Modeling of Dock Door Bracings for Hurricane Winds

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Abstract: The wind-load response of braced and un-braced loading dock doors installed in industrial facilities in hurricane-prone areas was evaluated using Abaqus. Horizontal and combination of horizontal and vertical bracing designs were evaluated for a typical dock door made of steel slats sliding inside guiding rails and assembled to form a curtain rolled in a coil on the top of the opening. Analysis was performed using shell elements, hinged connections and selected boundary conditions. Result interpretation was based on three failure criteria: a conservative criterion based on the onset of plastic deformation that leads to the lowest critical winds, a 20% allowable plastic deformation criterion that leads to higher ratings and a slat-pullout criterion that results in even higher wind ratings. The critical wind load for the slat-pullout criterion is defined as the wind exerting pressures that can pull the door slats out of the guiding rails and breach the building envelope, allowing wind and rain to enter the building. Analysis using the yield criterion showed that the un-braced door has a wind resistance in line with the manufacturer's test results. The horizontal bracing scheme improved the wind resistance by less than 10% based on the yield criterion, by about 50% based on the 20% permanent deformation criterion and by about 100% if the door is allowed to deform until the building envelope is breached. Finally, the combination of horizontal and vertical bars may improve the wind resistance for the door by up to about 5 times compared to an un-braced door.

Keywords: Dock Doors, Hurricane Winds, Critical Wind Load, Design Evaluation.

1. Introduction

In a hurricane, it is critical that the building envelope keep its integrity. Hurricane winds generate pressure fields around buildings which cause lift on the roof and suction (negative pressure) on the leeward faces. If the building envelope is breached, the integrity of the structure is largely compromised because wind enters the building causing an increase in internal pressure. The internal building pressure in this case can roughly triple for a typical low-rise warehouse. Windows and doors are susceptible components of the building structure and good hurricane protection requires designs that allow these elements to remain in place throughout the storm and withstand the wind pressure without failure.

Loading dock doors in warehouse facilities located in hurricane prone areas need to be rated for the appropriate wind speed to ensure that the building and stored contents remain intact. Most of the states in U.S. coastal zones have adopted the International Building Code (ICC, 2009), and some of the states such as Florida have developed their own building codes (ICC, February 2008). Wind provisions and calculation of wind-load pressures for these codes come from the Standard ACSE-7 (ASCE/SEI, 2005). For different wind-speed requirements, ASCE-7 can be applied to obtain the required design wind loads in psf (pounds per square foot). Information about wind design of construction elements can also be found in documents published by the insurance industry (FM Global, 2011). The majority of commercial door manufacturers that test and have their products certified include the wind-load ratings (in psf) in the product specification sheet. Doors that can be used in a certain region should have a rating equal or higher than the design load (in psf) required by the building codes for that region. However, many non wind-rated dock doors are still installed in hurricane prone areas. The design pressure for these doors is only about 20 to 22 psf and one mitigating solution is to design appropriate bracing for these doors to increase their wind resistance.

The general purpose finite element program Abaqus/Standard (Dassault Systèmes, 2004-2012) was used to determine the wind resistance of a typical braced and un-braced, non-wind rated door. The door was approximately 10-ft wide and 12-ft high with 22 gage (0.0295”) cold formed steel slats. The door slats were assembled in a hinge-like connection to form a curtain as shown in Figure 1. The curtain was rolled in a coil on the top of the door – the hood. The sides of the curtain were held inside vertical guides. There was a 1.75” projection of the slats into the guides on each side. The bracing designs examined, which are also shown in Figure 1, consisted of a pair of horizontal or a combination of vertical and horizontal tubes located inside and outside of the door. The braces were positioned at various distances from the door face, specifically at 0”, 2” or 4”. For analysis purposes, only negative wind pressures (due to suction) were considered because, based on experimental data for wind rated doors, negative pressures generally result in larger deflections and lower wind ratings than those resulting from positive pressures (DASMA, 2005).

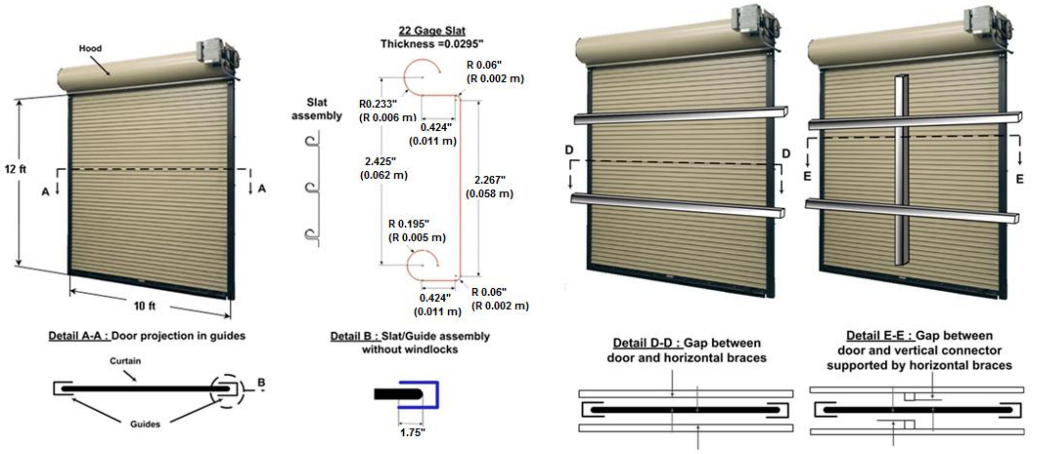

Figure 1. Rolling dock door and bracing designs

The design evaluation was based on three failure criteria:

1. Yield of different parts of the door; Interpretation of the results was focused on areas away from the corners of the door, because the stress values there can include numerical inaccuracies as a result of the application of the boundary conditions. The wind pressure that caused the bracing system to yield was also estimated when applicable.
2. Permanent deformation; According to this criterion, the critical wind pressure results in a permanent deformation, after unloading, of about 20% of the maximum deformation achieved at maximum load. This failure mode is based on the widely accepted Testing Application Standard (TAS) 202-94: “Criteria for Testing Impact and Non-Impact Resistant Building Envelope Components Using Uniform Static Air Pressure” (ICC, February 2008) and section 1625.2 of the Florida Building Code (ICC, February 2008) that provides pass/fail criteria to ensure that the door will still be operable after testing.
3. Slats pulling out of the guides; This failure mode occurs when the deformation is such that the door pulls out of the guides leaving some of the originally closed area open to air and water penetration.

2. Finite element model

We modeled a door that was approximately 10’ wide and 12’ high with 22 gage (0.0295”) cold formed steel slats. Attached to the bottom slat were two 1.5” x 1.5” x 1/8” angles of A36 steel bolted back to back in order to increase its stiffness. The slat material was A 653 Grade 40. There was a 1.75” projection of the slats into the guides on each side with no wind-locks, meaning that the slats were not axially restrained. Since the design was symmetric, only half of the door was modeled. Geometric, material and contact non-linearities were taken into account. Two different tube geometries made of A500 were used for the bracing: 4”×2” ×1/4” (horizontal) and 3” ×2” ×3/16” (vertical). Table 1 shows the material properties used in the analysis.

Table 1. Material properties used for FEA models

Material	Property	US units	SI units
A653 Grade 40	Young’s Modulus	29.6×10^6 psi	20×10^{10} Pa
	Poisson’s Ratio	0.3	0.3
	Yield Stress	40,000 psi	275×10^6 Pa
A36 Steel	Young’s Modulus	29.1×10^6 psi	20×10^{10} Pa
	Poisson’s Ratio	0.26	0.26
	Yield Stress	36,400 psi	250×10^6 Pa
A500 Grade B	Young’s Modulus	29.1×10^6 psi	20×10^{10} Pa
	Poisson’s Ratio	0.3	0.3
	Yield Stress	46,000 psi	316×10^6 Pa

2.1 Modeling technique

The schematics in Figure 2 show that the assembly of the door curtain brings the curved surfaces of the slats in contact when the wind pressure is applied in the positive direction. When the load is applied in the negative direction, the curved surfaces of the slats rotate inside each other allowing the door to bow in the opposite direction. Modeling the interactions between the front edges of the horizontal surface and the curving of the slat curtain when negative pressure is applied was achieved by use of the Abaqus 6.6-1 contact capabilities and a set of hinge connectors at the back edge of the horizontal surface, right before the curved section of the slats. Figure 2 demonstrates that the model can simulate both the contact and rotations of the door.

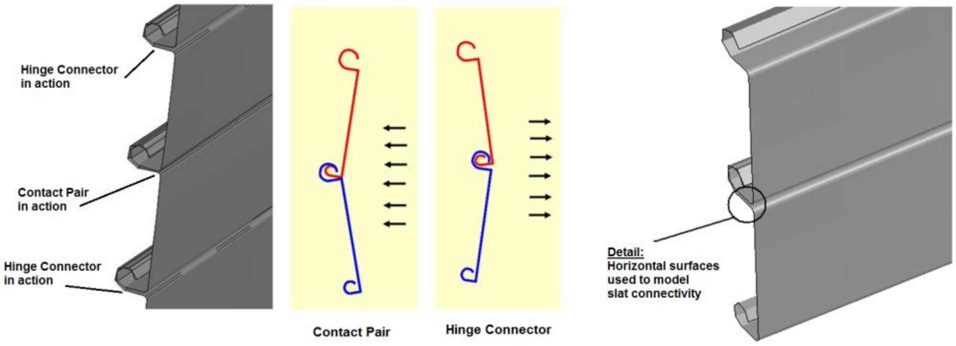

Figure 2. Slat connectivity with hinge-type connectors and contact pairs.

2.2 Mesh

The mesh used for all the analyses, which allowed both computational efficiency and reasonably accurate stress calculations is shown in Figure 3 and consisted of approximately 55,000 4-node shell elements with approximately 60,000 nodes and about 400,000 degrees of freedom.

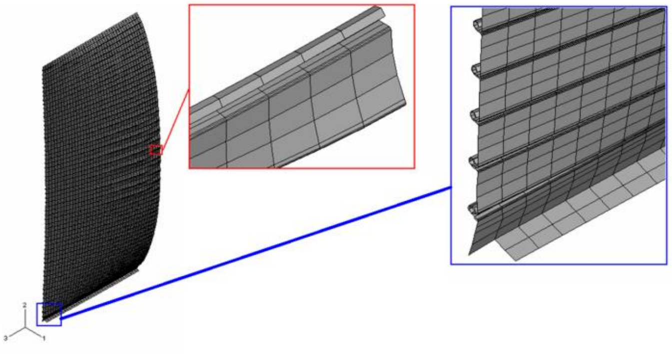

Figure 3. Mesh density used for all door models with and without bracing

2.3 Boundary conditions

In Figures 4 and 5, X, Y and Z axes are shown as 1, 2 and 3, respectively. The boundary conditions applied to the model of the door with no bracing are shown in Figure 4. The top of the door was only allowed to rotate about Z, the middle axis of the door (right end of the model) was assigned symmetry boundary conditions and the far end of the guide (left end of the model) was assumed to be ‘restrained’ in all directions, and allowed all rotations.

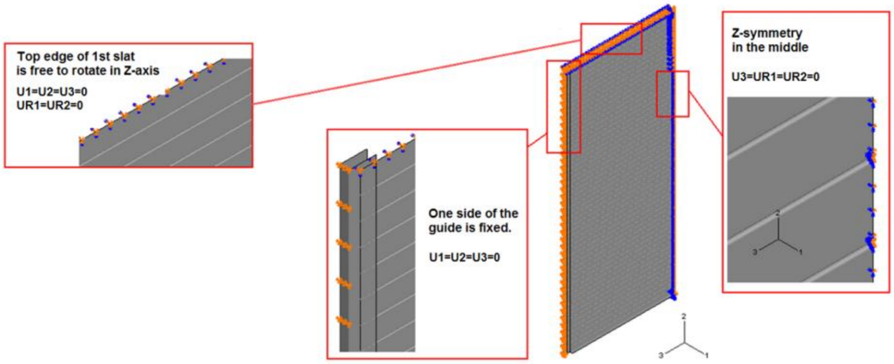

Figure 4. Boundary conditions as applied to the door with no bracing

For the models that included bracing, the mid-plane of the brace was assigned Z-symmetry conditions similar to the mid-plane of the door, and the far end of the brace was restrained (fixed) as shown in Figure 5. Other designs for brace installations will require different boundary conditions (e.g., simply supported). The vertical connectors, when located in the middle of the door width were cut in half, assigned Z-symmetry along their length and ‘tied’ to the horizontal braces as shown in the same figure.

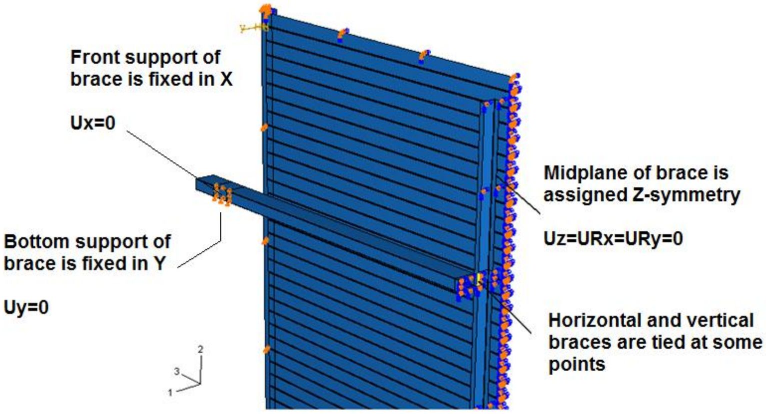

Figure 5. Boundary conditions as applied to the horizontal braces

2.4 Model validation

Initially, the model's deflection in the middle of the door was compared with the value calculated by the analytical solution of a simply supported beam with the same slat inertia. The equation of maximum deflection is shown in Figure 6 with *w* being the load per unit length, *L* being the total length of the beam, *E* being the Young's modulus and *I* being the moment of inertia of the beam.

The moment of inertia of the section was approximately 0.0083 in^4, the total length outside the guides was 116.5 in. and the elastic modulus for A653 Grade 40 galvanized steel was 29.6×10^6 psi. The width of the slat was 2.267 in. and the load per unit length *w*, which is a function of the applied wind pressure P, in psf, is $w = 0.01574$ P. Table 2 shows the values of the maximum deflection of the beam under uniform loads that correspond to wind pressures of 21 psf and 31.5 psf and the corresponding values calculated by FEA that differ by less than 10%.

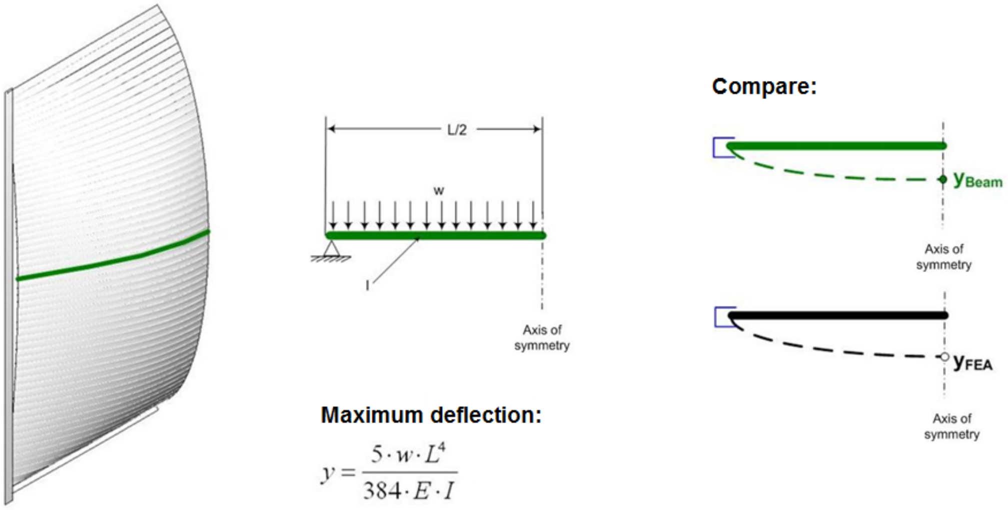

Figure 6. Comparison using the simply supported beam analytical solution

Table 2. Comparison of analytical solution of a simply supported beam with FEA

Wind Pressure (psf)	Length (in)	Young's Modulus (psi)	Moment of Inertia (in^4)	Line Load (psi-in)	Deflection (in) analytical	Deflection (in) from FEA
21	116.5	29,600,000	0.0083	0.01574□21	3.23	3.0
31.5	116.5	29,600,000	0.0083	0.01574□31.5	4.84	4.8

The model results were also compared with deflections measured during a static pressure test for a rolling dock door made of corrugated sheet with a profile shown in Figure 7 taken from the test report (Dixon, 2005). All the relevant data from the Test Report according to ASTM E330 (ASTM International, 2010) are shown in Table 3. Table 4 compares dimensions, inertia and deflection of the door analyzed by FEA and the corrugated sheet door.

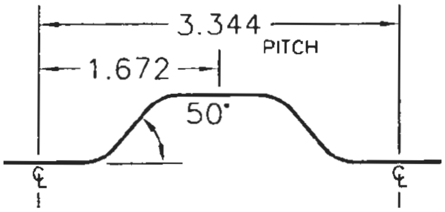

Figure 7. Profile of corrugated sheet door

Table 3. Test Results for the corrugated sheet door

Door dimensions	8'-8" wide x 7'-0" high
Curtain design	Corrugated steel
Sheet thickness	0.018"
Material	A 653 Grade 80
Test procedure	ASTM E 330
Location of measurement of deflection	41.5" from the bottom, and center of 8'-8" span
Measured deflections	
@ - 21 psf	6.5"
@ - 31.5 psf	10"

Table 4. Relative dimensions of slat and corrugated sheet doors

	Door analyzed in this study (FEA)	**Corrugated Sheet Door**
Width of slat	2.267 in	3.344 in
Length	116.5 in	104 in
Moment of inertia	0.0083 in^4	0.0047 in^4
Deflection @ -21 psf	3 in	6.5 in
Deflection @ -31.5 psf	4.8 in	10 in

As seen from the equation in Figure 13, the deflection is proportional to the load *w*, the fourth power of the lengths *L*, and inversely proportional to the moment of inertia *I*. Hence, we can calculate an adjustment factor for the corrugated sheet door as follows:

$$y_{FEA} = \frac{\left(\frac{w_{FEA}}{w_{corrugated}}\right)\cdot\left(\frac{L_{FEA}}{L_{corrugated}}\right)^4}{\left(\frac{I_{FEA}}{I_{corrugated}}\right)} y_{corrugated} \quad \Rightarrow y_{FEA} = 0.6\, y_{corrugated}$$

Table 5 shows the deflection values measured for the corrugated sheet door, the corresponding adjusted values and the deflections predicted by FEA for the typical slat door analyzed here. Given the crude conversion and other differences of the two types of doors that could not be taken into account in the adjustment factor, the adjusted results of the corrugated sheet door are very well within the order of magnitude of the FEA results.

Table 5. Adjusted results for the corrugated sheet door and comparison with FEA

	Corrugated Sheet Door Test Results	Corrugated Sheet Door (Adjusted Results)	FEA for slat door calculated in this study
Deflection @ -21 psf	~ 6.5 in	3.9 in	3.0 in
Deflection @ -31.5 psf	~ 10 in	6.0 in	4.8 in

The results shown in the following section were obtained using the Abaqus/Standard version 6.6-1 with automatic stabilization. Due to extensive contact interactions between parts, very small increments were required and the solution time for the various cases was between 48 and 72 hours using a single CPU.

3. Results

All results presented here apply under the condition that the anchors of the frame of the door are able to withstand the forces applied by the wind pressure. Local buckling and strain hardening of the braces was not taken into account.

3.1 Unbraced door

Figure 8 shows the von Mises stresses and the deflection normal to the door plane at 47 psf negative wind pressure, at which the lateral deflection of the slats is about 1.75” equal to the initial projection of the door into the guides, as shown in Figure 1, Detail A-A. Figure 8 also shows the lateral deformation of the edge of the door as it progressively pulls out of the guides at various wind pressures.

With increasing wind pressure, various areas reach yield. Figure 9 shows snapshots of the deformed door at various wind pressures. Circled in red are areas where yield is initiated at the corresponding shown pressure. The model shown on the right of Figure 9 is a front view of the deformed door at wind pressure of 80 psf. The areas shown in black at the sides and bottom are openings of the door area.

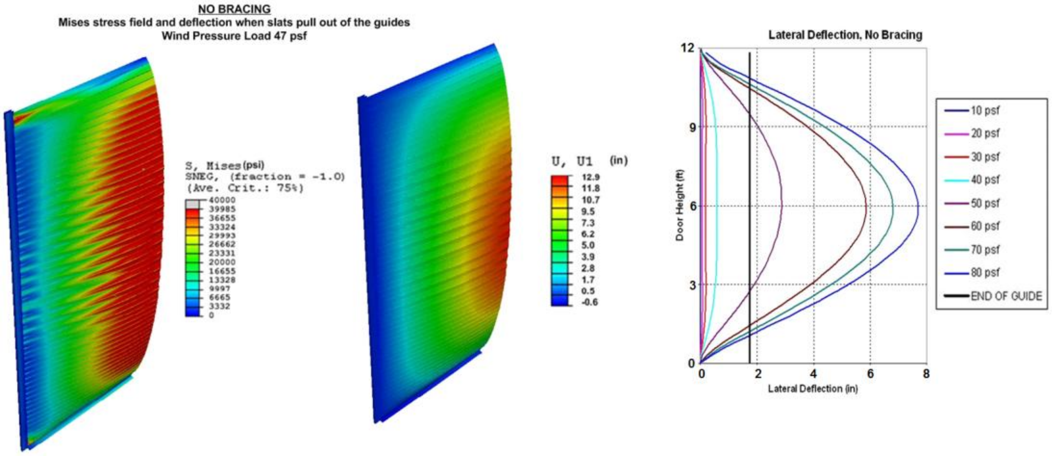

Figure 8. Von Mises stress and deflection fields at 47 psf negative wind pressure and lateral deflection at the edge of the door

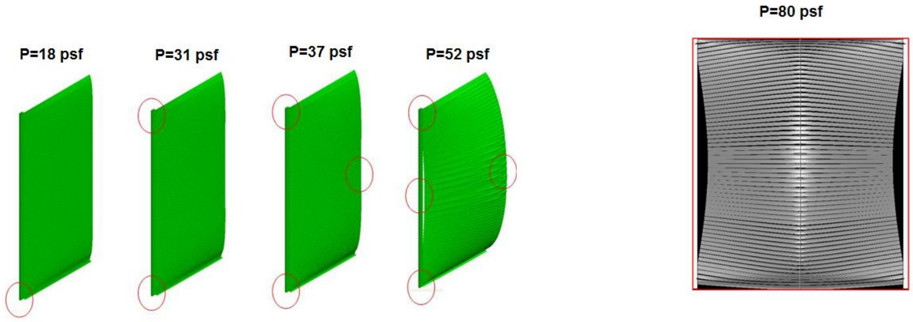

Figure 9. Yield locations for various wind loads and deformed shape at 80 psf

Figure 10 shows the variation of maximum deflection with wind pressure as the door was loaded up to a maximum wind pressure and then the pressure was gradually removed. From the figure, it is estimated that if the door is loaded up to 40 psf, approximately 20% of the maximum deformation achieved at 40 psf will permanently remain after the door is fully unloaded. The top curve in the same figure shows the deflection at the center of the door as the pressure increases to

80 psf. At about 52 psf which is about the same time that the door pulls out of the guides the slope of the curve changes. The analysis was not continued to show the unloading phase.

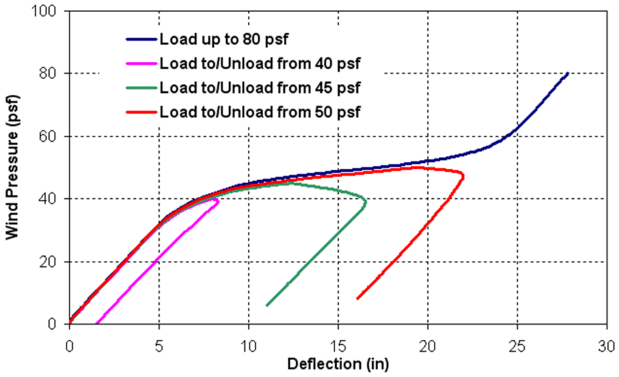

Figure 10. Estimation of permanent deformation for various wind pressures

3.2 Door with two horizontal braces

The left hand side of Figure 11 shows the door braced with two horizontal braces along its height. We considered 0", 2" and 4" gaps between the bracing and the door. When there was no gap between the horizontal braces and the door, the slats pulled out of the guides at 127 psf , whereas if the braces were located 2" and 4" away from the door face, the slats pulled out of the guides at a pressure of about 98 psf.

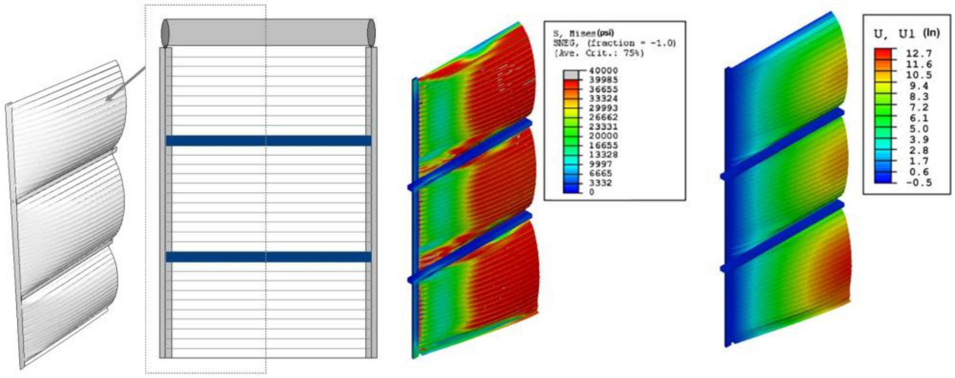

Figure 11. Door with two horizontal braces and von Mises stress and normal deflection fields for a 4" gap and 98 psf wind pressure

When there was no gap between the horizontal braces and the door, the normal deflection when the slats pulled out of the guides was 11.8” and it increased to 12.7” for 2” and 4” gaps. Figure 11 also shows the von Mises stress and normal deflection of a door with bracing at a 4” gap exposed to negative wind pressure of 98 psf.

The analysis showed that, as the load approached the value that forced the door to come out of the guides, the lower third of the door experienced higher deflections. Figure 12 shows a comparison of the deflections at the bottom third of the door for doors with horizontal bracing at variable gaps.

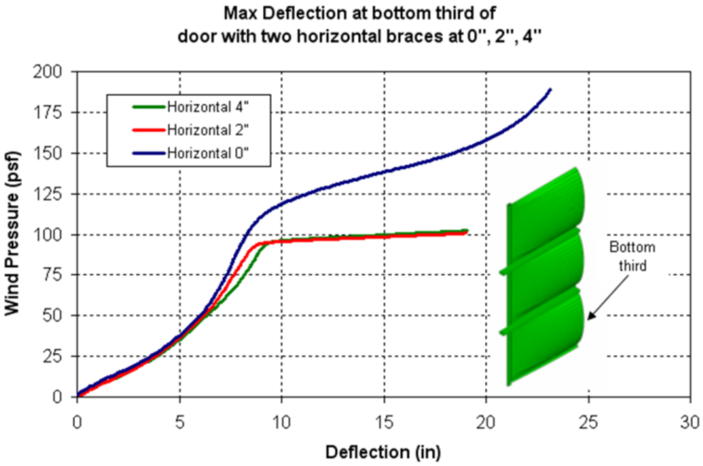

Figure 12. Maximum deflection vs. pressure at the bottom third of a door with horizontal braces and 0”, 2” and 4” gaps

Figure 13 shows the variation of the maximum deflection with wind pressure for doors with horizontal braces and different gaps, when loaded up to different levels of wind pressure and subsequently unloaded.

In summary, a door with two horizontal braces will start to yield at wind pressures of about 39 to 40 psf, when the maximum displacement is about 5.5”. Based on the permanent deformation criterion, the critical pressure is 60 psf for 4” gap, 62 psf for 2” gap and 70 psf for no gap and the displacement is between 7.5”to 8”. Finally, the slats begin to pull out of the guides at 98 psf for 2” and 4” gaps and at 128 psf for no gap, while the displacements are about 12”for all gap values.

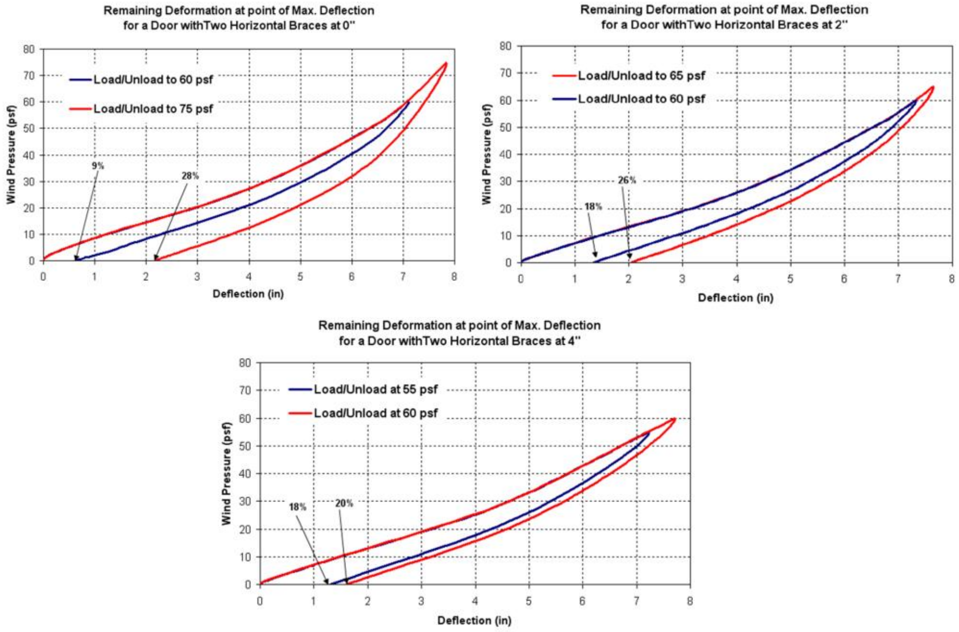

Figure 13. Loading/unloading cases for a door with horizontal braces

3.3 Door with two horizontal braces with vertical connector

Figure 14 shows a design using a set of two horizontal braces connected to a vertical bar. The vertical brace is located between the door face and the horizontal bars. Two cases were analyzed, one with the vertical bar in contact with the door face (gap=0") and one with a 2" gap. The von Mises stresses and deflection at the time when the slats are pulling out of the guides for a door with 2" gap is also shown in Figure 14.

Two calculations for a wind pressure up to approximately 233 psf were done for bracing at 0" and 2" gaps. The slats did not pull out of the guides for the model with 0" gap for pressures up to 233 psf. The 2" gap case performed also well, as the slats did not pull out of the guides for wind pressure up to 220 psf. The location of maximum deflection on the door changed as the wind pressure increased.

For the 0" gap case, loads up to 220, 230 and 240 psf were applied and then removed. The permanent deformation was very small for the first two cases and increased when the maximum load of the cycle became 240 psf. For the 2" gap case, several cases with loading up to wind pressures between 70 and 220 psf and then unloading were investigated. The results indicated that for maximum load of 200 psf, the permanent deformation was about 7% whereas for maximum load of 220 psf, it was about 48%.

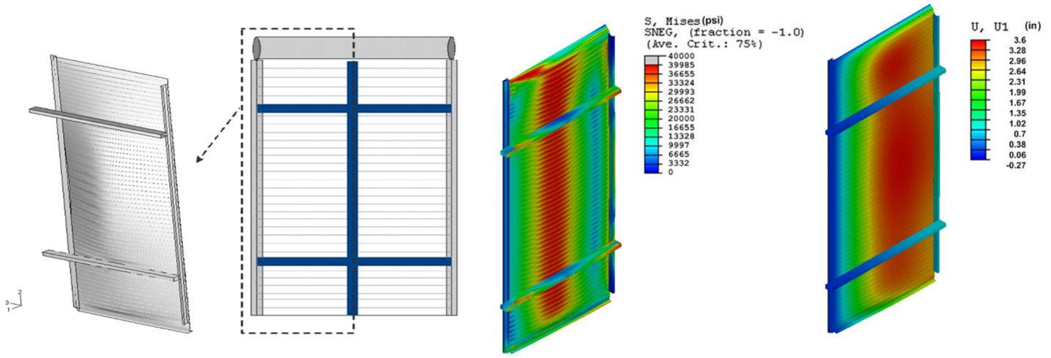

Figure 14. Door with combination of horizontal and vertical bracing and von Mises stress and deflection fields for 2" gap at 220 psf negative wind pressure

For the 2" gap case, the critical pressure after which the door began to yield was 215 psf, a little higher than the 0" case for which yield started at 200 psf, because the presence of the gap allowed the door curtain to move freely until it touched the bracing and then it became restrained and the slats started deforming in the horizontal direction.

The bracing system itself reached yield at a wind pressure of about 200 psf. The deflection associated with this wind pressure, in the middle of the horizontal part of the bracing was about 0.17". Note that the brace is assumed fixed in this study at the boundaries. Other boundary conditions may change the results. The increase of the maximum deflection of the horizontal bars for wind pressures between 200 psf (when the bars began to yield) and 233 psf (when the slats of the door with bracing at 0" gap began to pull out of the guides) was about 0.04". Therefore, it is reasonable to assume that the bracing, although it will deform plastically, will remain sufficiently in place and support the door until the slats themselves fail.

4. Discussion

In general, the results showed that bracing improved the wind performance especially when combining horizontal braces and a vertical connector.

The analysis showed that the bracing system itself had sufficient stiffness. Stresses on the braces did not exceed 20 % of yield for wind pressures up to 100 psf for any of the scenarios examined. The maximum deflection of the braces for wind pressures up to 100 psf was about 0.15". If the design of the bracing supports is different, the boundary conditions at that location will need to be modified. In case that the braces are for example pinned rather than fixed, the maximum deflection and stress on the brace for wind pressures up to 100 psf was calculated analytically to be 0.7" and 55% of yield, respectively.

Table 6 summarizes the results for the three failure modes for the un-braced door and doors with horizontal and combination of horizontal and vertical braces.

When applying the first criterion, the middle of the un-braced door begins to yield at about 37 psf, whereas the middle of the door with horizontal braces with a 0” gap yields at 39 psf. If the braces are installed with 2” or 4”gaps, the middle of the door experiences yield at 40 psf. For a door braced with a pair of horizontal braces and a vertical connector, the pressure causing yield increases to about 200 psf for 0” gap and 215 psf for 2” gap. Practically, the gap cannot be much greater than 2” because in that case the gap between the horizontal bars and the door would be more than 4”. The horizontal braces at the connection to the vertical bar reached yield at a wind pressure of about 200 psf.

The 20% permanent deformation criterion shows that the critical pressure for the un-braced door is 40 psf and for the door with two horizontal braces at 0” gap is 70 psf, at 2” gap is 62 psf and at 4” gap is 60 psf. A significant increase in wind resistance occurs when the doors are braced with a combination of horizontal and vertical braces, and the critical pressures become 230 psf for a 0” gap and 210 psf for a 2” gap.

The un-braced door begins to pull out of the guides at a wind pressure of about 47 psf, whereas doors with horizontal bracing will only do so at a pressure of about 98 psf for a 2” gap between the door and the bars and at about 127 psf for the no gap case. The case of horizontal braces with a vertical connector improves the door wind resistance significantly, where the door remains in the guides for wind pressures close to 230 psf at 0” gap, and up to 220 psf for a 2” gap. In general, the presence of a small or no gap will hold the door in place for higher pressures.

Table 6. Wind resistance for different failure modes

Failure Criteria	**No bracing**	**Horizontal Bracing**			**Horizontal Bracing with Vertical Connector**	
		0”	**2”**	**4”**	**0”**	**2”**
1. Middle door starting to yield	37 psf	39 psf	40 psf	40 psf	200 psf	215 psf
2. 20% permanent deformation	40 psf	70 psf	62 psf	60 psf	230 psf	210 psf
3. Slats pulling out of guides	47 psf	127 psf	98 psf	98 psf	> 233 psf	220 psf

It should be mentioned that all results presented assumed no safety factor. If a wind rating is desired, a safety factor should be applied. For example, the Miami-Dade Protocol 202-94 (ICC, February 2008) uses a safety factor of 1.5 to reduce the test pressure at failure and derive a wind rating in the form of a design pressure.

5. Conclusions

The wind resistance depends on the failure criterion used with yield being the most conservative, a 20% allowable plastic deformation criterion leading to higher critical winds and a slat pull-out criterion being the least conservative and leading to the highest wind ratings. Analysis using the yield criterion showed that the un-braced door has a wind resistance in line with the manufacturers' specifications. Horizontal braces that are fixed at both ends improves the wind resistance by less than 10% based on yield, about 50% based on the 20% permanent deformation criterion and by about 100% if the door is allowed to deform right before the point that the building envelope is breached. A combination of the same horizontal bracing but combined with vertical bars was shown to improve the wind resistance for the door by 4 to 5 times compared to an un-braced configuration.

6. Acknowledgement

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