Finite Element Analysis of Saferooms Subjected to Tornado Impact Loads

Y Parfilko¹, F Amaral de Arruda² and B Varela³

¹ Graduate Student, Dept. of Mechanical Eng., Rochester Institute of Technology, Rochester, NY, USA
² Graduate Student, Dept. of Mechanical Eng., Rochester Institute of Technology, Rochester, NY, USA
³ Associate Professor, Dept. of Mechanical Eng., Rochester Institute of Technology, Rochester, NY, USA

E-mail: bexveme@rit.edu

Abstract. A Tornado is one of the most dreadful and unpredictable events in nature. Unfortunately, weather and geographic conditions make a large portion of the United States prone to this phenomenon. Tornado saferooms are monolithic reinforced concrete protective structures engineered to guard against these natural disasters. Saferooms must withstand impacts and wind loads from EF-5 tornadoes – where the wind speed reaches up to 150 m/s (300 mph) and airborne projectiles can reach up to 50 m/s (100 mph). The objective of this work is to evaluate the performance of a saferoom under impact from tornado-generated debris and tornado-dragged vehicles.

Numerical simulations were performed to model the impact problem using explicit dynamics and energy methods. Finite element models of the saferoom, windborne debris, and vehicle models were studied using the LS-DYNA software. RHT concrete material was used to model the saferoom and vehicle models from NCAC were used to characterize damage from impacts at various speeds. Simulation results indicate good performance of the saferoom structure at vehicle impact speeds up to 25 meters per second. Damage is more significant and increases nonlinearly starting at impact velocities of 35 m/s (78 mph). Results of this study give valuable insight into the dynamic response of saferooms subjected to projectile impacts, and provide design considerations for civilian protective structures. Further work is being done to validate the models with experimental measurements.

1. Introduction

Tornado saferooms are monolithic civilian protective structures engineered to guard against severe natural disasters such as tornados. An estimated 25,000 tornado saferooms were constructed with the support of FEMA [1], and an average of 1253 tornadoes affect US communities every year [2]. Despite the demand for saferooms and shelters, setting forth rigorous standards for the durability and damage protection has proved challenging due to the unpredictable nature of the damage expected from a tornado. In addition to high wind loads, tornadoes cause damage due to windborne debris. Figure 1 shows a saferoom in the aftermath of a tornado with a wide range of debris in the foreground, which could include projectiles such as trees, metal poles, and vehicles.
To assess the effectiveness of a tornado saferoom - defined as “the reduction in the likelihood of severe or fatal injury” [3] – our research team examined a wind-accelerated vehicle impacting a monolithic saferoom. The scope of the study was limited to collisions at the center of the wall or ceiling slab, since previous work [4] has shown the slab is prone to deformation and spalling there.

The saferoom used throughout this study was modeled after an existing product supplied by OZ Saferooms in Oklahoma. The saferoom is a monolithic room with reinforced concrete walls and ceilings, and can fit 6-8 people. External dimensions are 3.3 x 3.3 x 2.6 m and the enclosed area is 8.4 m². The goal in the following simulations was to characterize damage from a windborne vehicle impact, which are likely to be left abandoned in the vicinity during a tornado and are massive enough to pose a threat to the safety of occupants.

2. Methodology
The simulation was performed in the commercial finite element software LS-DYNA. The software is widely used in industry for impact modeling and offers a database of material models, robust contact algorithms and accurate timestep control. The following sections cover in detail the modeling and simulation procedure.

2.1 Concrete and soil material models
The concrete material used was the RHT model developed by Riedel, Hiermaier & Thoma at the Ernst Mach Institute [5]. The model incorporates a standard Mie-Grüneisen equation of state to describe the pressure-volume relation during shock loading, but includes additional models to track compaction and strain-rate dependence on material strength. The failure surface of a concrete element is described by a continuous smooth cap function, shown in Figure 2. A continuous surface cap is a robust way of modeling multimodal failures in concrete materials, since tensile, shear and compaction failures intersect smoothly. For elements exceeding the yield surface, the RHT model tracks cumulative damage by integrating the plastic strains and normalizing the value to the ultimate failure strength of concrete. The resulting damage variable is a useful visualization tool that shows damage from plastic strains on a scale of 0 to 1, and indicates zones of compaction, shear, or tensile cracking.
The soil in which the saferoom is grounded was modeled using LS-DYNA model MAT_147 [7], which utilizes a modified Mohr-Coulomb failure surface. The material models soil in civil engineering applications where the soil has at least one unconfined surface and was developed for the Federal High Way Administration. Material properties were taken from calibration tests conducted at University of Nebraska, the bulk modulus is approximately related to that of sand.

The full-scale saferoom mesh was assembled in ANSYS. The saferoom had its walls sectioned to enable a structured hexahedral mesh, which is recommended for impact applications [5]. The impacted wall mesh was refined to 30 mm in contrast to 50 mm in the other saferoom regions. The total saferoom mesh had from 210,000 to 470,000 elements, depending on the location of the refined region: roof, side or front wall. The RHT concrete, with compressive strength of 35.4 MPa, was applied to all shelter geometry. Reinforcement was modeled as purely elastic beam elements with properties of #4 rebar with a yield stress of 270 MPa and standard properties of steel. Rebar was coupled to the concrete through a Constrained Lagrange in Solid formulation.

2.2 Vehicle Model
For this series of simulations a Chevrolet C2500 Pickup model was selected from the National Crash Analysis Center Finite Element Model Archive. This model has been developed by NCAC of The George Washington University under a contract with the FHWA and NHTSA of the US DOT [8]. Figure 3 shows the cross section of the C2500 pickup FE model. The pickup has a substantial mass of 2000 kg, providing a more critical impact scenario in comparison with passenger vehicles. Preliminary rigid wall crash simulations were performed to evaluate the stability of the C2500 model.

2.3 Contact formulation and boundary conditions
Each simulation tracked 0.200 s of impact between the vehicle and saferoom at a velocity of 15.6 m/s (56.3 km/h). Compressive loads were transmitted by an automatic contact formulation based on penalty coupling. Time steps on the order of a microsecond were used, with the solver controlling time step scaling during the solution. The vehicle and saferoom were constrained only by contact pressures, while the soil was bounded by rigid constraints on the sides and bottom. A damage variable based on the Continuum Damage Mechanics Model [5], was utilized to track development of cracking zones.
Figure 4. Model of the vehicle and the saferoom. The green wall shows the contact area. The elements in red represent the soil foundation.

3. Simulation Results

Three possible scenarios were analyzed in this work, as shown in Figure 5. In the first scenario, a head-on collision is simulated into the center of the side wall. In the second scenario, an airborne vehicle crashes into the roof of the structure. In the third case, a rolling vehicle hits the front wall of the structure, which contains a doorway. Although the vehicle was significantly damaged, this work focuses on the damage patterns in the concrete only.

Figure 5. Three cases examined for vehicle impact.

3.1 Head-on collision into side wall.

In Scenario 1, localized damage forms on the outer surface, with no damage effects on the inner face. The wall has a maximum displacement of 1.65 mm, of which 1.13 mm corresponds to global displacement of the structure in the soil, and 0.68 mm corresponds to the slab deflection. Figure 6 shows the time history of a representative node in the center of the impact region. No global damage was observed in the structure. Sharp corners and ventilation holes experienced stress concentrations, but this result is mesh-dependent.
3.2 Free-fall collision into roof.
In Scenario 2, the “falling” vehicle was assumed to have a downward velocity similar to Scenario 1, and included effects of gravitational acceleration. The roof of the saferoom is much thicker than the walls, and as a result the deflection is not as significant. However, due to compaction of the concrete in the impact region, the local damage is more severe, as shown in Figure 7. Figure 8 shows the absolute structural displacement and the relative slab displacement.

![Figure 6](image1.png)  ![Figure 7](image2.png)  ![Figure 8](image3.png)

**Figure 6.** Relative and global displacement components of a node in the center of the impact region.

**Figure 7.** Damaged zones in the roof slab. A cross-section shows the depth of damage. On the right, the time history of the average damage progression (blue) is shown relative to the stress (red).

**Figure 8.** Relative and global displacement components of a node in the center of the impact region.

3.3 Sideways collision into doorway.
In Scenario 3, the vehicle impacted the doorway from the side, giving the most distributed impact area. The velocity and momentum of the vehicle were the same as in the previous scenarios, but the impact surface of the saferoom contained two unsupported edges. The test was carried out to determine potential weak spots in the design that would be prone to cracking damage instead of
catastrophic breakage. Figure 9 shows that after the impact, damage is localized in three zones, with an average of 40% damage (using RHT damage variable). The damage represents plastic tensile strain and cracking that would occur during the first, or perhaps subsequent impacts.

![Figure 9](image_url)

**Figure 9.** Damage from cumulative tensile strain is shown on the front, cross-section and back of the doorway. Damage penetrates through the plane of rebar. Two cracks form on the outside surface near the top and bottom of the doorway, one crack forms midway on the inside surface.

4. Conclusions

Three distinct scenarios modelled possible impacts of a car into a tornado saferoom. Vehicles are complicated projectiles that behave as rigid bodies at large scales, but deform at the contact area. In these scenarios, the saferoom was grounded in soil and not externally constrained. The simulation supports the hypothesis that the saferoom will not tip over or sustain structural failure in a vehicle crash. Overall, the tests confirm that a properly constructed saferoom can protect the lives of its occupants.

Scenario 1 shows that local deflections and global displacements do occur during a wind driven head-on collision, and that these displacements are on the same order of magnitude and must be studied concurrently. Scenario 2 extends these findings for airborne vehicles subject to initial velocity and gravitational acceleration. No life-threatening damage was observed in the roof and no evidence of spalling on the inside walls was found. Scenario 3 shows that the front face of the saferoom is the relatively weak region in its design. The saferoom in this configuration has the greatest plastic strain and deformation, and potential damage zones develop on the top and bottom edges of the exterior face of the saferoom wall. These include crack nucleation zones, and repeated stress is expected to cause crack propagation across the face of the wall. These results give important considerations when designing and installing a saferoom, especially when the location is close to a highway.
5. Acknowledgments
The authors would like to extend their gratitude to OZ Saferooms for their generous support of this research program. Additional thanks to the Rochester Institute of Technology Depts. of Mechanical Engineering and Research Computing.

References
[1] United States. Federal Emergency Management Agency., National Association of Home Builders of the United States., and Texas Tech University., *Taking shelter from the storm building a safe room for your home or small business*, 4th ed. Washington, DC: FEMA, 2014.
[2] S. P. Center, "U.S. TORNADOES* (1950-2015) ", ed. Online.; [http://www.spc.noaa.gov/wcm/#data](http://www.spc.noaa.gov/wcm/#data), 2016.
[3] United States Federal Emergency Management Agency, "Design and Construction Guidance for Community Saferooms", FEMA P-361, Second Edition, August 2008.
[4] Y. Parfilko and B. Varela, "Simulating Debris Impacts Into Tornado Saferooms with LS-DYNA," Canadian Congress on Applied Mechanics, London, On. Canada, 2015, pp. 339-341.
[5] T. Borrvall and W. Riedel, "The RHT Concrete Model in LS-DYNA," LS-DYNA Users Conference, 2011.
[6] US Department of Transportation. "Users Manual for LS-DYNA Concrete Material Model 159". Federal Highway Administration FHWA-HRT-05-062. May 2007.
[7] "LS-DYNA Keyword User's Manual," R7.1 ed: Livermore Software Technology Corp., 2014.
[8] NCAC. Finite Element Model of C2500 Pickup Truck. Model Year 1994, Version 7; October 2008. [http://www.ncac.gwu.edu/vml/models.html](http://www.ncac.gwu.edu/vml/models.html)