Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCEI'2006)
"Breaking Frontiers and Barriers in Engineering: Education, Research and Practice"
21-23 June 2006, Mayagüez, Puerto Rico.

Damage of Canopies in Gas Stations due to Hurricanes Katrina and Rita

Luis A. Godoy, Ph. D.
Director, Civil Infrastructure Research Center and Department of Civil Engineering and Surveying,
University of Puerto Rico at Mayagüez, Mayagüez, Puerto Rico 00681-9041, lgodoy@uprm.edu

Augusto Poitevin, P. E.
Doctoral candidate, Department of Civil Engineering and Surveying,
University of Puerto Rico at Mayagüez, Mayagüez, Puerto Rico 00681-9041, poite@msn.com

Abstract

A large number of canopies in gas stations were destroyed by Hurricane Katrina and Rita in the Gulph Coast of the United States in 2005. Canopies are structures formed by columns that support a roof and protect the gas pumps. Most collapses occurred in canopies with a single row of aligned columns, so that they are similar to cantilever structures. Other collapses occurred in canopies supported by two rows of columns. The design of canopies should fall under the category of open structures, but the wind load provisions do not address this topic adequately. This paper reports examples of collapses followed by structural analyses of three cases to illustrate that the columns were overstressed under wind. Further research is needed in this area, and design provisions should be improved to reduce the vulnerability of canopies.

Keywords

Canopies, Civil Infrastructure, Gas stations, Hurricane Katrina, Hurricane Rita, Structures, Wind.

1. Introduction

The hurricane season in 2005 was a devastating test for all infrastructure along the Gulph Coast of the United States (NIST 2006, Fratta and Santamarina 2006, Godoy et al. 2006, Godoy 2006). It has been pointed that storm surge was the most important cause of destruction due to Hurricane Katrina for constructions in general (Robertson et al. 2006), but there are also slender structures that were mainly affected by direct wind pressure. Of particular interest to us, the behavior of canopies in gas stations was observed during the reconnaissance missions carried out by the first author and colleagues to the areas affected by hurricanes Katrina and Rita in 2005. Dozens of collapsed canopies were observed, and only a few cases are discussed in this paper in order to identify basic failure modes and their probable causes.

The design of a gas station is usually provided by the gasoline supplier to the owner of the gas station, who receives plans for the construction. The construction itself, however, is usually carried out by the owner. For this reason, we have been able to find the same canopy design in stations located very close to each other, which failed in different modes associated with different construction details.

Some designs have one row of columns supporting the roof, whereas others have two rows of columns. It seems that the former are one of the preferred options, so that they were found in many locations in Texas and Louisiana, but they have less stiffness and redundancy than the more stable designs supported by two rows of columns. Most examples of failures shown in this paper correspond to the first type of design.

2. Collapse Observations

Figure 1 show schematically the geometry of two Exxon gas stations in Hillerbrandt, TX. The canopy is supported by four 0.30×0.30m columns aligned and equally spaced at 6.75m. A base slab with 125 mm thickness was used. In both cases, the age of the construction was about 7 years, as informed to us by the owner of one of the gas stations.

In the first Exxon station (shown in Figure 2), the canopy was pulled out from its foundation by wind uplift and the columns were lifted except for one. The complete canopy was thrown by the wind against the gas station building, which was some 20 meters away from the original location of the canopy and produced much damage, as seen in Figure 2a. The main reason for this failure seems to be a poor foundation construction, with the columns being buried only 0.30 m (Figure 2b). The station was located in open terrain.

Failure of the canopy in the second Exxon station, shown in Figure 3, was different. The foundation was such that the columns were buried about 1 m in the concrete slab, and resisted well the winds. The failure mode was associated to plastic hinges forming at the base of the columns (Figure 3b), and the canopy rotated as a mechanism, as shown in Figure 3a. The conditions of exposure to wind were similar in the two Exxon stations. A common denominator was that there is no frame action in the structure (since the columns are not attached to beams using rigid connections) with the consequence that the columns work as individual components.

Another failure mode was observed in a Chevron station in Vidor, TX, shown in Figure 4. This canopy was supported by just two aligned columns. The structure failed at its weakest point, which was the base of the columns. This section at the base had extensive corrosion (Figure 4c) and could not take moments or tensile stress as those required to provide equilibrium under wind pressures. The canopy was separated from its foundation and was found across the road some 20 m away from its original location, in an inverted position (Figure 4b). The cause of this failure should be associated to poor maintenance of the structure. The base of the columns was covered by a metal box and probably was never inspected to verify if corrosion was taking place. Across HW 10, there were two other gas stations that did not show any damage in their canopies and were selling gas at the time of the mission.

Another example of corrosion at the base of the columns was found in a gas station in Road 39, Chalmette, LA (Figure 5). Here the connection between the columns and the roof were effective and the structure rotated as a rigid body. Figure 5b shows the signs of corrosion at the base. Again, this column was covered with a metal box (presumably to protect it from the circulating cars) so that it was not visible. The rain water of the roof is usually diverted to the columns and this is a major cause of corrosion at the base.

Failure of the canopy in St. Bernard, LA (Figure 6a), can also be attributed to corrosion at the base of one column (Figure 6.b). The canopy had two columns; the second one did not fail at the base, but there was a failure of the joint with the beams as the roof rotated and collapsed.

The canopy of the Pure gas station in Violet, LA, close to New Orleans, is shown in Figure 7. The overall dimensions of the canopy were 50×6m in plan. It was constructed using five columns with 0.25×0.25m cross section, with spacing between the columns of 10m. Figure 7a shows that the columns did not fail and are still standing after hurricane Katrina, but there was no frame action, so that the roof was pulled out.

Hurricane Katrina destroyed the Chevron gas station in Meraux, LA (Figure 8). The overall dimensions were 16×8m in plan, with two columns at 12.5m, 0.25×0.25m cross section and 6.3mm (1/4in) thickness. Again, the columns did not have a proper connection with the roof beams.

The Texaco station in 39th Road, Port Arthur, TX (Figure 9) collapsed due to failure of the circular columns, initially in a sway mode. This seems to be a design problem, with extremely weak columns that are not capable of withstanding lateral forces. The structure collapsed on top of the gas pumps, producing their destruction (Figure 9a). The beams in the roof seem to be much stronger than the columns, but there is no connection between columns and beams.

A collapsed small canopy was observed in Road 90 and Wright St., New Orleans area (Figure 10). The overall dimensions are 8×8m in plan, with two 0.20×0.20m columns at 4.1m from each other. The beam-column connection did not fail, and fracture failure occurred at the base of one column (Figure 10c). The purlings were constructed hanging from the beams (Figure 10b). All elements were taken by screws.

Partial collapse of a canopy was identified in a Shell station in Port Arthur, TX (Figure 11). This was a station built some 20 years ago. The columns remained standing, and the roof collapsed by punching. Clearly, there is no frame action in the canopy, as the beams were detached from the columns. Other stations close to this one did not show any significant damage.

Other forms of damage were identified in the roof of canopies, as shown in the Chevron station, Port Arthur, TX, in Figure 12. Here the structure remained in good shape, and it was the plates and the sides of the roof that were damaged. The station was operating at the time of the mission..

Table 1 shows a summary of the failure modes observed during the reconnaissance missions, together with design or maintenance problems associated with them.

Probable Cause		**Failure mode**
Design Problems	**Maintenance**	
Weak foundation		Pull out of entire canopy.
Weak columns		Sway collapse.
Weak beam/column joint		Collapse of the roof.
Weak thickness at the base of columns		Plastic hinge at the base. Rigid body rotation of canopy.
	Corrosion at the base of columns	Pull out of entire canopy. Rigid body rotation of canopy.

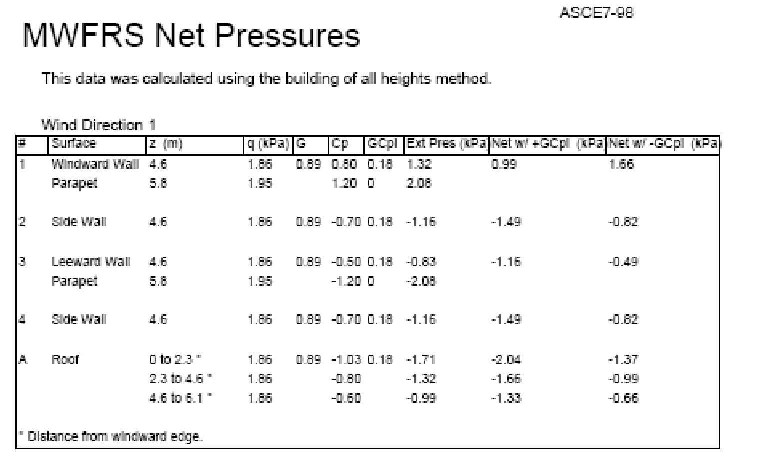
Table 1. Failure modes observed in canopies.

3. Assumed Wind Pressures and Computational Models

Several investigations followed our missions in order to understand the behavior of canopies in gas stations due to wind. There are various uncertainties regarding wind pressures.

The wind design code used for the analysis of structures in the United States is the ASCE 7 (2005). However, the current code is not very clear into what are the roof pressures in open structures, such as canopies. Some research publications suggest that in open structures the wind pressures are higher than in an enclosed structure. For the purposes of this analysis, a first scenario was considered in which only lateral forces were considered.

Experience from other structural types indicates that there may be uplift action on the horizontal surface of the roof, which would contribute to increase tensile stresses in the columns. Thus, a second scenario was assumed in which lateral pressures as well as suction were included in the loading conditions. The uplift pressures applied to the canopies were the wind pressures of an enclosed structure, and are indicated in Table 2.



ASCE7-98

MWFRS Net Pressures

This data was calculated using the building of all heights method.

Wind Direction 1

#	Surface	z (m)	q (kPa)	G	Cp	GCpi	Ext Pres (kPa	Net w/ +GCpi (kPa	Net w/ -GCpi (kPa
1	Windward Wall	4.6	1.86	0.89	0.80	0.18	1.32	0.99	1.66
	Parapet	5.8	1.95		1.20	0	2.08		
2	Side Wall	4.6	1.86	0.89	-0.70	0.18	-1.16	-1.49	-0.82
3	Leeward Wall	4.6	1.86	0.89	-0.50	0.18	-0.83	-1.16	-0.49
	Parapet	5.8	1.95		-1.20	0	-2.08		
4	Side Wall	4.6	1.86	0.89	-0.70	0.18	-1.16	-1.49	-0.82
A	Roof	0 to 2.3 *	1.86	0.89	-1.03	0.18	-1.71	-2.04	-1.37
		2.3 to 4.6 *	1.86		-0.80		-1.32	-1.66	-0.99
		4.6 to 6.1 *	1.86		-0.60		-0.99	-1.33	-0.66

* Distance from windward edge.

Table 2: Wind provisions according to ASCE-7.

Various cases were analyzed using three dimensional computer programs. The structural analysis program ETABS (2002) was used for the analyses. Linear elastic analyses were performed to evaluate stresses throughout the structure. The stress ratio refers to the ratio between the actual stresses and the allowable stresses using the Allowable Stress Design code. Three cases in particular were selected, which attempt to model some of the collapses observed during the site visits. The columns were modeled using 1/4in thickness in all cases.

Case 1. This case models the canopy shown in Figures 1-3. Figure 13b shows the deflected shape of the structure for loads acting in its weakest direction. Under the scenario of lateral pressures only, the stress ratios are shown in Figure 13c, and for the external columns they reach high values of 0.92. In the second wind pressure scenario this ratio becomes 1.3. The analysis confirms the overstress on the canopy columns, indicating that failure could have occurred in the mode shown in Figure 3a.

Case 2. The structure of Figure 4 has also been modeled using ETABS and two wind pressure-scenarios. The deflected shape is shown in Figure 14b for pressures in the strong direction of the structure. The stress ratio for lateral pressure in the weak direction is 0.65 on the columns, but as suction is included, the stresses increase to 0.99. The stress ratio on the existing columns was very close to the allowable stress permitted by code. This is a case of overstressed columns, which on account of the corrosion effect identified in Figure 4c, would explain the collapse observed in Figure 4b, in which the canopy was completely separated from the foundation system.

Case 3. The third case investigated is a model of the canopy shown in Figure 9, with four columns. The structure was analyzed in the strongest direction in view of the failure mode observed in Figure 9. Under lateral pressures, the stress ratio on the columns was 1.21, whereas this ratio increased to 1.50 under the assumptions of uplift on the roof. All the columns buckled sideways in one direction. This is clearly a deficient design in terms of providing enough resistance to withstand the applied loads. Specifically, the tubular columns employed are too weak and can only take gravity loads.

4. Conclusions

The main conclusions of this study, in which field observations were followed by structural analyses, are as follows:

- Extensive damage was identified in canopies of gas stations due to hurricane Rita. In many cases the reconnaissance mission identified collapse of the roof on top of the gas pumps, whereas there were cases in which the roof constituted debris that impacted a near building.
- Canopies in gas stations are engineered structures, and the plans are provided by the gasoline supplier, so that the best way to have a positive impact in the design would be to go through the gasoline providers (Texaco, Exxon, Chevron, Shell, and others.)
- A first lesson learned from the collapses is that canopies should be designed as frame structures, with proper rigid joint action being provided between the columns and the beams. This was not the case in most canopies for which we had access to observe the roof from the top.
- A second lesson is that maintenance is crucial to maintain the integrity of the canopy, especially in relation to corrosion of the columns at the base. This is a weak point and at the same time it is vulnerable to water and moisture action.
- A third lesson is that attention should be given to the construction of the foundations in order to secure a clamped condition at the base of the columns.
- A fourth lesson would be that the proper wind design codes should be used to analyze the canopy structures. It is evident that the resistance and capacity of the structures were under designed.
- Finally, low cycle fatigue seems to be a topic for further research and may be a factor influencing the collapse of some of the canopies during the recent hurricanes.

Acknowledgements

The authors thank graduate students at UPRM Hermes Calderón, Luis J. Galarza and Paul Kohan, who studied the fatigue problem for one canopy. This research was supported by a grant from National Science Foundation (“SGER: Identification of structural damage in tanks and industrial facilities due to hurricane Katrina”, Award number 0553986, 2005-2006), by the National Institute of Standards and Technologies (NIST) and by the Mid-America Earthquake Center (NSF-MAE). The authors thank this support.

References

ASCE/SEI 7-05 (2006), *Minimum Design Loads for Buildings and Other Structures*, ASCE, Reston, VA, 424 pp.

ETABS (2002), Integrated Analysis, Design and Drafting of Building Systems, Computers and Structures Inc., Berkeley, CA.

Fratta, D. and Santamarina, J.C. (2006), Daños causados por el Huracán Katrina en Biloxi, Mississippi, *Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil*, vol. 6(1), pp. 1-14.

Godoy, L. A. (2006), “Daños en tanques de almacenamiento de combustible debidos al Huracán Rita”, *Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil*, vol. 6(1), pp. 27-36.

Godoy, L. A., Portela G. and Saffar, A. (2006), “Daños en tanques de almacenamiento de combustible debidos al Huracán Katrina”, *Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil*, vol. 6(1), pp. 15-26.

NIST (2006), Performance of Physical Structures in Hurricane Katrina and Hurricane Rita: A Reconnaissance Report, National Institute of Standards and Technologies (US Department of Commerce), Gaithersburg, MD.

Robertson, I.N., Riggs, R., Yim, S. and Young, Y.L. (2006), Lessons from Katrina, ASCE Civil Engineering, vol. 76(4), pp. 56-63.

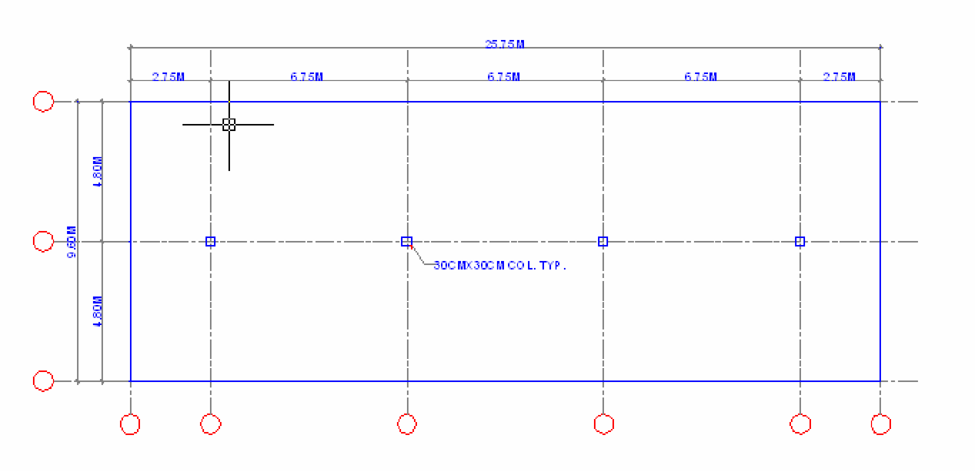


Figure 1. Exxon Gas Station. One is located at the intersection between Road 365 and Labelle Road, Hillerbrandt, and the second one is located in Road 365, about half mile from the first one.

Figure 2a. Exxon Gas Station, Road 365 and Labelle Road, Hillerbrandt, TX (Photograph taken on October 12).

Figure 2b. Exxon Gas Station, Hillerbrandt, TX (Photograph taken on October 12).

Figure 3a. Exxon Gas Station in Road 365, Hillerbrandt, TX, about half mile from the one of Figure 2. (Photograph taken on October 12).

Figure 3b. Exxon Gas Station, Hillerbrandt, TX. Plastic hinges formed at the base of the columns. (Photograph taken on October 12).

Figure 3c. Exxon Gas Station, Hillerbrandt, TX. There was effective frame action. (Photograph taken on October 12).

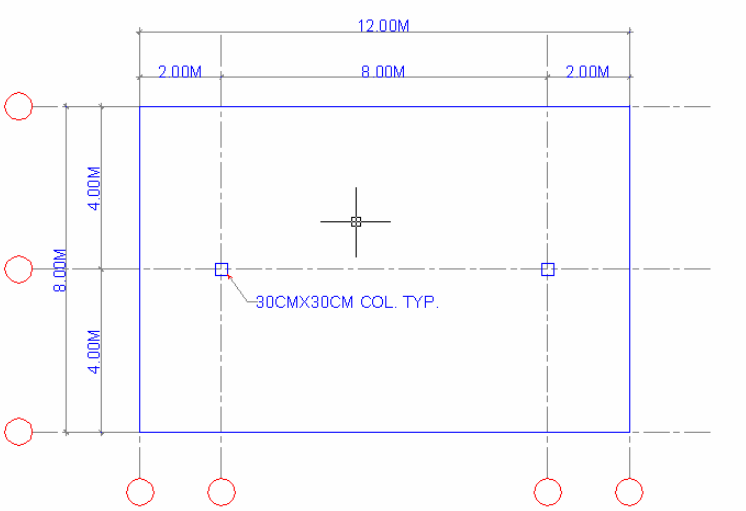


Figure 4a. Chevron gas station in Vidor, TX (Road 105 and HW 10).

Figure 4b. Chevron gas station in Vidor, TX (Photograph taken on October 12).

Figure 4c. Chevron gas station in Vidor, TX (Photograph taken on October 12).

Figure 5a. Road 39, Chalmette, LA. The connection between column and roof was effective. (Photograph taken on November 18).

Figure 5b. Road 39, Chalmette, LA. Evidence of corrosion at the base of the columns. (Photograph taken on November 18).

Figure 6a. St. Bernard, LA. One of the columns failed due to plasticity. (Photograph taken on November 18).

Figure 6b. St. Bernard, LA. One of the columns had extensive corrosion at the base. (Photograph taken on November 18).

Figure 7a. Gas Station in Violet, LA. (Photograph taken on November 18).

Figure 7b. Gas Station in Violet, LA. (Photograph taken on November 18).

Figure 8a. Chevron gas station in Meraux, LA. (Photograph taken on November 17).

Figure 8b. Chevron gas station in Meraux, LA. The columns did not have connection with the roof. (Photograph taken on November 17).

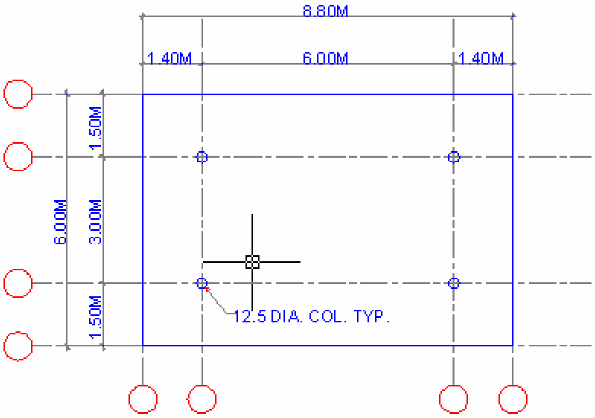


Figure 9a. Texaco gas station in Port Arthur, TX (39^{th} Ave.)

Figure 9b. Texaco gas station in Port Arthur, TX (Photograph taken on October 11).

Figure 9c. Texaco gas station in Port Arthur, TX (Photograph taken on October 11).

Figure 10a. Road 90 and Wright, New Orleans area, LA. (Photograph taken on November 18)

Figure 10b. Road 90 and Wright, New Orleans area. Purlings hang from the beams. (Photograph taken on November 18)

Figure 10c. Road 90 and Wright, New Orleans area. Fracture at the base. (Photograph taken on November 18).

Figure 11. Port Arthur, TX. (Photograph taken on October 13).

Figure 12. Port Arthur, TX, Chevron gas station (Photograph taken on October 11).

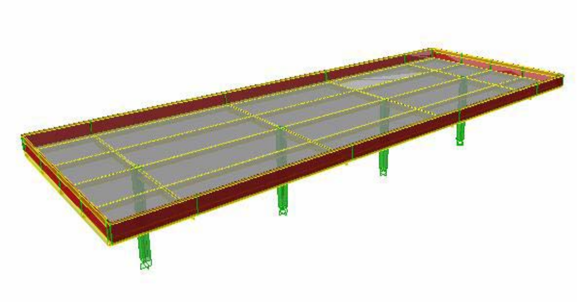


Figure 13a. Geometry of the canopy.

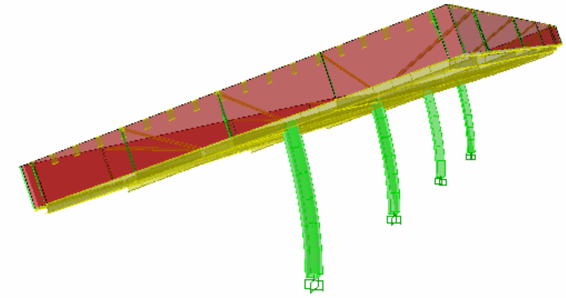


Figure 13b. Deformed shape of the canopy with the wind loads applied to the structure.

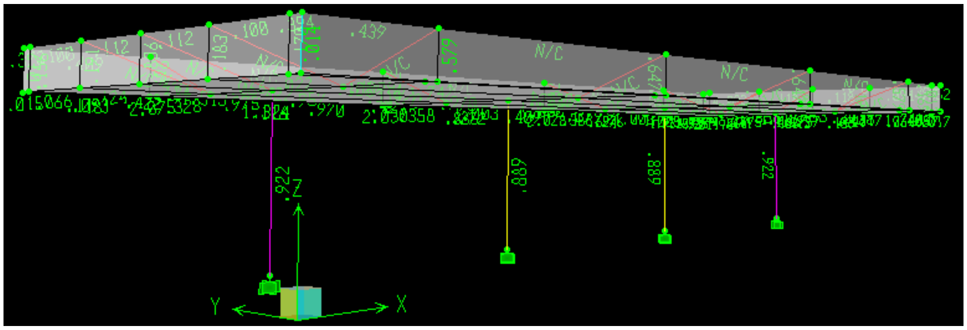


Figure 13c. Stress ratios computed using ETABS, for lateral pressures only.

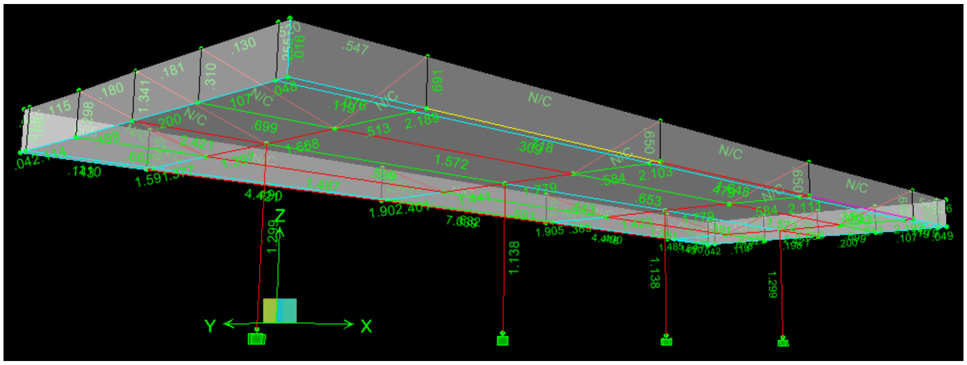


Figure 13d. Stress ratios computed using ETABS, for lateral pressures and uplift on the roof.

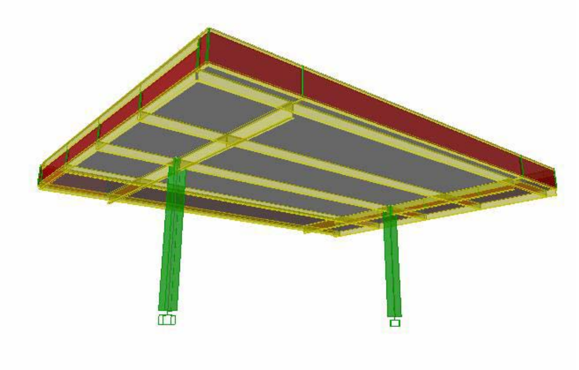


Figure 14a. Geometry of the canopy.

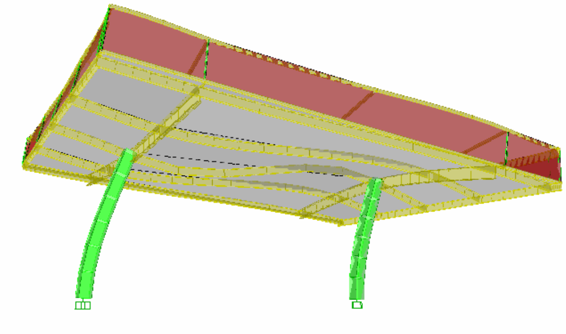


Figure 14b. Deformed shape of the canopy with the wind loads applied to the structure.

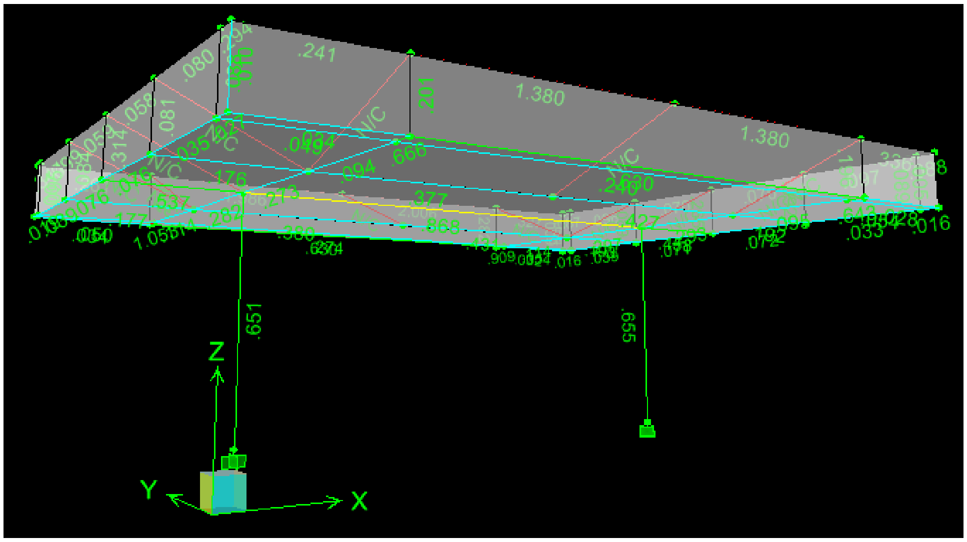


Figure 14c. Stress ratios computed using ETABS, for lateral pressures only.

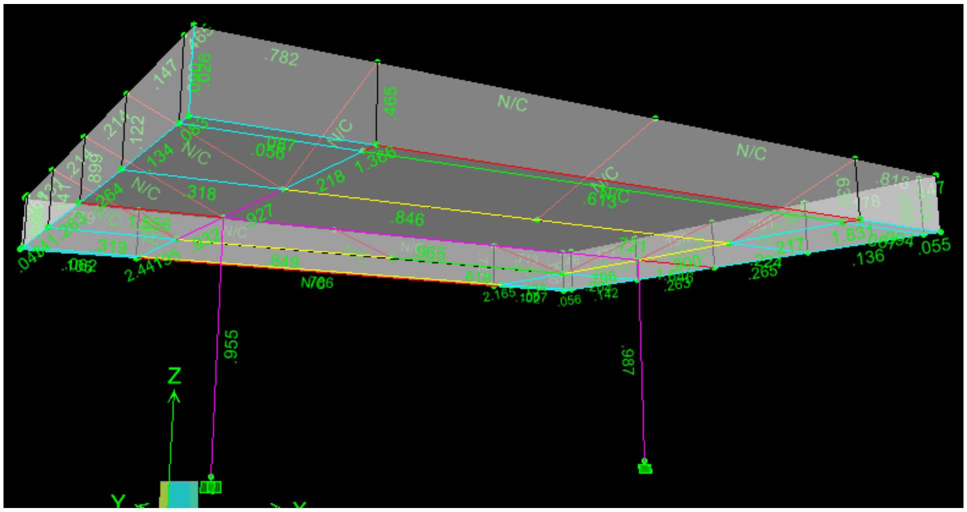


Figure 14d. Stress ratios computed using ETABS, for lateral pressures and uplift on the roof.

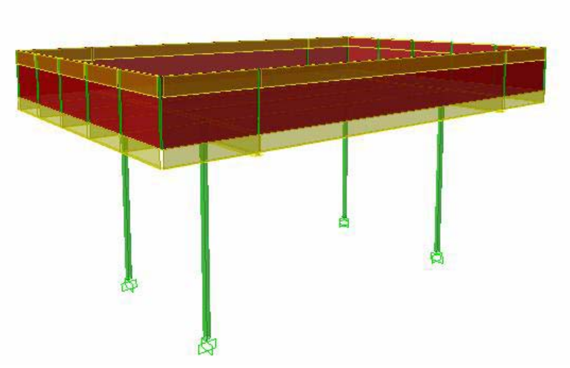


Figure 15a. Geometry of the canopy.

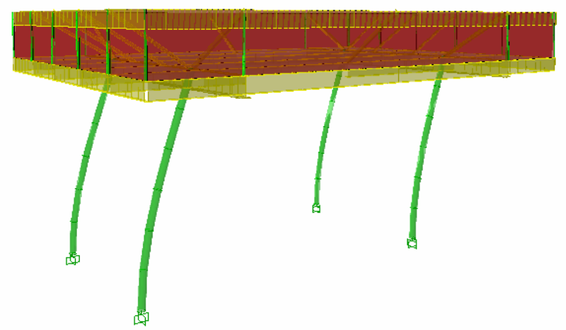


Figure 15b. Deformed shape of the canopy with the wind loads applied to the structure.

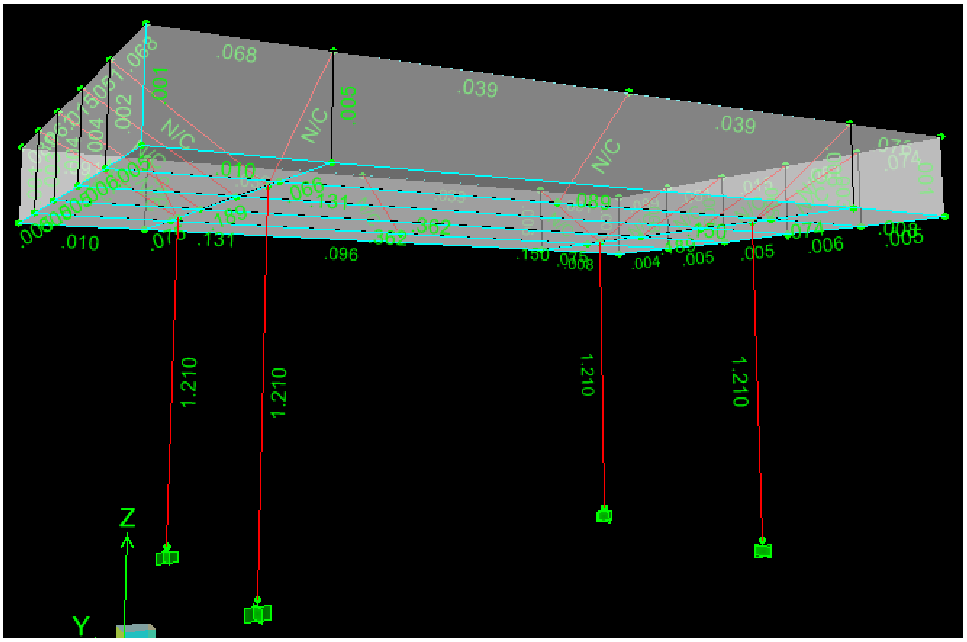


Figure 15c. Stress ratios computed using ETABS, for lateral pressures only.

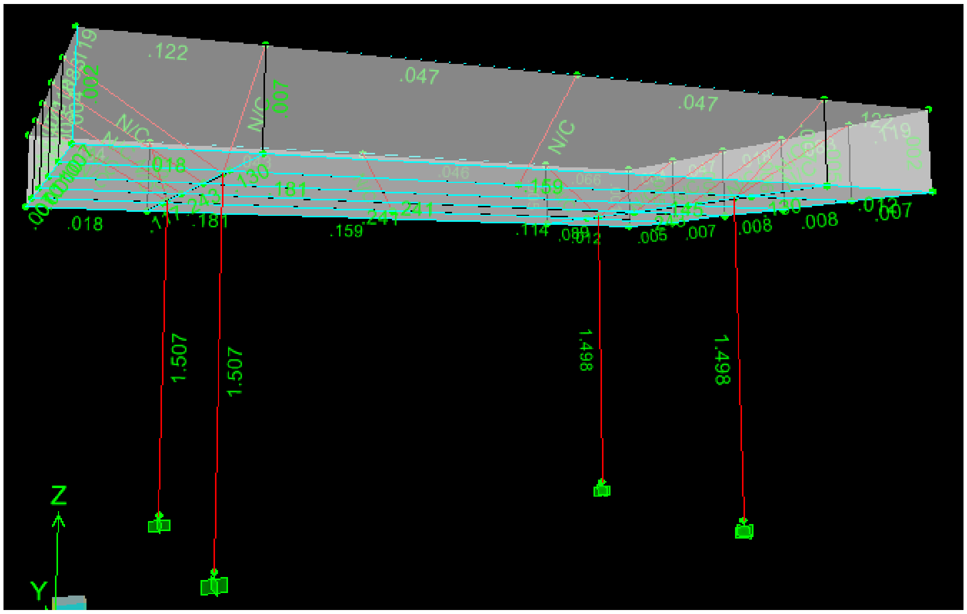


Figure 15d. Stress ratios computed using ETABS, for lateral pressures and uplift on the roof.

Authorization and Disclaimer

Authors authorize LACCEI to publish the papers in the conference proceedings. Neither LACCEI nor the editors are responsible either for the content or for the implications of what is expressed in the paper.