International Specialty Conference on Cold-Formed Steel Structures

Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures 2018

Nov 7th, 12:00 AM - Nov 8th, 12:00 AM

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Recommended Citation

Early, Adrianna M.; Mohammadi, M. Ebrahim; Wood, Richard L.; and Peterman, Kara D., "Behavior of Cold-Formed Steel Metal Industrial Buildings" (2018). *International Specialty Conference on Cold-Formed Steel Structures*. 1.
https://scholarsmine.mst.edu/isccss/24iccfss/session8/1

Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 7 & 8, 2018

Behavior of Cold-Formed Steel Metal Industrial Buildings

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Abstract

This paper presents research focused on understanding the observed behavior of cold-formed steel (CFS) metal buildings during Hurricane Harvey, which made landfall Friday, August 25, 2017 between Port Aransas and Port O'Connor, Texas. Through the Geotechnical Extreme Event Reconnaissance (GEER) association (funded by the National Science Foundation) a team of structural engineers and researchers performed rapid and detailed assessments of structural damage caused by the hurricane. The National Science Foundation gathered photographs, damage assessments sheets, and three-dimensional laser point cloud data of severely damaged cold-formed steel industrial buildings. The Port Aransas County Airport experienced severe damage to several cold-formed steel small aircraft hangars. The failure of one of these hangars is the basis for this investigation. The laser point cloud data was utilized to create a model of a hangar structure in MASTAN2. Multiple analyses were completed in MASTAN2 to determine the failure mode and damage propagation mechanisms. Also, analyses were completed to determine the behavior of the undamaged structure and the structure after loss of the hangar doors. The objective of this research is to determine the behavior of cold-formed steel structures under extreme loads to form

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recommendations for future construction. Furthermore, this work is among the first to use post-disaster data to examine structural cold-formed steel performance.

Introduction

The behavior of structures under extreme loading conditions for hot-rolled steel and structural cold-formed steel structures is a complicated field of research that continues to expand after each natural disaster, specifically hurricanes. Most of the research on structural cold-formed steel focuses on individual cold-formed steel structural components rather than the entire structural system, such as roofing systems, cladding, columns, shear walls, gravity walls, and diaphragms. Most research that analyzes structures under extreme loading utilizes experimental data from a laboratory setting to analyzes the behavior of the structure.

The research presented in this paper is one of the first to focus on the behavior of a cold-formed steel structural system under extreme loading conditions, and to utilize post-disaster data to observe the behavior of the cold-formed steel structural system. This research is a part of a larger effort to develop an understanding of the behavior of structures under extreme loading conditions, such as natural disasters. Additional research observing the performance of structures under extreme loading conditions utilizing post-disaster data from Hurricane Harvey is being conducted at universities across the nation, such as the University of Massachusetts Amherst, University of Nebraska-Lincoln, and Notre Dame University.

This paper presents the results of this research, which were obtained by running a multitude of analyses in MASTAN2. Laser point cloud data was utilized to provide global and cross-section geometries for the hangar structure in MASTAN2, and the American Society of Civil Engineers (ASCE 7-10 and ASCE 7-93) codes were used to determine loading conditions. In addition, ASCE 7-10 and ASCE 7-93 codes were used to determine and compare the adequacies of current and previous design code standards. The objective of this research is to determine the behavior of cold-formed steel structural systems under extreme loading conditions to make recommendations for future design and code standards to hopefully increase structural resilience against natural disasters.

Literature Review

Simulation research has been completed to analyze how buildings and roofs act during a wind storm. One simulation test commonly practiced is the pull-over strength test (AISI, 2008) that is designed to mimic the wind uplift and suction of wind storms. At the University of Florida, Ellifritt et al. (1990) conducted pull-over testing that is in accordance with the American Iron and Steel Institute's testing specification. The test conducted by Ellifritt et al. (1990) was used as a basis for the specification presented in the 1992 Cold-Formed Steel Manual. The objective of these experiments was to simulate a real roof system in a building subjected to wind uplift or suction to determine how much force would be required to pull fasteners through the roof panel (Ellifritt et al.1990). The pull-over test simulated both dynamic and static wind suction conditions. Results and analysis of the pull-over test determined that a factor of 0.4 when applied to the test would provide a good estimate of the strength of the fastener in real applications. It is extremely important to note that this is only applicable to Grade E cold-formed steel and configurations identical to the conditions specified in the experimental program (Ellifritt et al. 1990). Although this research is relatively dated, it provides important and relevant insight to the performance of cold-formed steel roof fasteners under extreme static and dynamic wind conditions. This is applicable to this research because a substantial portion of the roof of the hangar structure collapsed, which in speculation is believed to be the cause of the full structural collapse.

In addition to Ellifritt et al (1990) studying the strength of roofing components, Fehr et al. (2012) conducted flexural strength tests of roof joists in a standing seam roof. The objective of the experiments performed on open-web steel joists laterally braced by a standing seam roof was to determine the strength of the joists and to determine the most likely failure modes of the joists (Fehr et al. 2012). An open-web steel joist is a light-weight truss system made of triangulated webs and chords, which typically supports the roofing component exposed to the wind, rain, and snow (Fehr et al. 2012). The experimental program was designed to perform flexural tests on open-web steel joists systems that simulated real seam roof applications. Results of test and analysis determined that most of the joist failed by out-of-plane buckling (Fehr et. al 2012).

Results from the experimental program conducted by Fehr et al (2012) were used as a comparison of accuracy for a new strength prediction method of open-web steel joists partially braced by a standing seam roof developed by Moen and colleagues (Moen et al. 2012). The objective of this work was to determine the accuracy of the new strength predication method for open-web steel joists partially braced by a standing seam roof. The predication method is for the top chord lateral flexural buckling limit state. It is important to note that it is assumed the top chord of the joist behaves as a column under varying axial load that has experienced flexural lateral buckling deformations (Moen et al. 2012). The conclusion was that the presented strength method was accurate for predicating the strength of the joists with respect to the conditions outlined in the experiment (Moen et al. 2012). The experimental and analysis work completed by Moen et al. (2012) and Fehr et al. (2012) does not focus on extreme loading condition; however, their work focuses on the strength capacity of light-weight steel roofing systems, which is pertinent to this research. In the hangar structure, the light-weight steel roofing system completely collapsed, thus the research completed by Moen et al. (2012) and Fehr et al. (2012) provides a valuable understanding of the performance of light-weight steel roofing systems.

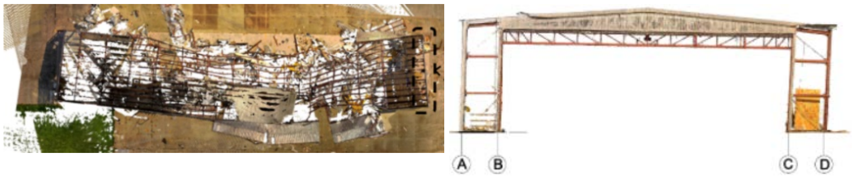
In addition to roofing systems, research studies in the United States have been completed on the seismic response of cold-formed steel structures. A portion of the research focused on the seismic response of cold-formed steel structures is part of the National Science Foundation Network for Earthquake Engineering Simulation (NEES) Research Program at John Hopkins University and Bucknell University. The project that specifically focused on cold-formed steel is titled Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures, shortened to CFS-NEES. Nakata et al. (2012) provide extensive detail on the CFS-NEES multi-year project. The paper also provides extensive detail on the construction and design criteria of the two-story CFS-framed office building used throughout the research program (Nakata et al. 2012).

Peterman et al. (2016 a) performed a phase of CFS-NEES project, which was focused on seismic tests of the two-story cold-formed steel structure. Seismic testing of the building was completed at the University at Buffalo. The two-story CFS-framed office building was tested in two phases. Testing included nondestructive tests, design basis earthquake-level testing, and destructive tests at the maximum considered earthquake level (Peterman et al. 2016 a). Test results and analysis showed that CFS-framed building performed well under seismic excitation. It is important to note that the performance of the CFS-building is relative to the full system-level response (Peterman et al. 2016 a). In a second companion paper, analysis of the subsystem-level results of the same two-story CFS-framed building was completed by utilizing extensive instrumentation to observe the response of components of the building separate from the full-system response (Peterman et al. 2016 b). Even though this work focuses on the performance of structural cold-formed steel under extreme seismic loading and not performance under extreme wind loading, this research is still relevant as it provides a strong basis of how cold-formed steel performs under an extreme loading condition.

One noticeable difference between the research presented in this paper and that of the research in this literature review is that the research presented in this paper utilizes post-disaster data, while the literature review revealed there are very limited research studies that utilize post-disaster data to analyze structural responses. The work presented in this paper utilizes post-disaster data to assess the accuracy of design codes and standards. Also, this research attempts to shrink the gap in the understanding of the performance of cold-formed steel under extreme wind loading conditions. One goal of this research is to start a conversation and inspire future studies of cold-formed steel performance under extreme loading conditions. More importantly, to motivate fellow researchers to get involved in disaster reconnaissance and utilize data from previous storms to better enhance the understanding of the behavior of structures during natural disasters. This is in hopes of creating more adequate design and building codes for all types of structures that will hopefully result in reduced structural failures, collapses, and loss of life in natural disaster events.

This work is motivated by the structural damage caused by Hurricane Harvey. On August 23, 2017, Hurricane Harvey made landfall between Port Aransas and Port O'Connor, Texas. The Hurricane caused $125 billion in damages and destroyed over 135,000 homes (worldvision.org 2018) In early September, the Geotechnical Extreme Event Reconnaissance (GEER) association (funded by the National Science Foundation) sent a team of researchers and structural engineers to parts of Texas to assess the level of damage caused by the Hurricane. During the trip, researchers and engineers filled out detailed rapid damage assessments sheets, photographed damaged structures, and collected laser point cloud data of severely damaged structures. The laser point cloud data has been made available to the public via the University of Nebraska-Lincoln website. The fundamental basis of this research is the laser point cloud data of a severely damaged hangar structure at the Port Aransas County Airport. The hangar structure is constructed of structural cold-formed steel and hot-rolled steel structural members. A photograph of the damaged hangar structure is shown below in Figure 1. Images of the laser point cloud data of the collapsed hangar structure is shown below in Figure 2.

Figure 1 Damaged Hangar Structure at Port Aransas County Airport. Photo taken on September 9, 2017 during GEER reconnaissance trip



(a) birds eye view *(b) X-Y view*

Figure 2: Laser point cloud data of Port Aransas County Airport Hangar, collected using LIDAR sensing

Methodology

The first step of this research was archiving and analyzing data collected by the GEER team of researchers and engineers. Archiving and analyzing the raw data collected by the GEER team showed that Hurricane Harvey destroyed major sections of Port Aransas and Port O'Connor, Texas. In coastal areas, a handful of homes experienced flooding and surge damage caused by the increased flow of the Gulf of Mexico due to the high wind speeds sustained during the Hurricane. In inland areas, extensive wind damage destroyed many homes and large industrial buildings. It was reported that Hurricane Harvey sustained wind speeds up to 136 miles per hour (63 meters per second) (worldvision.org 2018). The design three-second wind gust for Texas in the ASCE 7-10 code is 136 miles per hour (63 meters per second). Based off the data collected on site, it was assumed that the hangar structure was built prior to 2000. Therefore, the structure was not designed to meet the current code standards. However, the extensive damage to the hangar structure suggests the current code (ASCE 7-93) at the time the structure was constructed was not adequate for the building's design life.

Most of the structures in the path of the storm sustained extensive roof damage. In a handful of detailed damaged assessments sheets, severely damaged structures were deemed occupiable. The term occupiable simply means people can safely enter and reside in the building. Occupiable does not infer that the building had running water, electricity, and four walls and a roof. Therefore, most of the damage assessments are misleading without access to the photographs of each site. The damage assessments sheets, photographs, longitude and latitude locations of the sites, and laser point cloud data files have been made available to fellow researchers through the Natural Hazards Engineering Research Infrastructure (NHERI) database.

The laser point cloud data of three cold-formed steel structures were collected in Port Aransas, Texas. Professor Wood and a research student, from the University of Nebraska-Lincoln, carefully collected the laser point cloud data in Port Aransas, and graciously upload the data to the University of Nebraska-Lincoln website for easy access and navigation. The basis of this research is the laser point cloud data of a hangar structure at the Port Aransas County Airport. The hangar structure was constructed of hot-rolled steel and structural cold-formed steel members. The structure had a metal roof covering, which was complete destroyed during Hurricane Harvey. The hanger structure experienced an extensive amount of damage and can be classified as a structural collapse because a large middle portion of the roofing system collapsed on itself and brought the building to the ground.

The laser point cloud data from the collapsed hangar structure was used to determine the structural steel members used to construct the building. Once the structural steel members were determined, a MASTAN2 Model of the hangar structure was created. MASTAN2 drawings of the model are presented below in Figure 4 and 5. The MASTAN2 model was used to analyze the behavior of the structure under the hurricane wind loads. The loading conditions applied in MASTAN2 were determined in accordance to ASCE 7-10 wind design codes and ASCE 7-93 wind design codes. Tables of the loading conditions with respect to windward wall, leeward wall, and roof loads are presented in Table 1, 2, and 3, respectively. The year the hangar structure was built is unknown; however, based off knowledge from the airport Manager and inspection of the structure by the GEER team, it was inferred the structure was built prior to 2000. Therefore, the ASCE 7-93 code was used to determine loading conditions to understand how the designers predicted the structure to act under expected loading conditions. The ASCE 7-10 loading conditions were analyzed to serve as a comparison between older and newer codes to observe the updates to the newer codes. This enables accurate, feasible, and reasonable recommendations to be made to enhance future design codes.

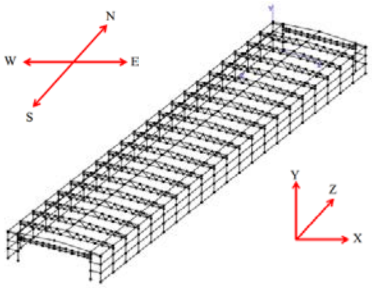


Figure 4 Isometric View of Hangar Structure at Port Aransas County Airport, TX

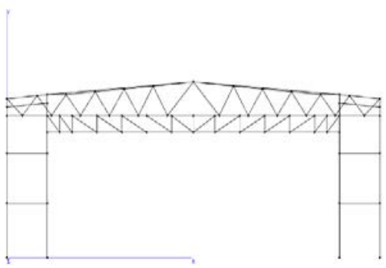


Figure 5 X-Y View of Hangar Structure at Port Aransas County Airport, TX

Table 1 Windward Wall Loading Conditions for ASCE 7-93, ASCE 7-10 Enclosed Structure, ASCE 7-10 Partially Enclosed Structure

Windward Wall Loading Conditions			
	Loads (Kips/in)		
height (in)	**ASCE 7-93**	**ASCE 7-10 Enclosed**	**ASCE 7-10 Partially Enclosed**
0-180	0.0567	0.079	0.014
180-228	0.0597	0.079	0.0169
***Notes:**	Positive loads act toward member		

Table 2 Leeward Wall Loading Conditions for ASCE 7-93, ASCE 7-10 Enclosed Structure, ASCE 7-10 Partially Enclosed Structure

Leeward Wall Loading Conditions			
	Loads (Kips/in)		
height (in)	**ASCE 7-93**	**ASCE 7-10 Enclosed**	**ASCE 7-10 Partially Enclosed**
0-21	-0.041	-0.048	-0.0956
***Notes:**	Negative loads act away from member		

Table 3 Roof Loading Conditions for ASCE 7-93, ASCE 7-10 Enclosed Structure, ASCE 7-10 Partially Enclosed Structure

Roof Loading Conditions			
	Loads (Kips/in)		
distance (in)	**ASCE 7-93**	**ASCE 7-10 Enclosed**	**ASCE 7-10 Partially Enclosed**
0-21	-0.051	-0.172	-1.209
21-42	-0.051	-0.172	-0.899
42-60	-0.047	-0.105	-0.742
***Notes:**	distance is the longitudinal distance from the windward wall		

The ASCE 7 code has differing design loading conditions that are dependent on the type of structure. The hangar structure was analyzed as a main wind force resisting system enclosed rigid structure and a main wind force resisting system partially enclosed rigid structure. The reason the hangar structure was analyzed as an enclosed and a partially enclosed structure is the hangar doors made up a substantial portion of the structure, and the doors were one of the first components to fail during the hurricane. Once the hangar doors were removed, the structure became a partially enclosed, which greatly increases the internal pressure on all walls and the uplift on the roof leading to a more crucial loading condition. The behavior of the hangar structure has been analyzed under extreme loading as a pre-damaged structure and post-damaged structure, deepening the understanding of the performance of cold-formed steel structures under extreme loading conditions. Definitions of building type and equations used to calculate loading conditions can be found in ASCE 7-10 Chapter 26 and Chapter 27, and ASCE 7-93 Chapter 6. In both analyses loading conditions for positive and negative pressures were calculated and analyzed. This paper only reports the most critical loading conditions and results. Below in Figure 6, a representative sketch shows the loading conditions for the north exterior frame. The interior frames and south exterior frame have similar loading conditions only varying in magnitude.

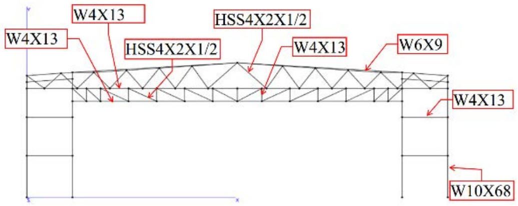


Figure 5 Frames and Callout of W-Shapes in Hangar Structure (X-Y View) Port Aransas County Airport, TX

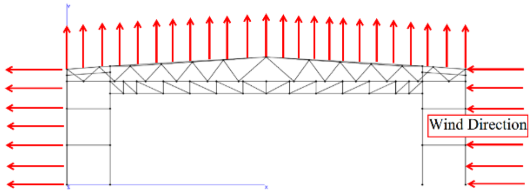


Figure 6 Loading conditions on the north exterior members Arrows do not show magnitude of wind forces.

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Discussion of Results

The MASTAN2 Model was analyzed utilizing ASCE 7-10 Wind Design standards and ASCE 7-93 Wind Design standards. To assess the accuracy of the model the deflections and drifts of the exterior columns were computed and compared to the recorded data collected by the GEER team of engineers and researchers in Port Aransas, Texas. In the MASTAN2 Model, deflection and drift data were computed for the four exterior corners of the hangar structure. The recorded field data deflections and drifts were reported for the four columns of the North exterior frame. Therefore, there are two main reference points between the two data sets: the North East exterior column and the North West exterior column. The recorded field data deflections and drifts are presented below in Table 4. The MASTAN2 Model analysis results of ASCE 7-93 loading conditions for enclosed structures is presented in Table 5. The MASTAN2 Model analysis results of ASCE 7-10 loading conditions for an enclosed structure and a partially enclosed structure are presented in Table 6 and Table 7, respectively.

Table 4 Field Data Obtained from Point Cloud Data

Field Data Recorded by the GEER team						
Deflection (in)				**Drift (%)**		
Corner	X	Z		**Corner**	X	Z
N.E I*	12.60	-67.72		**N.E I**	6.44	34.61
N.W I	6.30	-7.87		**N.W I**	2.99	3.77
N.W E	6.30	-1.57		**N.W E**	2.99	0.75
N.E E	12.20	-74.80		**N.E E**	6.31	38.7
***Notes:**	N.E I = Northeast Interior Column					
	N.W I = Northwest Interior Column					
	N.W E = Northwest Exterior Column					
	N.E E = Northeast Exterior Column					

Table 5 ASCE7-93 Deflection and Drift results from MASTAN2 Analysis

ASCE7-93 Code								
Deflection (in)					**Drift (%)**			
Corner	X	Y	Z		**Corner**	X	Y	Z
S.W E	0.020	0.003	-0.007		**S.W E**	0.009	0.001	0.003
S.E E	-0.534	0.005	0.017		**S.E E**	0.228	0.002	0.007
N.W E	-1.720	-0.011	-0.008		**N.W E**	0.735	0.005	0.003
N.E E	-3.110	-0.036	0.015		**N.E E**	1.329	0.015	0.007

Table 6 ASCE 7-10 Deflection and Drift results from MASTAN2 analysis of an Enclosed structure

ASCE 7-10 Code Enclosed Structure								
Deflection (in)					**Drift (%)**			
Corner	X	Y	Z		**Corner**	X	Y	Z
S.W E*	0.087	0.004	-0.008		**S.W E**	0.037	0.002	0.003
S.E E	-0.625	0.006	-0.449		**S.E E**	0.267	0.003	0.192
N.W E	-2.342	0.029	-0.010		**N.W E**	1.001	0.012	0.004
N.E E	-4.951	0.061	0.482		**N.E E**	2.116	0.026	0.206
***Notes:**	S.W E = Southwest Exterior Column							
	S.W I = Southeast Exterior Column							

Table 7 ASCE 7-10 Deflection and Drift results from MASTAN2 analysis of a Partially Enclosed structure

ASCE 7-10 Code Partially Enclosed								
Deflection (in)					**Drift (%)**			
Corner	X	Y	Z		**Corner**	X	Y	Z
S.W E	4.543	0.064	-0.106		**S.W E**	1.941	0.028	0.045
S.E E	-4.915	0.072	0.156		**S.E E**	2.100	0.031	0.067
N.W E	11.25	0.425	-0.064		**N.W E**	4.808	0.182	0.027
N.E E	-14	0.475	-0.053		**N.E E**	5.983	0.203	0.023

The analysis of the MASTAN2 Model using ASCE 7-93 Wind Design standards showed the building did not fail under the maximum loading conditions considered in the ASCE 7-93 codes. In addition, the ASCE 7-93 code did not accurately predict the actual lateral and longitudinal deflections of the hangar structure. The deflections were consistently lower than the actual deflections and the deflections determined by the ASCE 7-10 analysis. The discrepancies in the data analysis between the ASCE 7-93 and the ASCE 7-10 code can be attributed to the update in code between the two manuals. The ASCE 7-10 is significantly more conservative than the ASCE 7-93. In addition, ASCE 7-93 only defines two buildings types: enclosed and open. However, ASCE 7-10 defines partially enclosed buildings, which yielded the most accurate drift and deflection results of the hangar structure. Also, the maximum design wind speed significantly increased between the two codes. In 1993 the maximum wind speed for Port Aransas, Texas was 95 miles per hour (45 meter per second) and in the 2010 the maximum wind speed for Port Aransas, Texas was 136 miles per hour (61 meters per second). The discrepancies between the 1993 code and the actual deflections and drifts of the hanger structure is due to the static loading conditions defined in ASCE 7-93. The actual hanger structure experienced intense dynamic loading conditions and those dynamic loading conditions were not considered in the MASTAN2 model.

Compared to the GEER team field data, the MASTAN2 Model more accurately predicted lateral deflection than longitudinal deflection. Furthermore, the MASTAN2 Model was analyzed as an enclosed and partially enclosed structure, in accordance to the definitions in ASCE 7-10. The magnitude of deflection and drift between the partially enclosed and enclosed analysis were significantly different. Although, the hangar structure failed in both analysis. In a typical design failure is defined by a drift greater than or equal to 2% in any direction. The maximum drift in the enclosed analysis was 2% compared to the maximum drift of 6% in the partially enclosed analysis. In addition, the MASTAN2 Model analyzed as a partially enclosed model was significantly more accurate in predicting the actual defection and story-drift of the hangar that was caused by Hurricane Harvey. The lateral deflection of the top of the North East Exterior column determined by MASTAN2 Model Partially Enclosed Wind Load analysis was 14 inches (0.36 meters). The GEER team field data deflection of the top of North East Exterior column was recorded as 12.7 inches (0.31 meters). The MASTAN2 model has about a 10% percent error when predicating the lateral deflection of a column. The MASTAN2 Model yields a lateral deflection about 10% greater than the actual lateral deflection caused by Hurricane Harvey.

In terms of longitudinal deflection, the MASTAN2 Model Partially and Fully Enclosed analyses were inaccurate in predicating the actual longitudinal deflection of the columns. Most of longitudinal deflections computed by MASTAN2 were a magnitude lower than the actual longitudinal deflections recorded by the GEER team. The discrepancies in the longitudinal deflection data computed by the MASTAN2 model is most likely attributed to the static wind loading conditions. The actual hangar experienced significant dynamic wind loading and dynamic loading considerations were not considered in the MASTAN 2 Model.

Conclusions

The results of this research show that the ASCE 7 design codes have progressively and successfully become more adequate and accurate at predicting the actual response a structure will have to extreme wind events, such as hurricanes. In addition, engineers should take into consideration and be cautious of the definition of partially enclosed structures in ASCE 7-10. Currently, ASCE 7-10 defines a partially enclosed structure as a structure with each wall at least 80% open. By this definition, the hangar structure after the doors were removed is technically not a partially enclosed structure. However, analysis shows that the deflection and drifts computed using the ASCE 7-10 partially enclosed conditions were significantly more accurate than the results from the analysis that uses the ASCE 7-10 enclosed conditions. Therefore, engineers should be cautious of the meaning of enclosed and partially enclosed and use their engineering judgement to assess the condition rather than blindly following the code definition.

In addition, the partially enclosed analysis presented in ASCE 7-10 adequately predicated the damage caused to the structure after some damage was completed. Prior to damage, the structure was entirely enclosed; however, the hangar doors being ripped off by the high-speed winds create a wind tunnel effect inside the hangar structure. The change in the building geometry during the hurricane transformed the structure into a partially enclosed structure. Also, the change in the building geometry greatly increased the loading conditions the structure experienced; therefore, intensifying deflections and story drift of the structure. The partially enclosed analysis in ASCE 7-10 accurately predicted the lateral deflections the hangar experienced. Thus, practicing engineers should highly considered using the partially enclosed analysis to determine the possible response of a structure during a high wind event.

This research is one of the first to analyze the performance of a structure during extreme loading and utilize actual disaster reconnaissance data to comment on the validity of analyses performed in MASTAN2 and the adequacy of current wind design code standards. The analyses presented in this paper are not a perfect representation of the actual loading conditions the hangar structure experienced during the hurricane. These analyses only examine static loading conditions; however, the hangar structure experience significant dynamic loading conditions during the hurricane. In the future, it would beneficial to include dynamic loading conditions in this analysis to determine if the design codes remain adequate. In general, future research in the field of structural resilience during disasters should focus on utilizing post-disaster relief data to determine the behavior of a building or material under extreme loading conditions. This field of research has the potential to make significant recommendations to enhance design codes, which has the possibility of resulting in more safe and effective structures.

Acknowledgements

The authors of this paper greatly acknowledge the Geotechnical Extreme Event Reconnaissance Association and the National Science Foundation for funding the reconnaissance trip to Port Aransas, Texas. Also, the authors would like to thank the team of engineers and researchers that joined the GEER team in Texas. Any opinions, and recommendations in this paper are representative of the authors only, and do not represent the beliefs nor opinions of the Geotechnical Extreme Event Reconnaissance Association and the National Science Foundation.

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