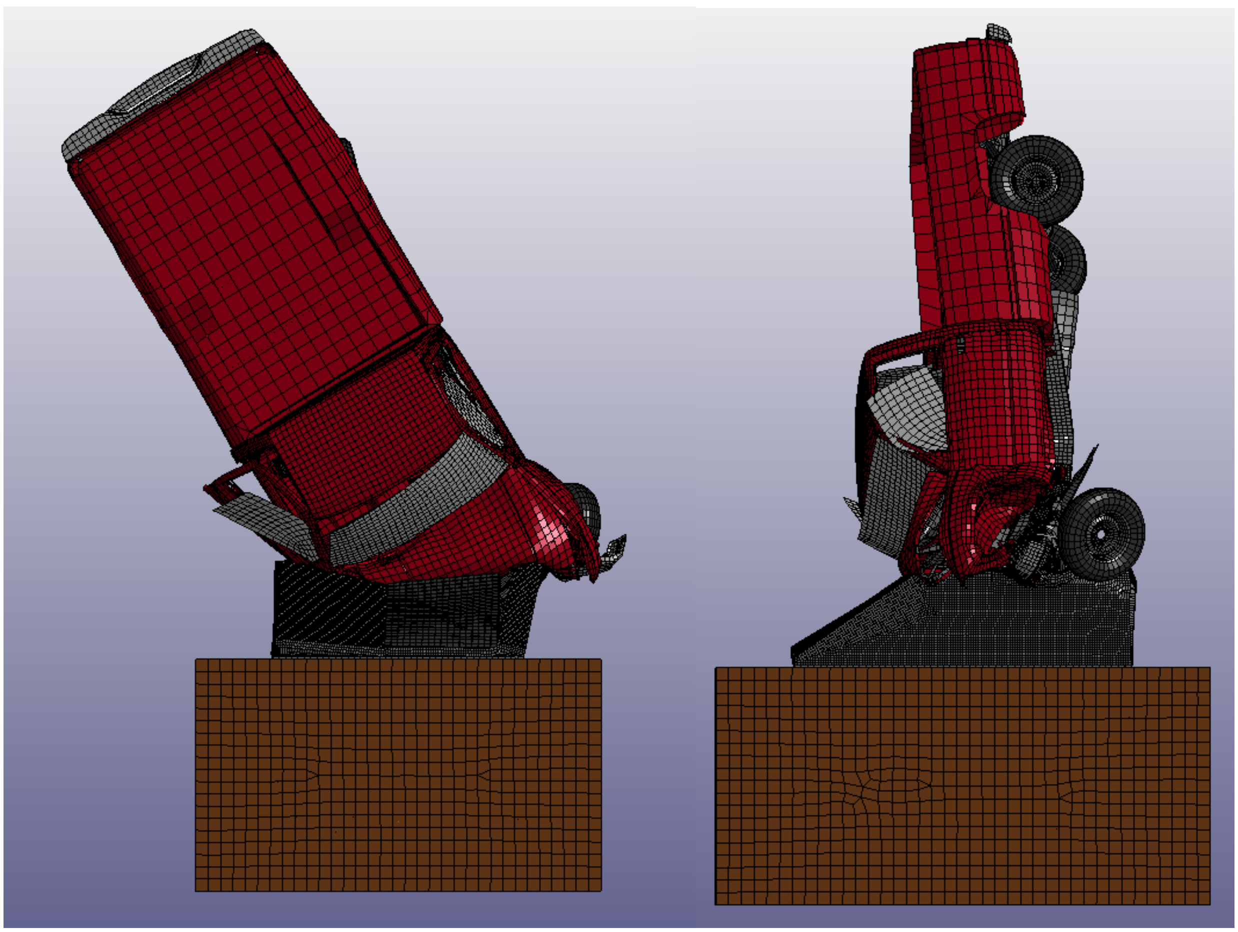


Figure 5.1: Post-simulation collision of the pickup truck into the slope face shelter.

5.1 20° Drop Test on the 12-Inch slope face shelter Rebar Model (12" Run 6)

This simulation was performed with the same parameters used in the OZ Saferoom analysis [6]. Results show that the roof of the 12" rebar model failed from the center, with cracks propagating outward toward the corners of the structure, typical of reinforced concrete failure. Damage was also seen at the perimeter of the concrete structure as the weight began to accumulate on the rooftop and put pressure on the surface. The roof displayed visible deflection, indicating the beginning of a collapse in the design. Holes formed by the end of the simulation, demonstrating that the shelter was unable to withstand the impact. It was also observed that the door warped and lost contact at its supports. The following figures show key instants in time where cracks and holes began forming on the shelter top. For clarity, only the top part of the shelter is shown. A separate figure displays the damage to the door post-simulation. The full animation of the simulation is captured on the attached CD, under filenames **RUN6_Front.wmv** and **RUN6_top_HV4.wmv**.

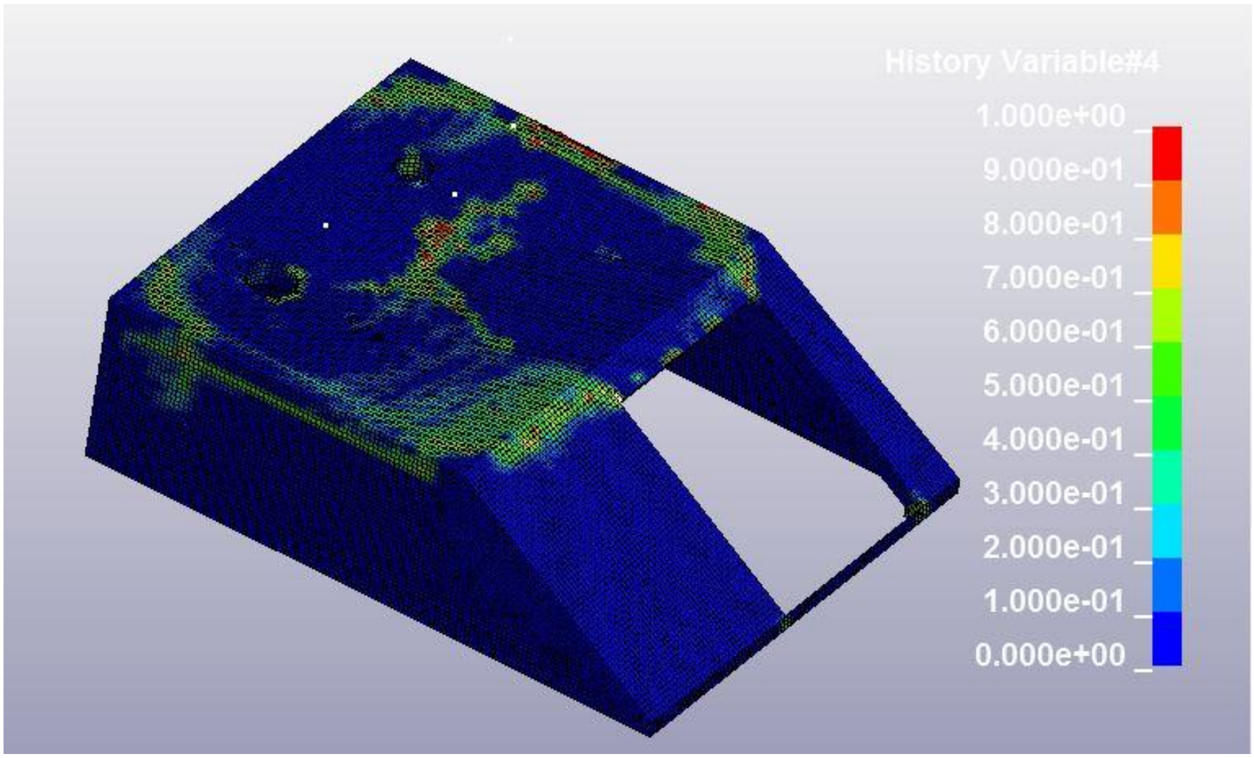


Figure 5.1.1: 12-Inch slope face shelter (12" Run 6) impact at 0.049s. The first cracks are appearing in the center of the roof.

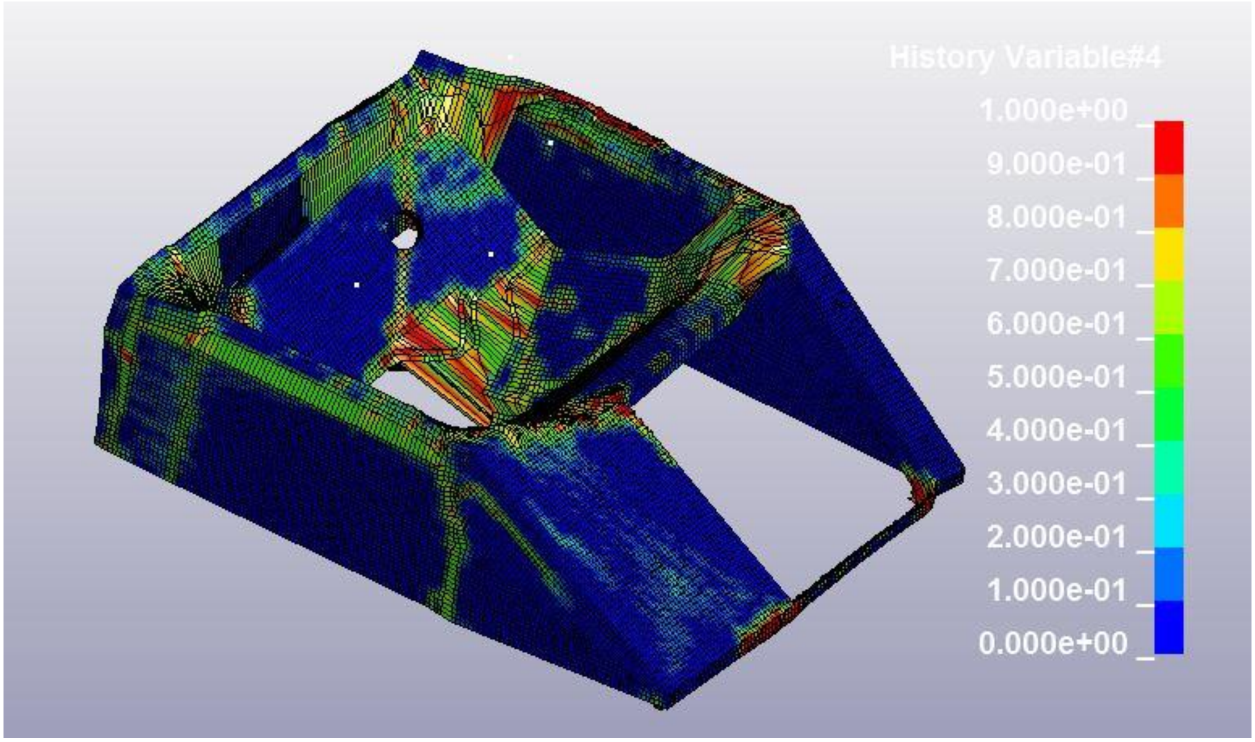


Figure 5.1.2: 12-Inch slope face shelter (12" Run 6) impact at 0.150s. Holes have formed in the shelter roof. The simulation has reached normal termination.

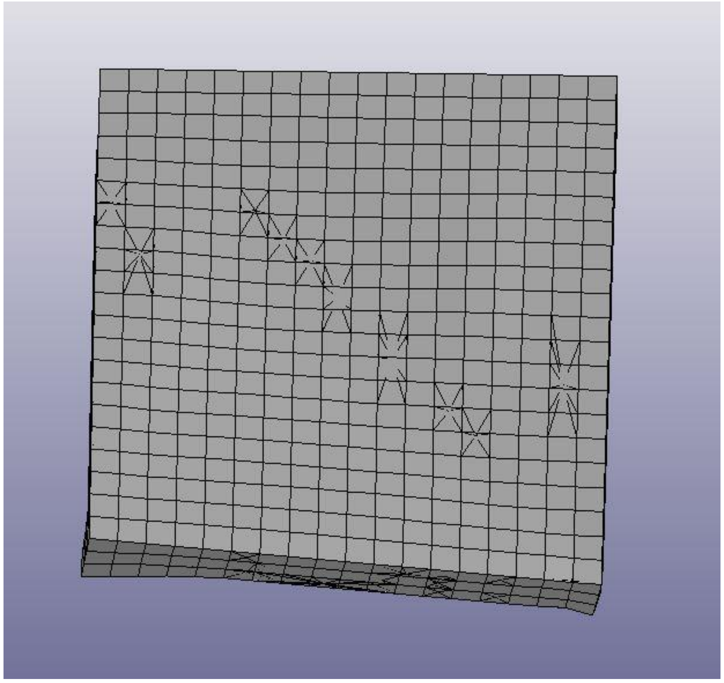


Figure 5.1.3: 12-Inch slope face shelter (12" Run 6) door at the end of the simulation, showing warpage.

Figure 5.1.4 shows the cross-sectional view of the maximum displacement immediately before holes formed in the structure. This image shows large plastic deformation on the roof of the structure during impact and shearing of the elements on the edges. **Figure 5.1.5** shows the rigid body displacement for the top during the time of simulation. Averaging the entire rigid body vertical displacement of the roof, the top of the shelter sinks 146 mm. However, selecting nodes at the center of the shelter roof, the displacement was seen to be 175 mm immediately before holes began forming. The maximum vertical acceleration was 75 m/s^2, shown in **Figure 5.1.6**.

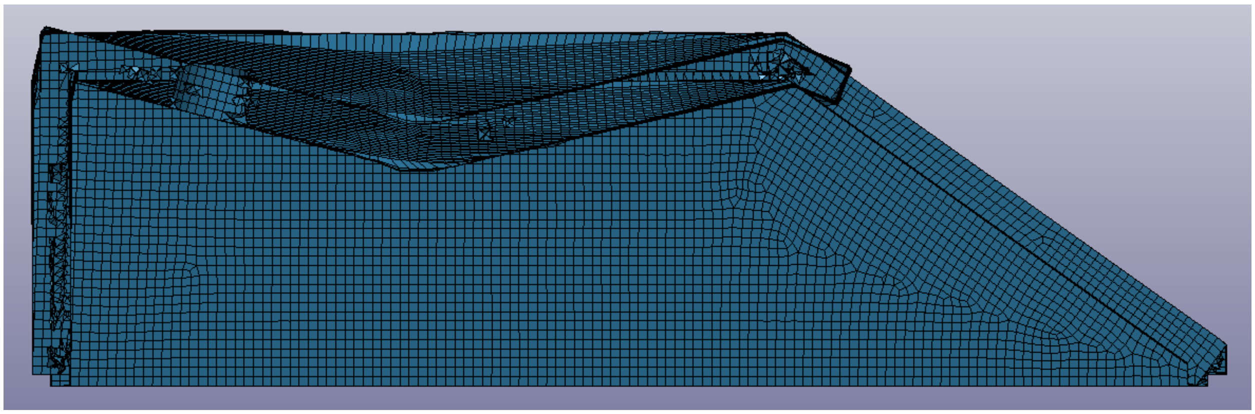


Figure 5.1.4: 12-Inch slope face shelter Rebar Model (12" Run 6) cross section, displaying maximum deflection in the concrete before holes formed in the structure. The capture was taken 0.063s into the simulation.

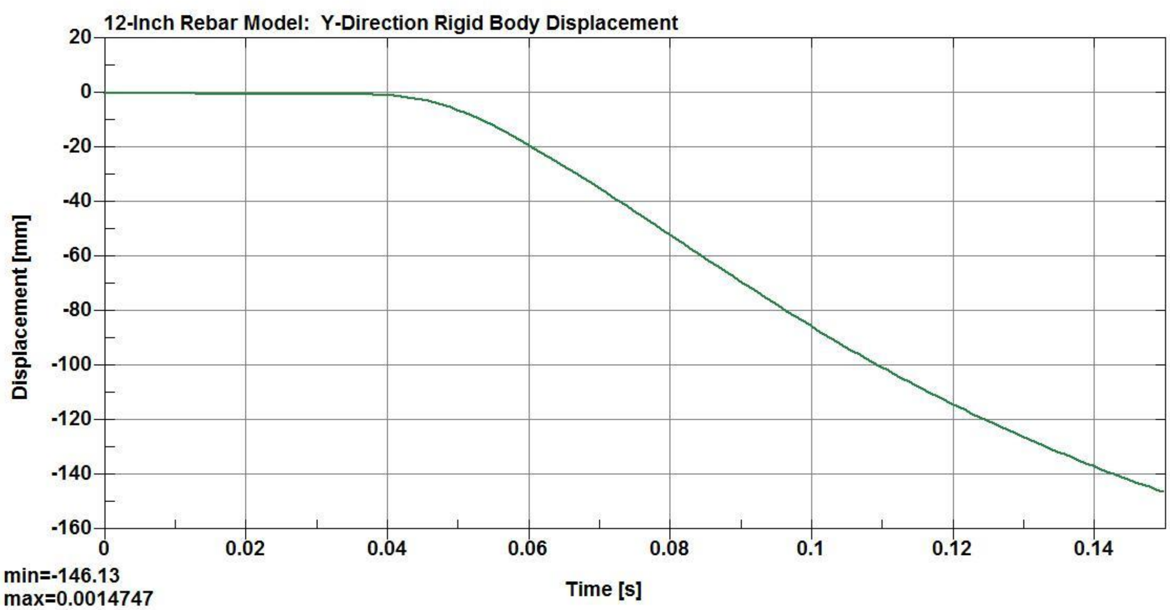


Figure 5.1.5: 12-Inch Rebar Model (12" Run 6): Rigid Body Vertical Displacement of the slope face shelter top with no filter applied.

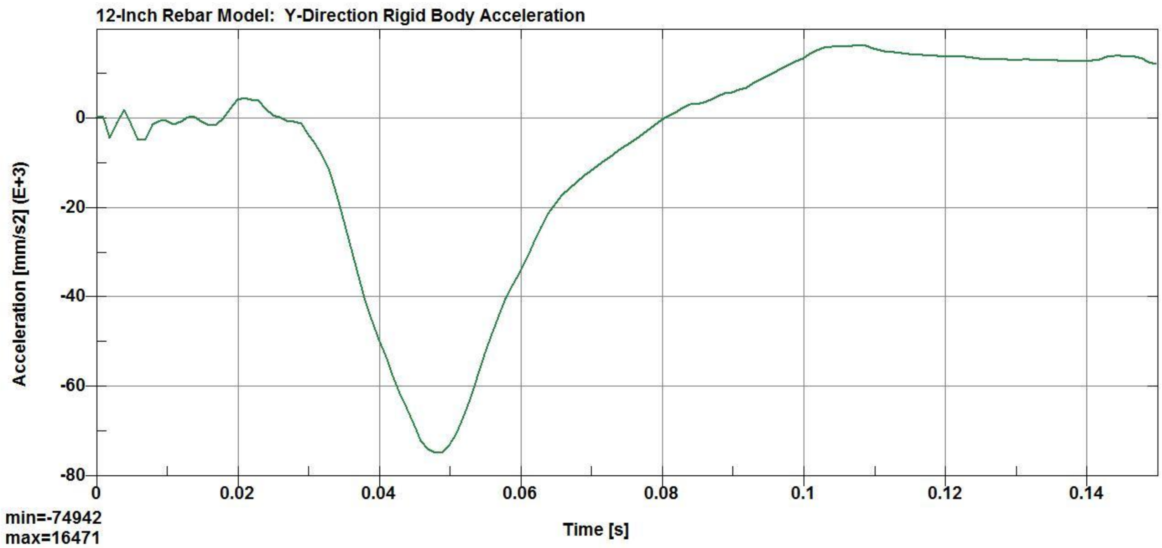


Figure 5.1.6: 12-Inch Rebar Model (12" Run 6): Rigid body acceleration of the slope face shelter top in the vertical direction. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise.

5.2 20° Drop Test on the 14-Inch Slope Face Shelter Rebar Model (14" Run 3)

A separate simulation was run using a rebar structure spaced 14" with the same parameters used in the 12" rebar model analysis. Results show that the roof of the 14" rebar model failed in the same way that the 12" model failed, with cracks forming along the perimeter and in the roof center. The following figures show key instants during the simulation where cracks and holes began forming on the shelter top. For clarity, only the top part of the shelter is shown. A separate figure displays the damage to the door post-simulation. The full animation of the simulation is captured on the attached CD, under filenames **RUN3_Front_HV4.wmv** and **RUN3_Top_HV4.wmv**.

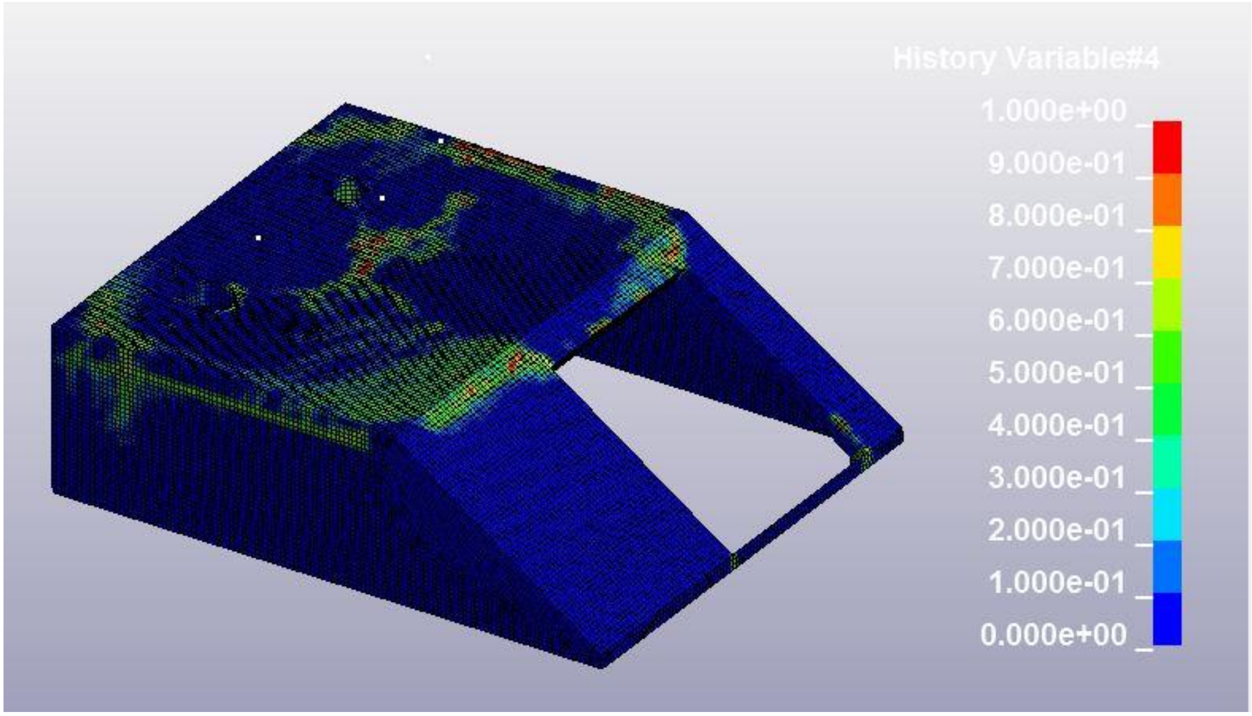


Figure 5.2.1: 14-Inch slope face shelter (14" Run 3) impact at 0.049s. The first cracks are appearing in the center of the roof.

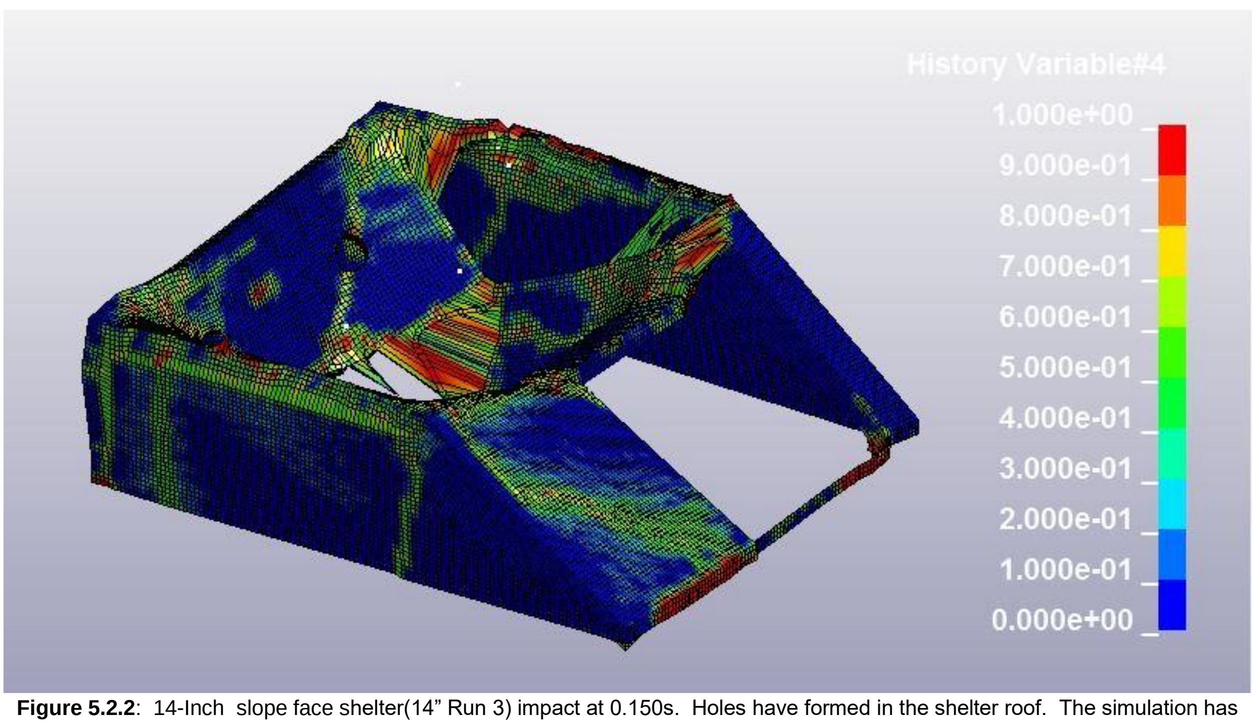


Figure 5.2.2: 14-Inch slope face shelter(14" Run 3) impact at 0.150s. Holes have formed in the shelter roof. The simulation has reached normal termination.

Figure 5.2.3 shows the cross-sectional view of the maximum displacement immediately before holes formed in the structure. This image shows large plastic deformation on the roof of the structure during impact and shearing of the elements on the edges. The maximum rigid body displacement was found to be 137 mm, while the elements at the center displace 172 mm. The rigid body deflection in the vertical direction is shown in **Figure 5.2.4.** The maximum acceleration was 78 m/s^2, shown in **Figure 5.2.5**.

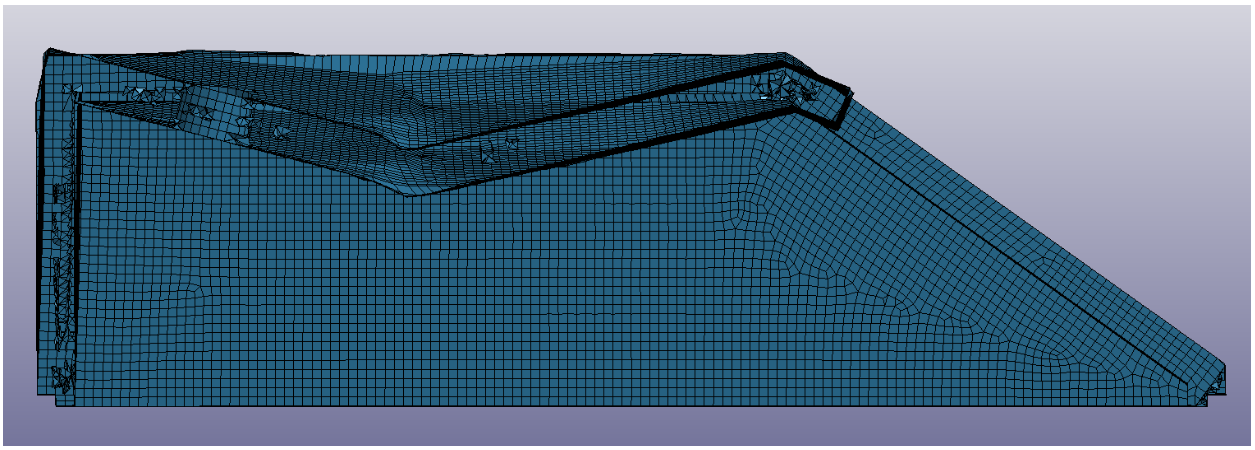


Figure 5.2.3: 14-Inch Rebar Model (14" Run 3) cross section, displaying maximum deflection in the concrete before holes formed in the structure. The capture was taken 0.063s into the simulation.

Figure 5.2.4: 14-Inch Rebar Model (14" Run 3): Rigid Body Vertical Displacement of the slope face shelter top with no filter applied.

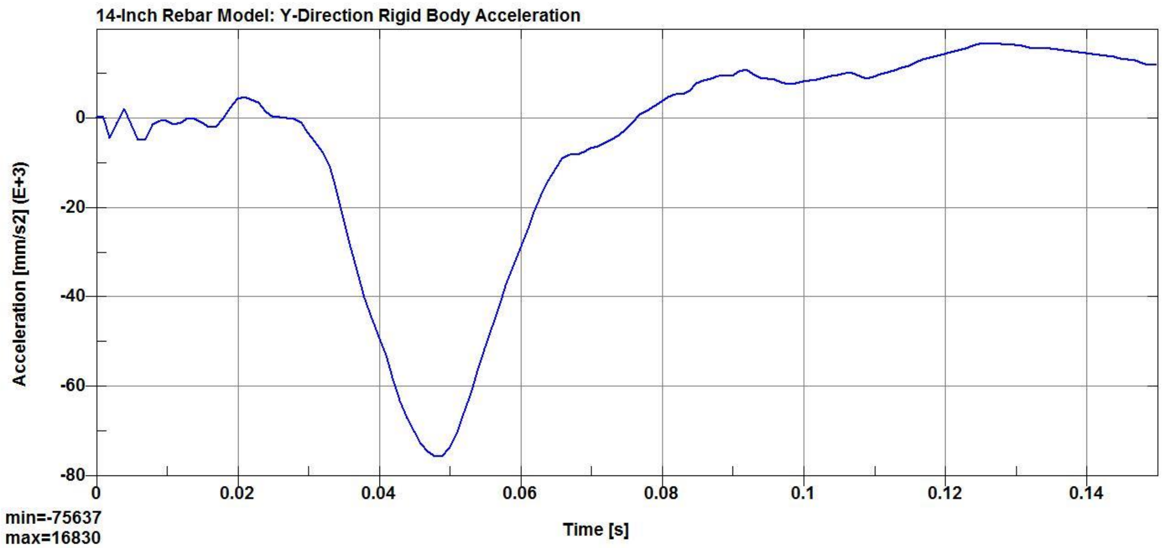


Figure 5.2.5: 14-Inch Rebar Model (14” Run 3): Rigid body acceleration of the slope face shelter top in the vertical direction. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise.

From this set of simulations run on the slope face shelters, it was concluded that there were no significant differences to using one internal rebar design versus the other. The damage, deflections, and accelerations were analogous, but ultimately all corresponded to failure in the shelter design when tested against the pickup truck impact. These results were consistently reinforced through all 24 simulations.

6. MODIFYING PARAMETERS

Following the results from Section 5, parameters and drop conditions were modified to analyze the damage effects on the shelter. The simulations varied the drop angle, initial velocity, Hourglass parameter, and Eroding Plastic Strain parameter. The corresponding results were compared to the initial test results. The Hourglass parameter modifies the non-physical energies associated with deformation that produce zero stress and strain. The Eroding Plastic Strain parameter controls the degree to which elements can stretch before failing in simulation. These simulations were performed to determine whether the Hausner shelters could withstand the truck impact under a different set of conditions. This section presents a summary of findings after varying different parameters.

6.1 20° Drop Test on the 12-Inch Slope Face Rebar Model (12" Run 14)

In this simulation, all conditions from the 20° Slope face shelter impact test were maintained with the exception of the Eroding Plastic Strain parameter and the Hourglass parameter. The Eroding Plastic Strain Parameter was set to a value of 1. In previous runs, this parameter had a value of 2. The lower Eroding Plastic Strain value causes the concrete elements to stretch less before failing and disappearing from the simulation. Hourglass settings were also added where they had previously been absent. **Figures 6.1.1** and **6.1.2** show the shelter deformation at key instants during the simulation. The full animation of the simulation is captured on the attached CD, under filenames **RUN14_Top_HV4.wmv** and **RUN14_Front_HV4.wmv**.

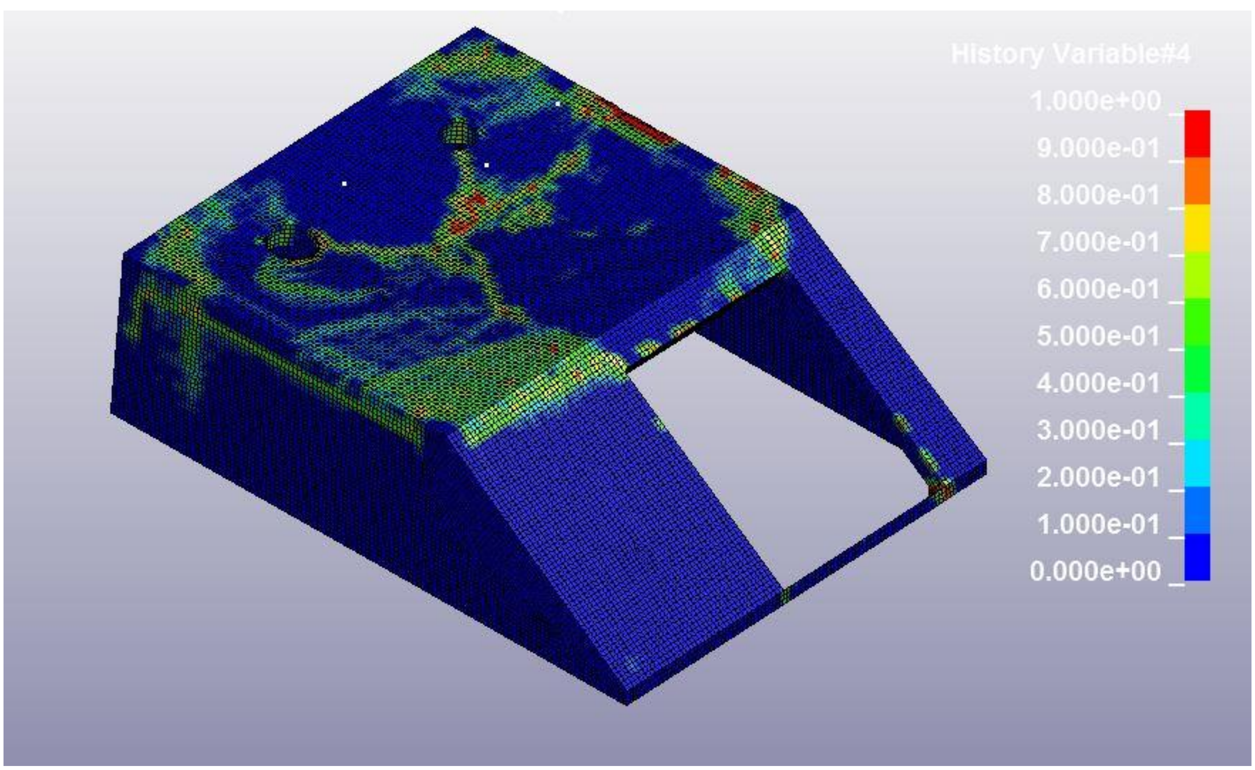


Figure 6.1.1: 12-Inch slope face shelter (12" Run 14) impact at 0.049s. The first cracks are appearing in the center of the roof.

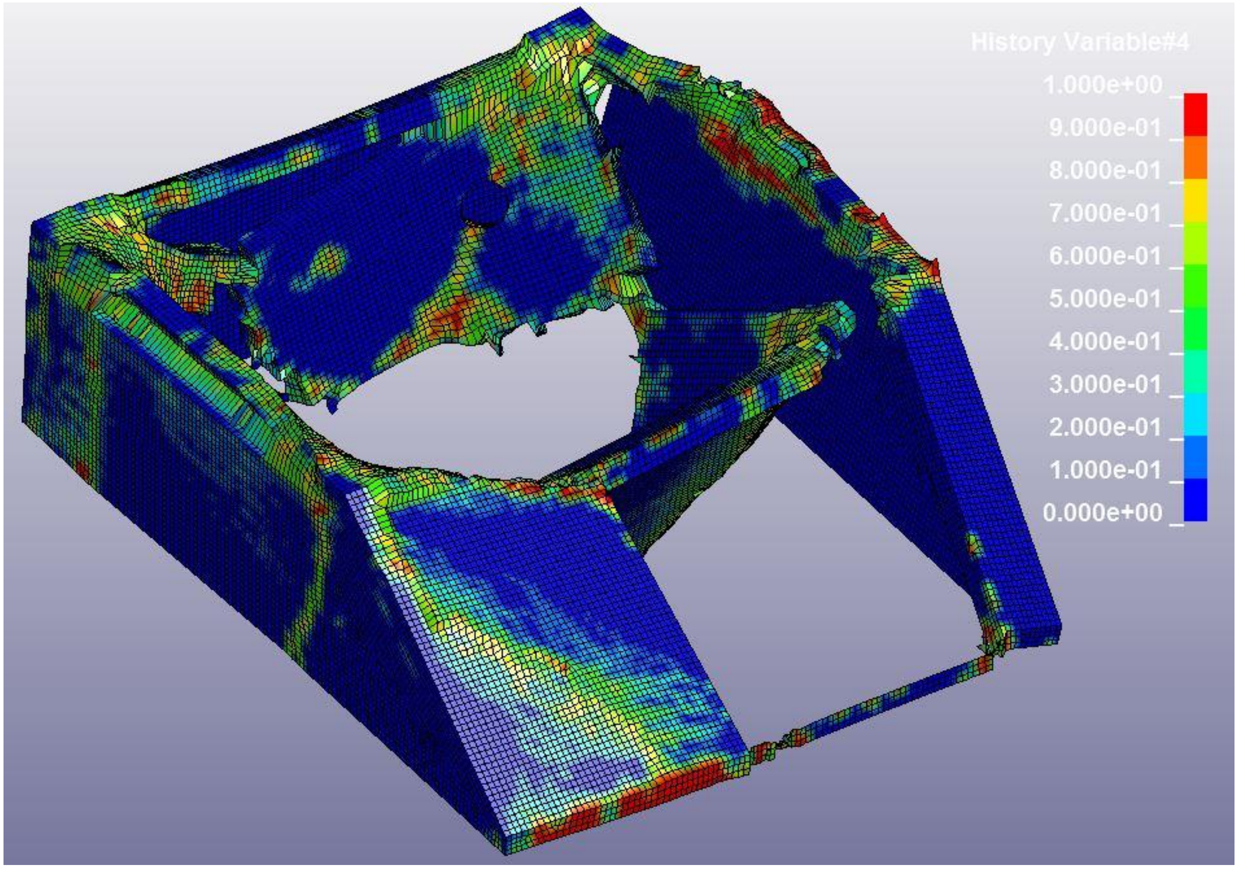


Figure 6.1.2: 12-Inch slope face shelter (12" Run 14) impact at 0.167s. Holes have formed in the shelter roof.

From **Figures 6.1.1** and **6.1.2**, it can be seen that the slope face shelter begins failing as previously observed. Under these conditions, one of the side walls experienced large deflection in the lateral direction, causing the roof to detach from the wall. The roof continued to sink and deflect until it failed catastrophically. **Figure 6.1.3** shows the cross-sectional view of the maximum displacement immediately before holes formed in the structure. **Figure 6.1.4** shows the rigid body displacement for the top during the time of simulation. Averaging the entire rigid body displacement of the roof, the top of the shelter sinks 148 mm. However, selecting nodes at the center of the shelter roof, the displacement was seen to be 201 mm immediately before holes began forming. The maximum acceleration was 73.5 m/s^2, as shown in **Figure 6.1.5**.

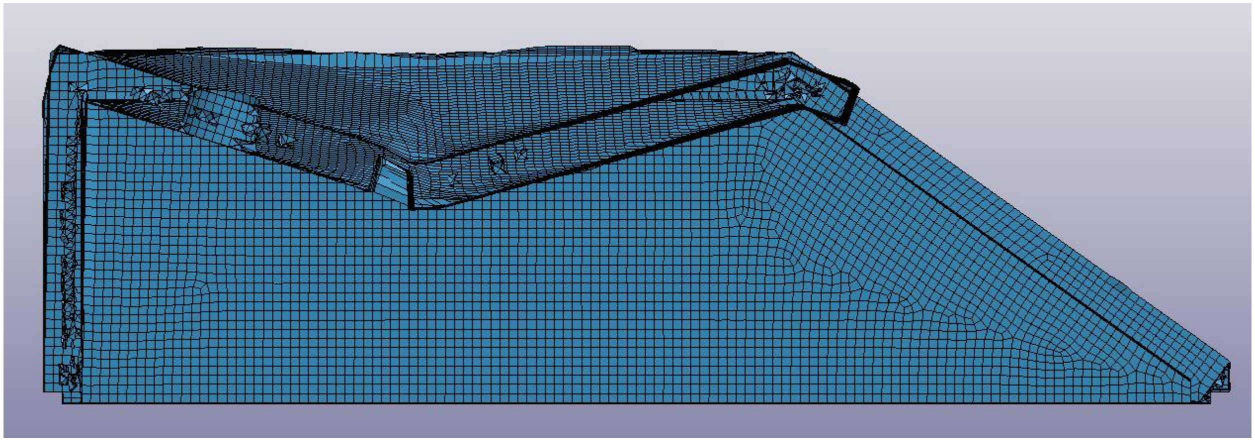


Figure 6.1.3: 12-Inch Rebar Model (12" Run 14) cross section, displaying maximum deflection in the concrete before holes formed in the structure. The capture was taken 0.063s into the simulation.

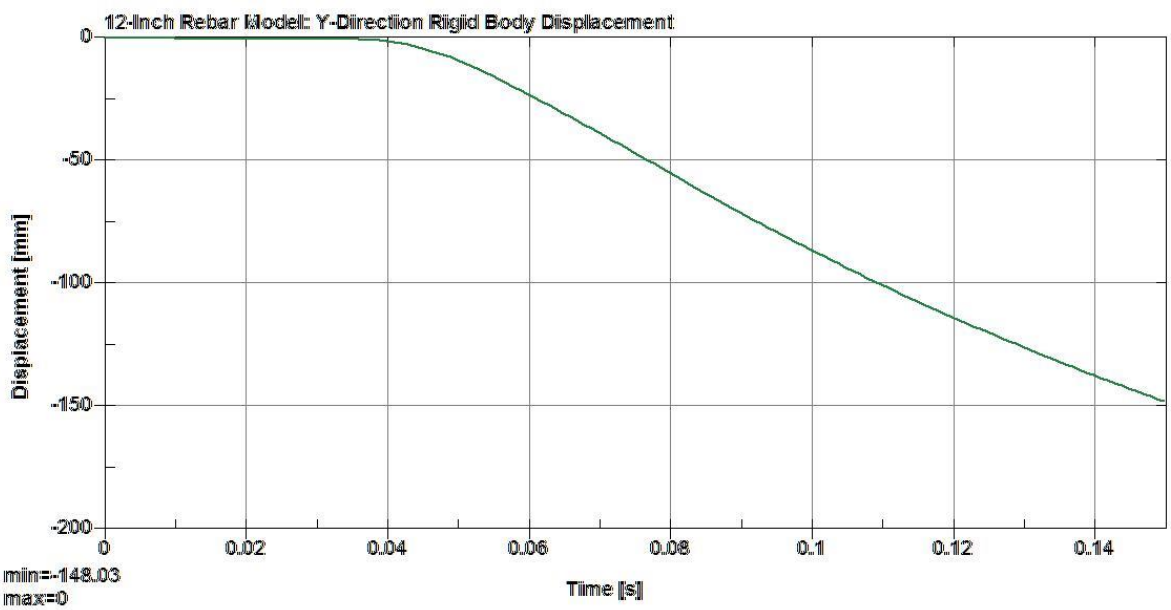


Figure 6.1.4: 12-Inch Rebar Model (12" Run 14): Rigid Body Vertical Displacement of the slope face shelter top with no filter applied.

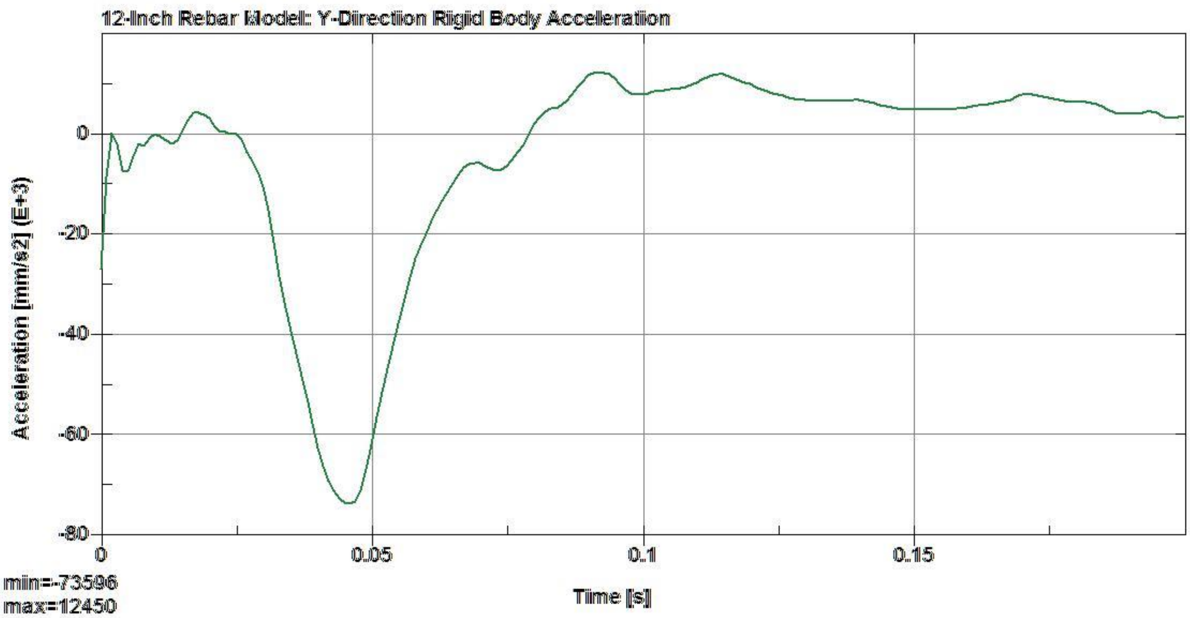


Figure 6.1.5: 12-Inch Rebar Mode (12" Run 14)l: Rigid body acceleration of the slope face shelter top in the vertical direction. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise.

6.2 Lateral Drop Test on the 12-Inch Slope Face Shelter Rebar Model (12" Run 12)

For this simulation, the truck was repositioned horizontally, maintaining the same downward initial velocity of 35 mph, as seen in **Figure 6.2**. An Eroding Plastic Strain parameter of 1 and the Hourglass settings used in Section 6.1 were incorporated.

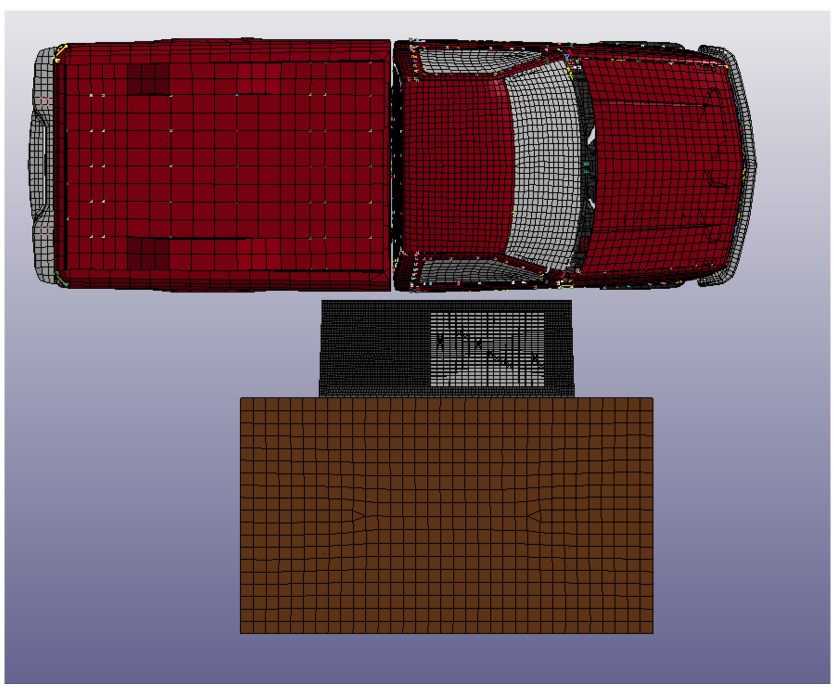


Figure 6.2: Experimental setup of lateral pickup truck drop using detailed Chevrolet C2500 model, as provided by the NCAC/CCSA [3].

Figures 6.2.1 and **6.2.2** show the progression of damage accumulated by the shelter roof during the lateral impact at key instants during the simulation. The full animation of the simulation is captured on the attached CD, under filenames **RUN12_Top_HV4.wmv** and **RUN12_Front_HV4.wmv.**

From these figures, it can be seen that the shelter begins to fail along the edges before caving in at its center and forming holes. As in all previous cases, the door lost contact with its supports and warped as a result of the impact.

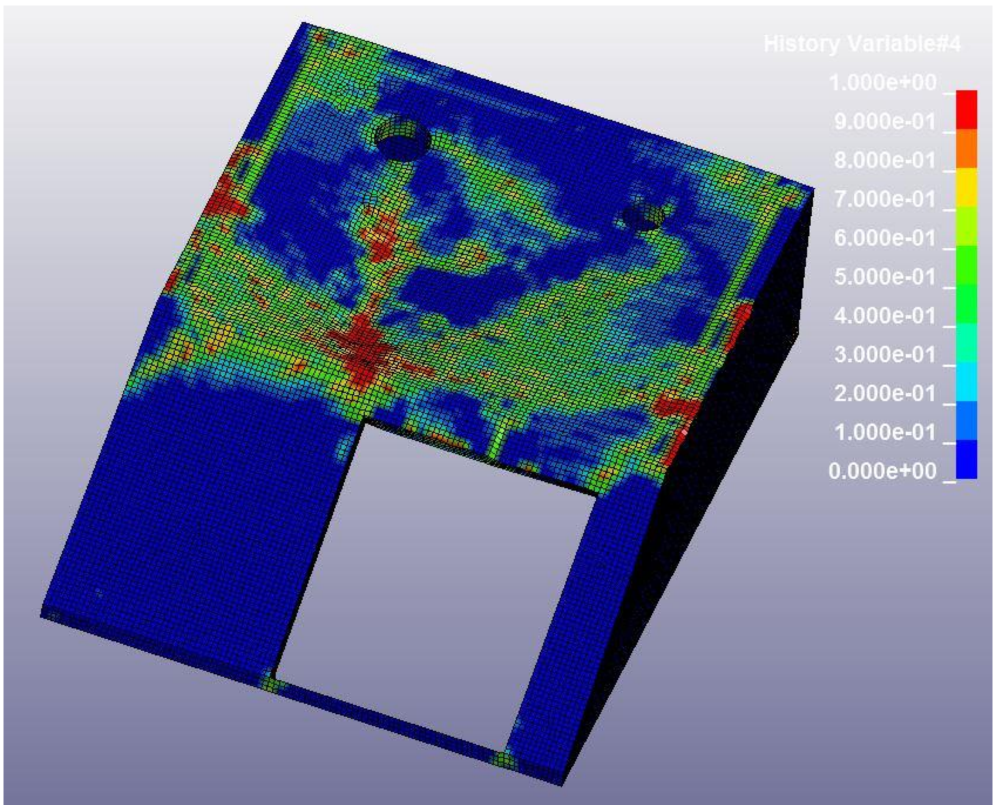


Figure 6.2.1: 12-Inch Lateral slope face shelter (12" Run 12) impact at 0.020s. Cracks begin forming on the edges of the shelter and damage is seen more evenly distributed across the roof.

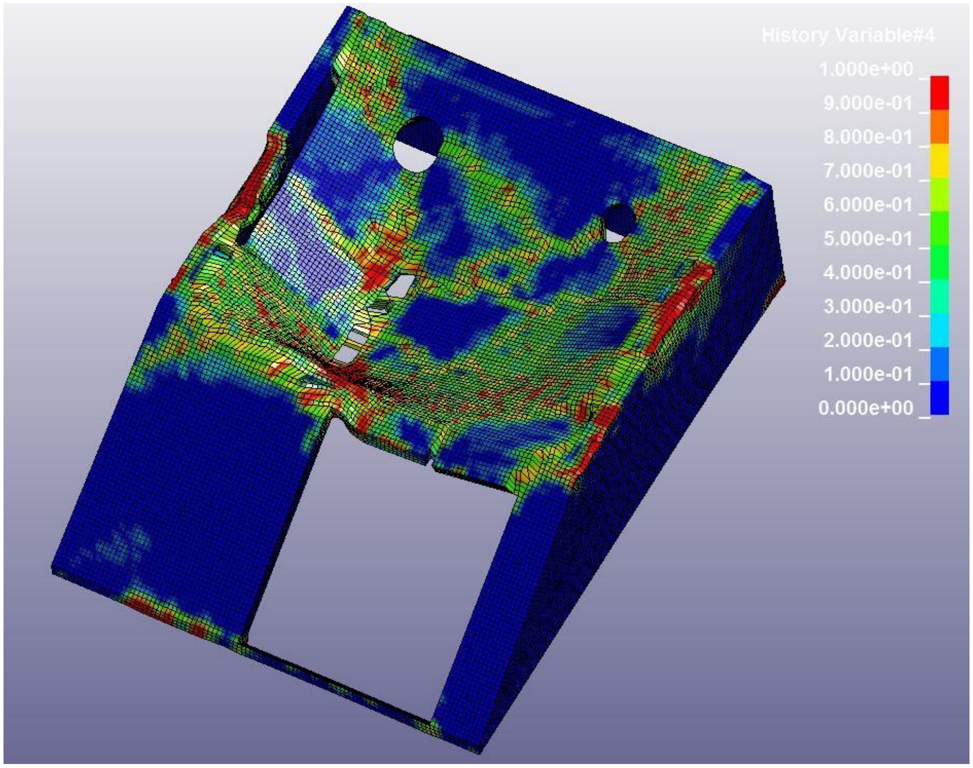


Figure 6.2.2: 12-Inch slope face shelter (12" Run 12) impact at 0.095s. The edges of the shelter have accumulated considerable damage and holes are forming at the center.

Figure 6.2.3 shows the cross-sectional view of the maximum displacement immediately before holes formed in the structure. **Figure 6.2.4** shows the rigid body displacement for the top part during the time of simulation. Averaging the entire rigid body displacement of the roof, the top of the shelter sinks 77 mm. However, selecting nodes at the center of the shelter roof, the displacement was seen to be 287 mm immediately before holes began forming. The maximum acceleration was 25 m/s^2, shown in **Figure 6.2.5**.

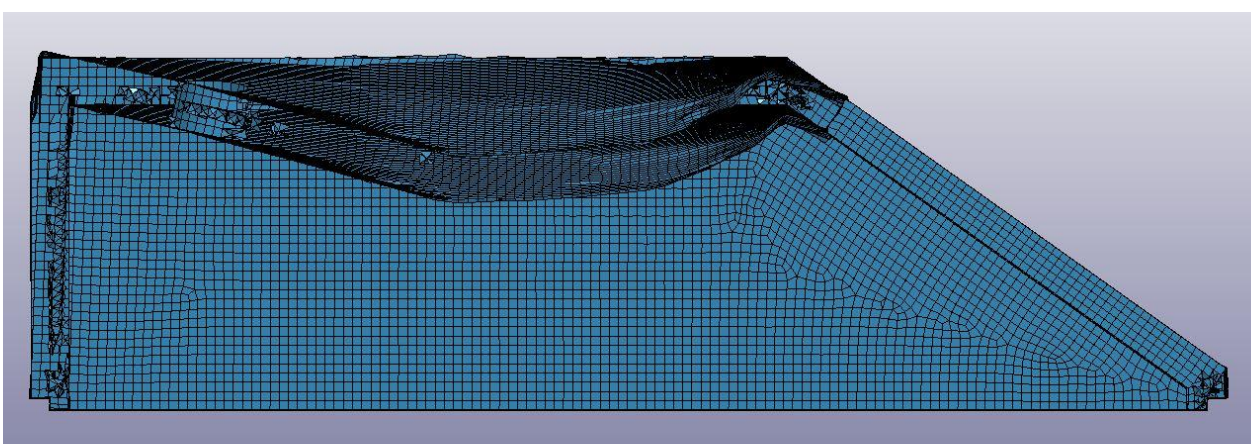


Figure 6.2.3: 12-Inch Rebar Model (12" Run 12) cross section, displaying maximum deflection in the concrete before holes formed in the structure. The capture was taken 0.43s into the simulation.

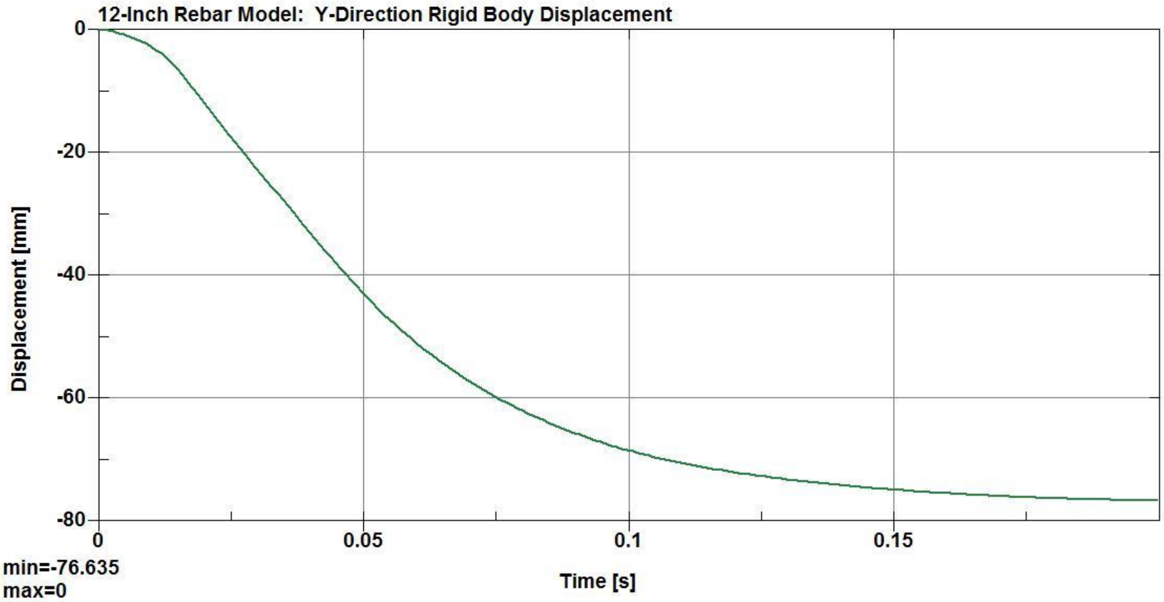


Figure 6.2.4: 12-Inch Rebar Model (12" Run 12): Rigid Body Vertical Displacement of the slope face shelter top with no filter applied.

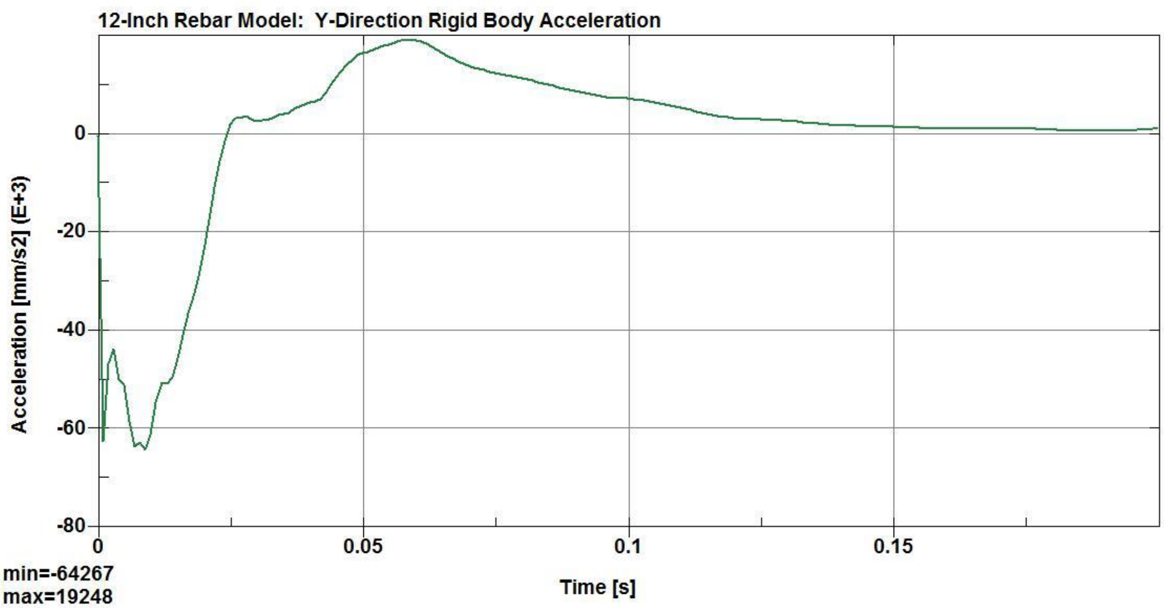


Figure 6.2.5: 12-Inch Rebar Model (12" Run 12): Rigid body acceleration of the slope face shelter top in the vertical direction. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise.

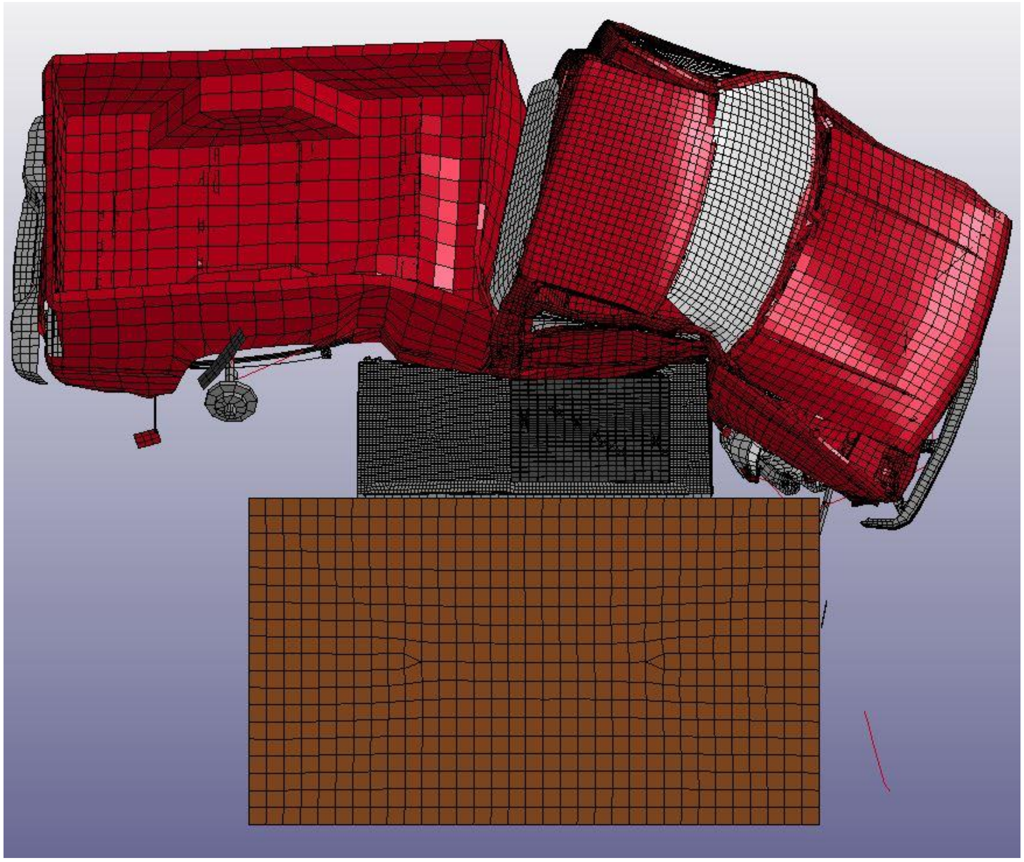


Figure 6.3: Post-simulation lateral collision of the pickup truck into the slope face shelter.

7. COMPARATIVE ANALYSIS WITH THE OZ SAFEROOM

Previous research analyzed the OZ saferoom using the same techniques described in this report [6]. For comparative analysis, the 20° and lateral drop tests on the OZ saferoom are discussed in this section.

7.1 OZ Saferoom Model Results for 20° Impact Scenario

For the 20° impact test, the OZ saferoom withstood the impact of the airborne vehicle without warping or failing under the same initial conditions and input parameters. **Figure 7.1.1**, displaying only the roof of the saferoom, presents the damages experienced during simulation. Only minor damage is seen on the top surface of the roof and no damage was incurred on the bottom surface. This indicates that there is no penetration of the truck to the saferoom and that the saferoom withstands the impact completely. The full animation of the simulation is captured on the attached CD, under filenames **OZ20deg_Top_HV4** and **OZ20deg_Front_HV4**.

According to **Figures 7.1.2** and **7.1.3**, a maximum vertical rigid body displacement of 0.0976 mm and a maximum vertical rigid body acceleration of 1.17 m/s^2 were seen in the OZ saferoom analysis. Therefore, the Hausner shelter vertically deforms approximately 1500 times more and accelerates approximately 60 times more than the OZ saferoom. From **Figure 7.1.2**, it can also be seen that the roof of the OZ saferoom oscillates to absorb the impact energy, whereas the roof of the slope face shelter sinks as seen previously in **Figure 7.1.5**.

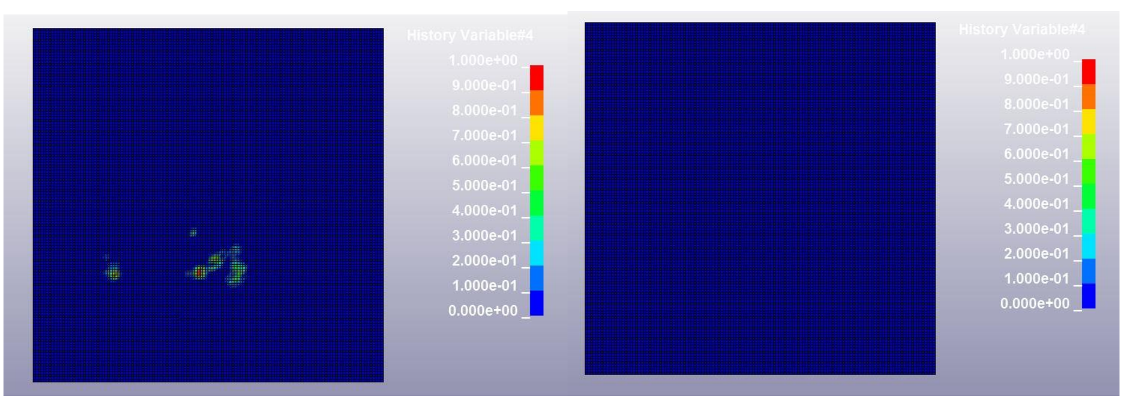


Figure 7.1.1: OZ Saferoom Model: Damage accumulation of roof elements. The left image displays the top surface of the roof. The right image displays the bottom surface. Notice that there is considerably less stress and warpage seen in the OZ saferoom than there was for either of the Hausner shelter designs.

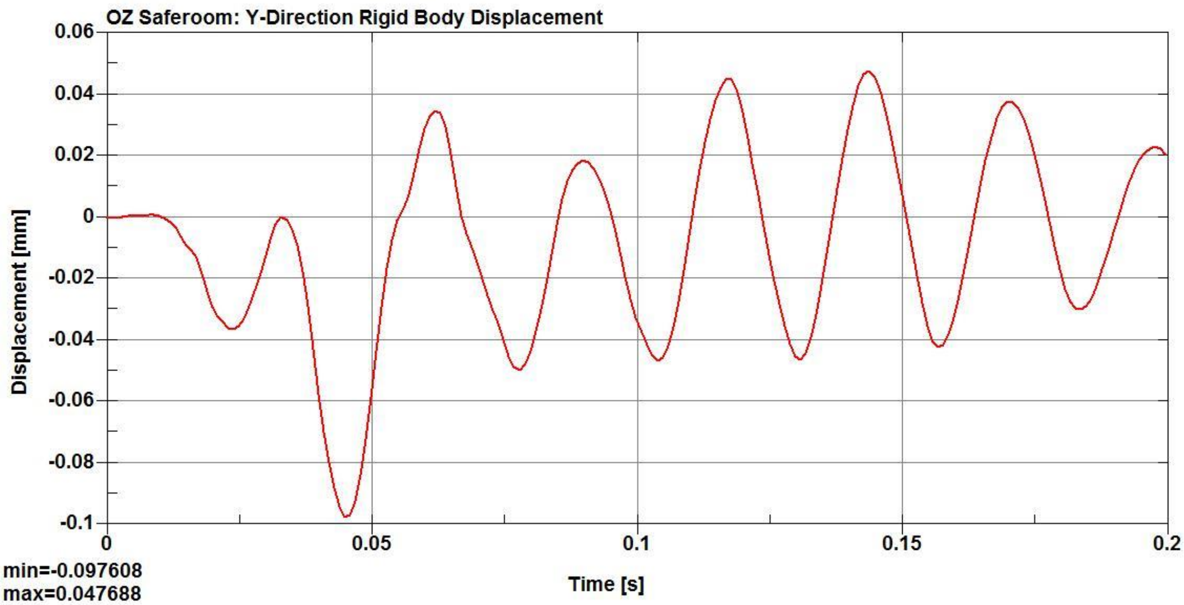


Figure 7.1.2: OZ Saferoom Model: Rigid body vertical displacement of the roof center with no filter applied. Notice that the displacement is oscillatory in nature, absorbing the shock and suffering minimal damage consequently.

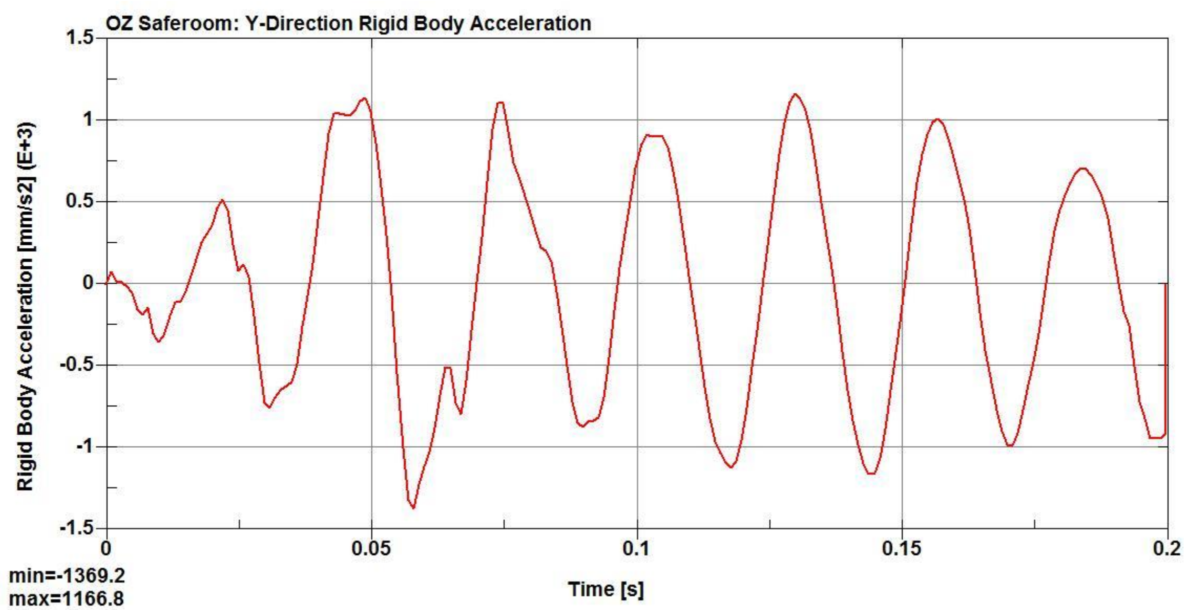


Figure 7.1.3: OZ Saferoom Model: Rigid body acceleration of the shelter top in the vertical direction. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise. The acceleration is oscillatory in nature, absorbing the shock and suffering minimal damage consequently.

7.2 OZ Saferoom Model Results for Lateral Impact Scenario

Similarly, in the lateral impact test, the OZ saferoom withstood the impact of the airborne vehicle. Once again, no warpage or failure was seen in the saferoom roof under the same initial conditions and input parameters. **Figure 7.2.1** displays the initial setup for this simulation. **Figure 7.2.2** displays a snapshot of the simulation at the greatest point of impact between the truck and the saferoom.

Figure 7.2.3 analyzes the damage accumulation on the top of the saferoom roof. An image displaying the bottom of the saferoom roof has been omitted, as once again, there was no visible damage. From **Figure 7.2.3**, it can be seen that some superficial damage exists primarily on the roof edges, but it does not penetrate through the thickness of the roof. As before, no penetration of the truck was observed during simulation. The full animation of the simulation is captured on the attached CD, under filenames **OZLat_Top_HV4.wmv** and **OZLat_Front_HV4.wmv**.

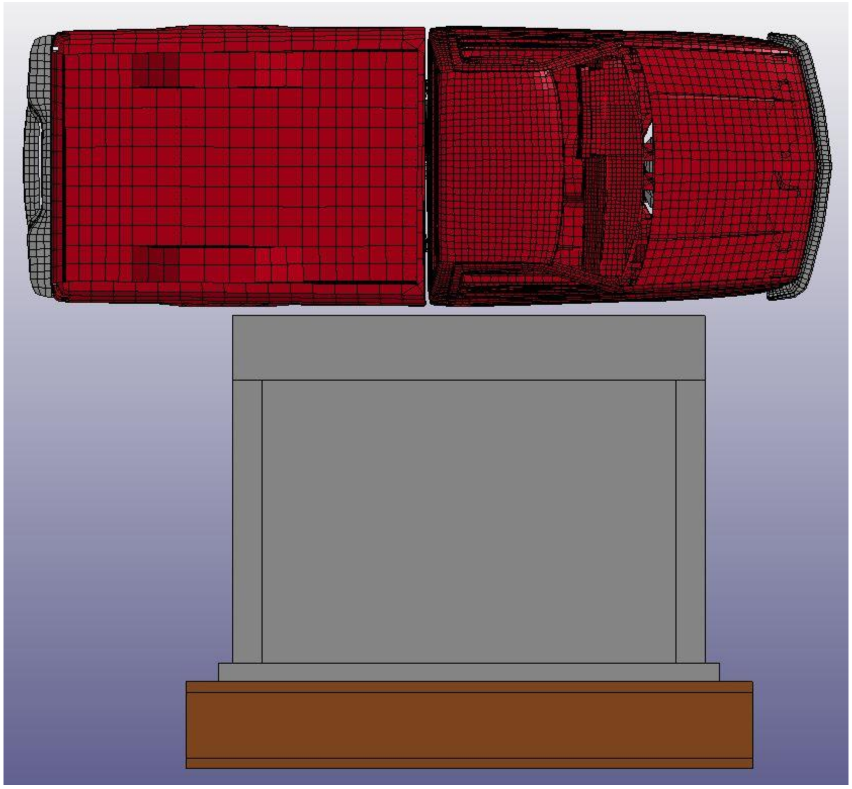


Figure 7.2.1: Experimental setup of lateral pickup truck drop on OZ saferoom.

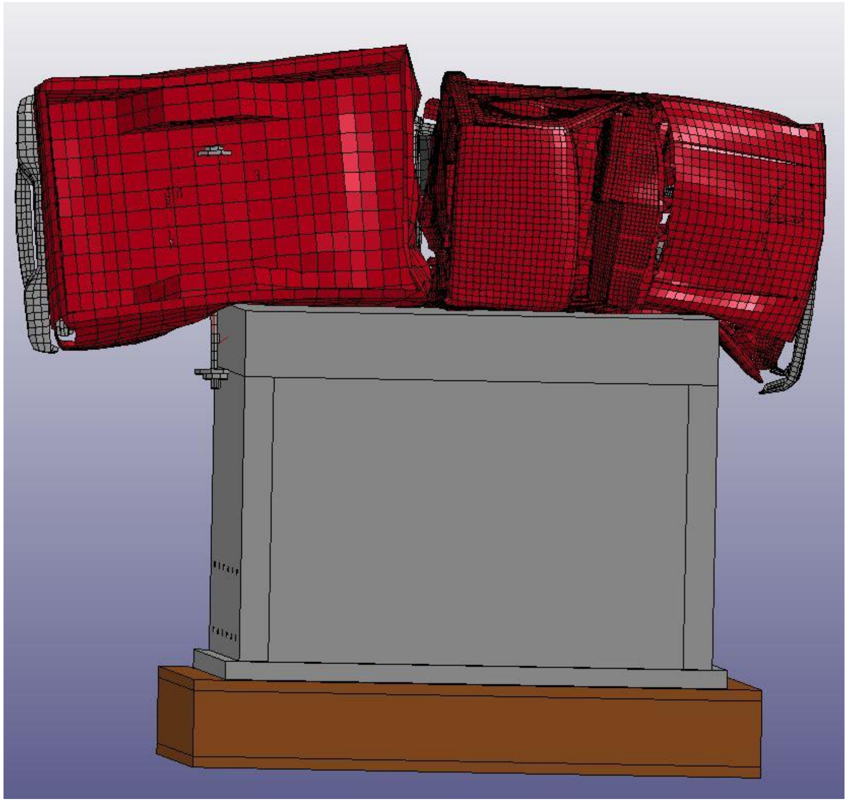


Figure 7.2.2: Post-simulation lateral collision of the pickup truck into the OZ saferoom.

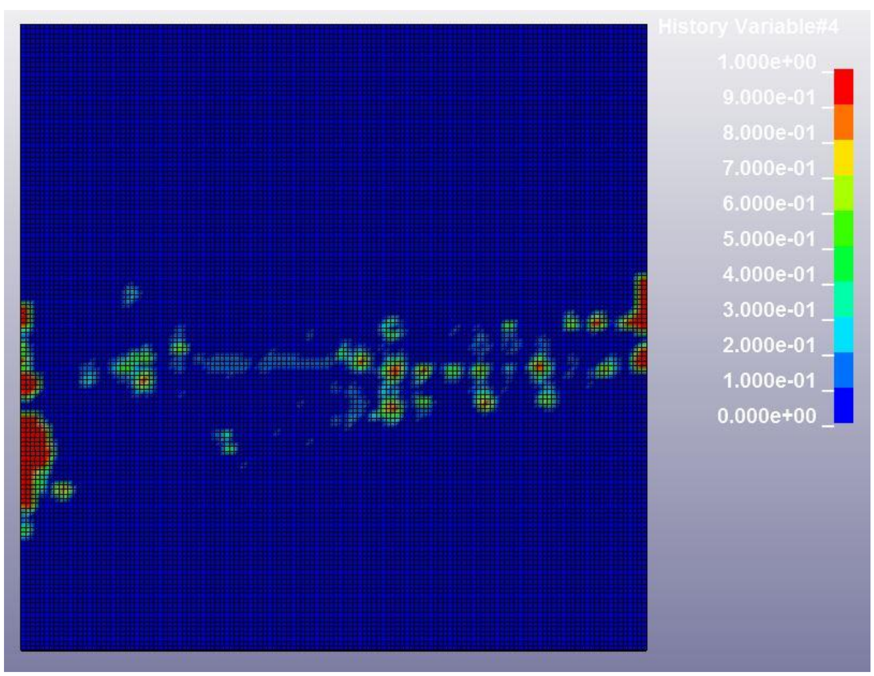


Figure 7.2.3: OZ Saferoom Model: Damage accumulation of roof elements post-simulation.

Figures 7.2.4 and **7.2.5** present the Rigid Body Displacement and Acceleration of the roof of the OZ saferoom up to the point of maximum contact between the truck and the roof. A maximum vertical rigid body displacement of 0.175 mm and a maximum vertical rigid body acceleration of 2.89 m/s^2 were seen in the OZ saferoom lateral analysis. Therefore, the Hausner shelter vertically deforms approximately 800 times more and accelerates approximately 25 times more than the OZ saferoom. From **Figure 7.2.4**, it can also be seen that the roof of the OZ saferoom again oscillates to absorb the impact energy.

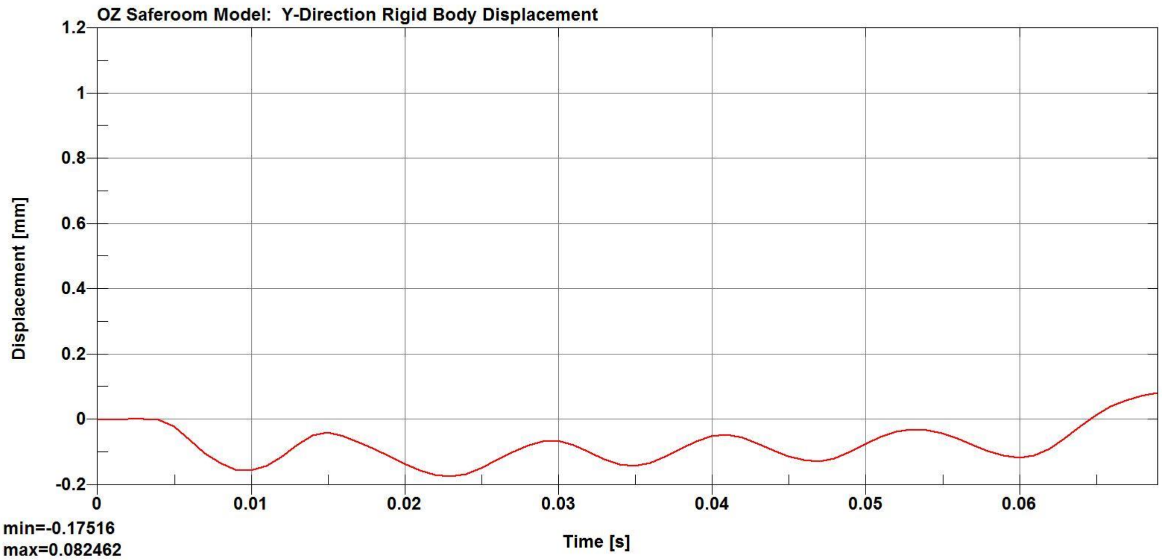


Figure 7.2.4: OZ Saferoom Model: Resultant nodal displacement of the roof center with no filter applied. Notice that the displacement is oscillatory in nature, absorbing the shock and suffering minimal damage consequently.

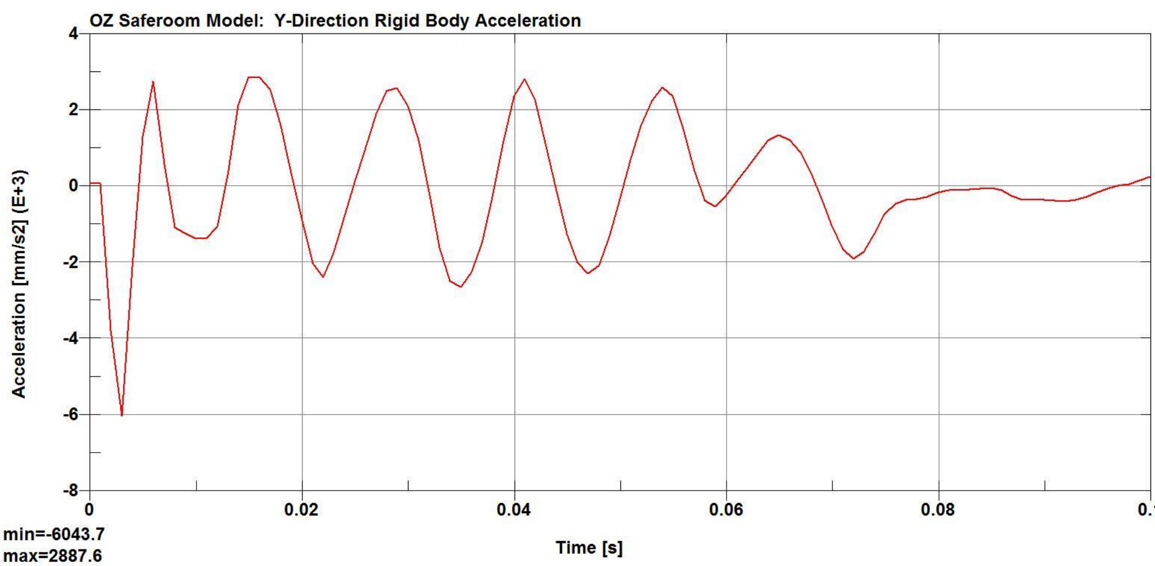


Figure 7.2.5: OZ Saferoom Model: Rigid body resultant acceleration of the shelter top. A 9-point averaging filter was applied to better isolate the acceleration signal from the noise. The acceleration is oscillatory in nature, absorbing the shock and suffering minimal damage consequently.

8. Simulation Results

Table 8.1: Summarized Results of Key Simulations

Metric	**Max Displacement**	**Max Acceleration**	**Damage Area**	**Damage Depth**
Units	mm	m/s^2	cm^2	mm
Slope Face Shelter (12” Rebar Run6)	146.13	74.942	31135	101.6*
Slope Face Shelter (14” Rebar Run3)	136.67	75.637	31135	101.6*
Slope Face Shelter (12” Rebar Run14)	148.03	73.596	31135	101.6*
Slope Face Shelter (12” Rebar Run12)	76.64	64.267	31135	101.6*
OZ Saferoom	0.098	1.369	2919	304.8
OZ Saferoom Lateral	0.175	6.044	5094	125.0

* the damage depth to the slope face shelter broke completely through the thickness of the roof, which was only 4 Inches. The OZ Saferooms shelter had a larger thickness of 18 Inches, and the damage penetrated further than 4 Inches into the concrete but didnot penetrate completely through.

9. CONCLUSIONS

In total, 24 simulations were run on the Slope face shelters in ANSYS and LS-DYNA following industrial standards. The precise behavior of the shelter after initial failure was difficult to predict due to the break-down of the concrete-rebar interaction. The simulations are most accurate until the point of shear failure at which point demonstrate that the Slope face shelter can't withstand the impact. After that point the simulation only gives approximate behavior of the solid materials. In these simulations, the rebar geometries were assigned rigid connections and treated as one elastic part which it is only suitable for problems with small deformations like in the case of the OZ Saferoom. Nevertheless the behavior of the concrete and the rebar is a good approximation that demonstrate the collapsing of the ceiling under all cases investigated.

An analysis of the damage incurred by each shelter indicates that the Slope face storm shelters were unable to adequately protect persons inside from an overhead vehicular impact while the OZ saferoom was. The observed differences were primarily a consequence of differences in slab thickness. The Hausner models utilized 4" thick concrete plates upon their top surfaces, while the OZ saferoom model utilized a considerably greater 18" of concrete for their roofs. This translated into a volume of 0.317 m^3 of reinforced concrete protecting persons in the slope face shelter models versus 4.98 m^3 of protection in the OZ saferoom. With more reinforced concrete protection, the OZ Saferoom did not collapse upon impact, but rather oscillated and diffused the impact energy. The Slope face shelters were deemed ineffective against airborne vehicular collisions since structural collapse was clearly seen in the simulations.

Conclusively, it can be noted that roof thickness and effective roof volume play a crucial role in storm shelter performance. Greater thickness allows for absorption of shock from impacts, while thinner surfaces tend to be brittle and shatter under appreciable impacts. Energy can consequently be dispersed throughout greater material volumes without creating sudden increases in kinetic energy that would cause the structures to collapse. While rebar aids in the absorption of impact energy, there were not considerable differences between the behaviors of the 12-inch and 14-inch Slope face shelter rebar models.

The OZ saferoom displacement and acceleration plots are more oscillatory than the Slope face shelter models' plots. When the truck impacted the OZ saferoom top, the concrete seemed to respond by reverberating and dampening the shock over time. This is why the graphs of acceleration and displacement display a spike at the instant of impact and then trend towards static equilibrium thereafter. In the Slope face shelter model plots, there is no oscillation. The displacements simply trend further from equilibrium while the accelerations display only a primary spike from the initial collision. This appreciable difference in graphical responses demonstrates how and why the OZ saferoom shelter didn't fail while the Slope face shelters did. A structure that absorbs impact through oscillation fairs better in impact tests than one that is unable to dampen the shock.

The Slope face shelters were unable to withstand the truck impact through any combination of initial conditions. The Eroding Plastic Strain parameter and Hourglass settings seemed to have minimal effect on the shelter's ability to protect persons inside, despite changing how the shelter deformed. Lower Eroding Plastic Strain values and added Hourglass settings caused elements of the shelter to disappear with less deformation, but larger values did not prevent the shelter from collapsing. The positioning of the truck only affected the damage area and how cracks formed in the roof. The 20° impact test presented a more damaging scenario, but even the lateral impact test saw failure in the Hausner shelter.

The penetration of the damage during the truck drop simulation appears to be much higher in the OZ Saferoom than in the Slope face shelter, however these results need to be interpreted as follow. In both tests, the damage is very localized in a small area of the OZ Saferoom and the nodes underneath this area will experience larger stresses and strains than allowed by the RHT concrete model, this means that these nodes are weaker than the ones in the rest of the structure but the damage does not penetrate to the interior face of the OZ Saferoom, therefore scabbing in the interior face is not observed. Since the damage is not extensive in area and penetration, compared to the total area and thickness of the OZ Saferoom roof, this damage is not significant to the structure. For the case of the Slope face shelter, the damage penetrates all the way through the roof causing cracks and collapse of the structure.

It was also observed that the door of the Slope face shelter tends to wrap and loose contact with the edges of the structure during the impact. In the case of an EF5 tornado it is more likely that with the forces caused by the wind and the impact, the door will be lost.

Ultimately, it can be said that the Slope face shelters were not designed to withstand an airborne pickup truck impact since catastrophic failure was seen in every simulation, this can cause serious injuries to the occupants of the shelter.

10. REFERENCES

[1] Small Arrow Engineering, LLC, 2016, “Oklahoma Typical Installation - Hausner’s Inc.,” Engineering Drawing, Proj. No. 11144.

[2] ASTM International, 2016, “Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement,” ASTM A615/A615M-16.

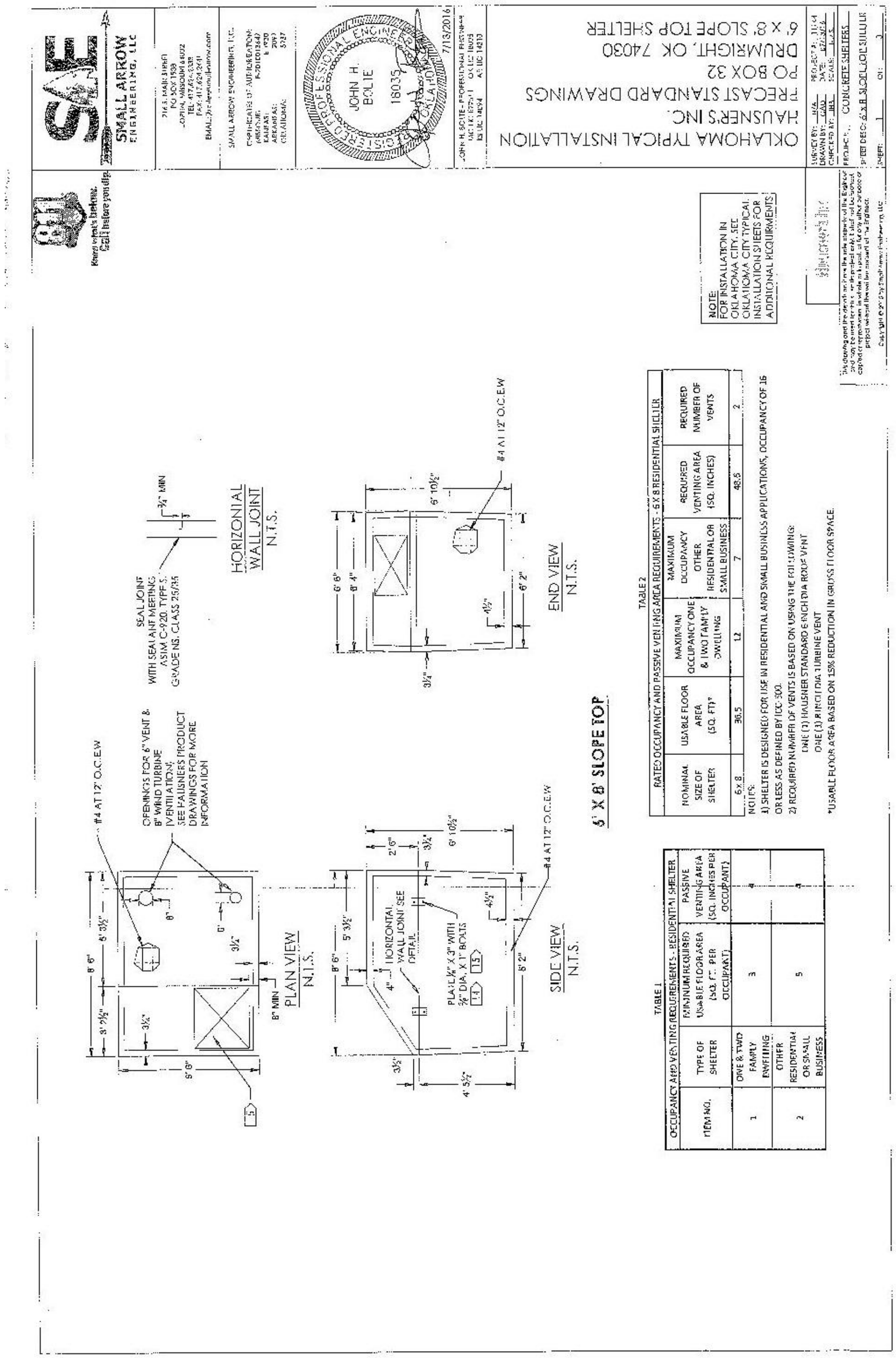
[3] Center for Collision Safety, n.d., “Chevrolet C2500, detailed model,” from https://www.ccsa.gmu.edu/models

[4] OZ Saferooms Tech, 2013, “Nine-Six OZ Saferoom,” Engineering Drawing.

[5] FHWA, 2004,”Evaluation of LS-DYNA Soil Material Model 147,” FHWA-HRT-04-094.

[6] Parfilko, Y., Amaral de Arruda, F., and Varela, B., 2017, “Finite Element Analysis of OZ Saferoom,” Rochester Institute of Technology, Rochester, NY.

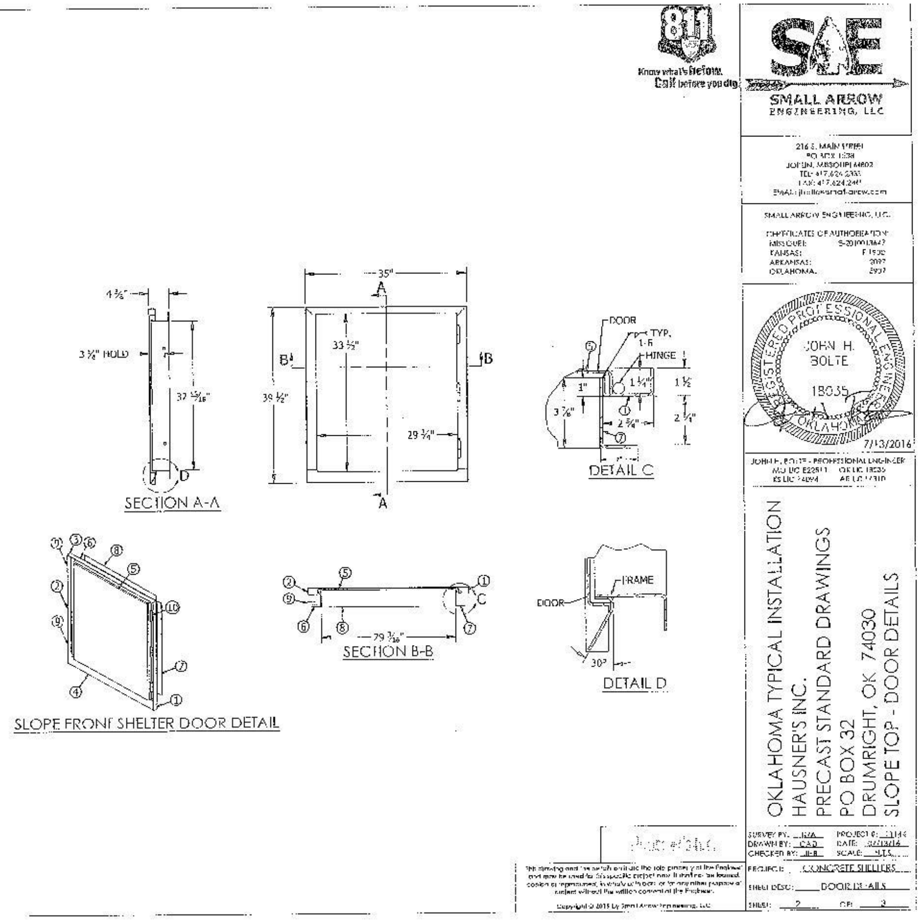
11. Appendix 1



Parts List		
ITEM	QTY	DESCRIPTION
1	1	(BOX FRM RIGHT) SHEET,HRS, 10GA
2	1	(BOX FRM LEFT) SHEET,HRS,10GA
3	1	(BOX FRM TOP) SHEET,HRS,10GA
4	1	(BOX FRM BTM) SHEET,HRS,10GA
5	1	(DOOR) SHEET,HRS,12GA
6	1	(INSIDE FRM LEFT) SHEET,HRS,10GA
7	1	(INSIDE FRM RIGHT) SHEET,HRS,10GA
8	2	(INSIDE FRM TOP/BTM) SHT,HRS,10GA
9	2	PIPE,CARBON STEEL,3/8"SCH40 X 3" LG (IN LEFT FRAME)
10	3	LIFT-OFF WELDABLE DOOR HINGE, MCMASTER-CARR #0636A200

GENERAL NOTES - DOOR

1. STRUCTURAL STEEL SHALL COMPLY WITH ASTM A 36 (STRENGTH = 36 KSI MIN.)
2. GAS SPRING DOOR CLOSER INCLUDED BUT NOT SHOWN 19.09" EXTENDED 7.87" CLOSE 56.2 LBS PRESSURE
3. WELDING SHALL COMPLY WITH AWS D1.1
4. HANDLE INCLUDED BUT NOT SHOWN BOLTED AT 4 POINTS WITH INSIDE OR OUTSIDE OPERATION. SECONDARY SPRING LATCHES WELDED TO INSIDE DOOR SKIN.
5. MODIFICATION OR ALTERATION OF THE DESIGN SHALL BE APPROVED BY THE ENGINEER COPYRIGHT HAUSNER'S INC.
6. SHELTER IS COMPLIANT WITH FEMA 320 FOR WIND AND MISSILE IMPACT FOR 250 MPH WINDS (3 SECOND GUST) FOR ZONE IV GEOGRAPHIC REGION. MISSILE IMPACT TESTING WAS COMPLETED BY TEXAS TECH WIND RESEARCH CENTER. MEETS OR EXCEEDS ICC 500.
7. DESIGNER CANNOT PREDICT ACTUAL PERFORMANCE BUT DESIGN INCORPORATES CURRENT KNOWLEDGE TO BEST PROTECT THE OCCUPANTS. NOT RESPONSIBLE FOR ACTUAL, INCIDENTAL, CONSEQUENTIAL DAMAGES FROM USE OF SHELTER.



GENERAL NOTES

1. THIS DESIGN CONFORMS TO ICC 500(2014), AND RECOMMENDATIONS OF FEMA P-320, FOURTH ADDITION, AND FEMA P-361, THIRD EDITION FOR RESIDENTIAL SAFE ROOMS.
2. THIS DESIGN IS BASED ON THE RECOMMENDATIONS OF THE FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA) PUBLICATION 361, AND IT IS INTENDED TO PROVIDE HIGH DEGREE OF OCCUPANT PROTECTION DURING SEVERE WINDSTORMS.
3. THE INSTALLATION CONTRACTOR SHOULD PROVIDE MEANS OF ACCESS TO THE SHELTER ACCORDING TO THE LOCAL BUILDING CODE REQUIREMENTS.
4. THE SHELTER IS DESIGNED TO SUPPORT THE FOLLOWING LOADS: (SEE DESIGN CRITERIA BELOW)
5. SEE HAUSNERS PRODUCT DRAWINGS FOR MORE INFORMATION ON DOOR OPENINGS AND VENTS. MISSILE IMPACT TESTING WAS COMPLETED BY TEXAS TECH WIND RESEARCH CENTER.
6. IT IS ADVISED NOT TO USE SHELTER IN A FLOOD HAZARD ZONE AS DEFINED BY FEMA.
7. DESIGNER CANNOT PREDICT ACTUAL PERFORMANCE BUT DESIGN INCORPORATES CURRENT KNOWLEDGE TO BEST PROTECT THE OCCUPANTS. NOT RESPONSIBLE FOR ACTUAL, INCIDENTAL, CONSEQUENTIAL DAMAGES FROM USE OF SHELTER.
8. ANY MODIFICATION OR ALTERATION OF THE DESIGN SHALL FIRST BE APPROVED BY THE ENGINEER.
9. IN AREA OF THE SHELTER PLACEMENT, EXISTING ORGANIC MATERIAL, UNSUITABLE SOIL, ABANDONED FOOTINGS, AND ANY OTHER EXISTING UNSUITABLE MATERIALS SHALL BE REMOVED.
10. CONSULT WITH LOCAL CODE OFFICIAL FOR VAPOR RETARDER RECOMMENDATIONS.
11. NOT ALL OPENINGS ARE SHOWN IN THESE DRAWINGS. ESTABLISH AND VERIFY ALL OPENINGS AND INSERTS FOR MECHANICAL, PLUMBING, AND ELECTRICAL WITH APPROPRIATE TRADES, DRAWINGS, AND SUBCONTRACTORS PRIOR TO CONSTRUCTION. OPENINGS MAY REQUIRE ADDITIONAL REINFORCING OR SUPPORTS AS SHOWN ON TYPICAL DETAILS. OPENINGS NEED TO BE PROTECTED PER ICC 500 SECTIONS 310.1 AND 306.3.
12. COMPLETE INSPECTION REQUIREMENTS SHALL BE AS DIRECTED BY THE LOCAL BUILDING DEPARTMENT.
13. THIS CERTIFICATION AND DESIGN IS VALID FOR THE SHELTER SHOWN IN TABLE 2 (SHEET 1).
14. OCCUPANCY AND VENTING REQUIREMENTS ARE SHOWN IN TABLE 1 (SHEET 1).
15. OCCUPANCY RATING SHALL BE AS SHOWN IN TABLE 2 (SHEET 1).
16. VENTILATION IS TO BE PROVIDED IN ACCORDANCE WITH THE LOCAL BUILDING CODE. PASSIVE VENTILATION SHALL BE PROVIDED AS SHOWN IN TABLE 2 (SHEET 1).

ABBREVIATION LEGEND

ACI	AMERICAN CONCRETE INSTITUTE
ASTM	AMERICAN SOCIETY OF THE INTERNATIONAL ASSOCIATION FOR TESTING AND MATERIALS
ASSY	ASSEMBLY
AWS	AMERICAN WELDING SOCIETY
CONC	CONCRETE
CONT	CONTINUOUS
DIA	DIAMETER
EW	EACH WAY
HORIZ	HORIZONTAL
ID	INSIDE DIAMETER
KSI	KIPS PER SQUARE INCH
LB	POUNDS
MAX	MAXIMUM
MFR	MANUFACTURER
MIN	MINIMUM
MISC	MISCELLANEOUS
NTS	NOT TO SCALE
OC	ON CENTER
PCF	POUNDS PER CUBIC FOOT
PSF	POUNDS PER SQUARE FOOT
PSI	POUNDS PER SQUARE INCH
REINF	REINFORCING
SF	SQUARE FOOT
SPEC	SPECIFICATIONS
T&B	TOP AND BOTTOM
TYP	TYPICAL
UNO	UNLESS NOTED OTHERWISE
W/	WITH

DESIGN CRITERIA

1. DESIGN CODES: ICC 500 (2014) / IBC 2015 / ASCE 7-10
   - RISK CATEGORY II
2. GRAVITY LOADS:
   - A. TYPICAL DEAD LOAD: SELF WEIGHT
   - B. LIVE LOADS:
     - TYPICAL ROOF LIVE LOAD (Lr): 100 PSF MIN
     - TYPICAL FLOOR LIVE LOAD (L): 40 PSF MIN
3. LATERAL LOADS:
   - A. WIND LOADS:
     - WIND SPEED: 250 MPH
     - WIND IMPORTANCE FACTOR (I): 1.0
     - EXPOSURE CATEGORY: C
     - DIRECTIONALITY FACTOR (Kd): 1.0
     - TOPOGRAPHIC FACTOR (Kzt): 1.0
     - INTERNAL PRESSURE (GCpi): ±0.18
   - B. SEISMIC LOADS
     - IN AREAS OF HIGH OR MODERATE SEISMIC DESIGN, CONSULT THE ENGINEER.

FABRICATION / CONSTRUCTION NOTES

1. CONSTRUCTION DRAWINGS SHALL NOT BE SCALED. DIMENSIONS APPLY. SIZES NOTED ARE MINIMUM.
2. CONTRACTOR SHALL VERIFY ALL DIMENSIONS BEFORE CONSTRUCTION.
3. THE DRAWINGS REPRESENT THE FINISHED STRUCTURE. THE CONTRACTOR IS SOLELY RESPONSIBLE FOR PROVIDING ALL MEASURES NECESSARY TO ENSURE THAT THE STRUCTURE IS PROTECTED DURING CONSTRUCTION. THESE MEASURES INCLUDE BUT NOT LIMITED TO SHORING AND BRACING FOR CONSTRUCTION LOADS AND WORKER SAFETY.
4. ALL CONCRETE SHALL OBTAIN A MINIMUM COMPRESSIVE STRENGTH OF 6000 PSI AT 28 DAYS. MATERIAL SHALL MEET THE REQUIREMENTS OF ACI 318. MAXIMUM WATER TO CEMENT RATIO SHALL BE .46 (NON-AIR ENTRAINED). SLUMP RANGE SHALL BE 5 TO 9 INCHES.
5. SEE HAUSNERS PRODUCT DWG FOR MORE INFORMATION ON ENTRY/EGRESS DOOR ASSY (SHEET 2).
6. REINFORCING STEEL SHALL CONFORM TO THE REQUIREMENTS OF ASTM A615. REINFORCING SHALL BE GRADE 40 (Fy=40 KSI) DEFORMED BARS FOR ALL BARS UNLESS NOTED OTHERWISE ON PLANS OR DETAILS.
7. ALL REINFORCING SHALL BE BENT COLD. BARS SHALL NOT BE STRAIGHTENED AND RE-BENT. FIELD BENDING OF REBAR SHALL NOT BE ALLOWED UNLESS SPECIFICALLY NOTED OTHERWISE.
8. REINFORCING BAR SPACING SHOWN ON PLANS ARE AT MAXIMUM ON CENTERS. ALL BARS SHALL BE DETAILED AND PLACED WITHIN 1/2" TOLERANCE IN ANY DIRECTION. SECURELY TIE ALL BARS IN LOCATION BEFORE PLACING CONCRETE.
9. REINFORCING BAR CLEAR COVER MINIMUM REQUIREMENTS (UNLESS OTHERWISE NOTED):
   - a. CONCRETE PLACED AGAINST EARTH: WALLS - 1" BOTTOM - 2 1/4"
   - b. ALL INSIDE SURFACES: 1"
10. PROVIDE BAR SUPPORTS: BOLSTERS, CHAIRS, SPACERS, AND OTHER DEVICES FOR SPACING, SUPPORTING, AND FASTENING REINFORCING BARS AND WELDED WIRE REINFORCEMENT IN PLACE. MANUFACTURE BAR SUPPORTS FROM STEEL WIRE, PLASTIC, OR PRECAST CONCRETE ACCORDING TO CRSI's "MANUAL OF STANDARD PRACTICE".
11. STRUCTURAL STEEL PLATE SHALL COMPLY WITH ASTM A1011 OR A1018 GRADE 36, OR ASTM A36.
12. ALL METAL SHALL BE PAINTED AND PRIMER COATED AND OR EQUAL TO FORM A PROTECTIVE FINISH OVER THE BARE METAL.
13. ALL OTHER NUT AND BOLT HARDWARE SHALL BE GALVANIZED, NICKEL PLATED, OR CADMIUM PLATED STEEL.
14. INSTALL HAUSNER'S 5/8" THREADED STEEL INSERT. THREADED INSERT PLACEMENT TO COINCIDE WITH REINFORCING BAR.
15. INSTALL ON "SIDE" WALLS ONLY.

DESIGN CRITERIA - CONTINUED

4. MISSILE IMPACT CRITERIA:
   - VERTICAL SURFACES: 15 POUND 2x4 AT 100 MPH
   - HORIZONTAL SURFACES: 15 POUND 2x4 AT 67 MPH
5. LATERAL SOIL PRESSURE LOAD:
   - 60 PSF MINIMUM ACTIVE PRESSURE PER FOOT OF (SOIL) DEPTH, IN ACCORDANCE WITH IBC 2015
   - OR
   - THE PRESSURE FROM SUBMERGED OR SATURATED SOIL PRESSURES INCLUDING THE WEIGHT OF THE BUOYANT SOIL PLUS THE HYDROSTATIC LOADS.
6. LATERAL LIVE LOAD SURCHARGE:
   - LATERAL EARTH SURCHARGE LIVE LOAD ON THE WALLS OF THE SHELTER FROM A VEHICULAR LOAD PER AASHTO SECTION 3.11.6.4, TABLE 3.11.6.4-1.

SAE
SMALL ARROW ENGINEERING, LLC

216 S. MAIN STREET
PO BOX 1539
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SMALL ARROW ENGINEERING, LLC
CERTIFICATES OF AUTHORIZATION:
MISSOURI: C 2010013547
KANSAS: E-1930
ARKANSAS: 2257
OKLAHOMA: 5937

REGISTERED PROFESSIONAL ENGINEER
JOHN H. BOLTE
18035
OKLAHOMA
7/13/2016

JOHN H. BOLTE - PROFESSIONAL ENGINEER
MO LIC E22511 OK LIC 18035
KS LIC 14094 AR LIC 14516

OKLAHOMA TYPICAL INSTALLATION
HAUSNER'S INC.
PRECAST STANDARD DRAWINGS
PO BOX 32
DRUMRIGHT, OK 74030
SLOPE TOP SHELTER NOTES

Hausner's Inc

SURVEY BY:	N/A	PROJECT #:	11144
DRAWN BY:	CAD	DATE:	07/13/16
CHECKED BY:	JHB	SCALE:	N.T.S.
PROJECT:	CONCRETE SHELTERS		
SHEET DESC:	SLOPE TOP SHELTER NOTES		
SHEET:	3	OF:	3