Testing Aerial Ladders in FEA: Wind Load Standard Equation vs CFD Wind Tunnel Analysis

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Introduction

To design and build an aerial ladder for a firetruck, the engineer needs to accurately determine the working loads the ladder will encounter. Some of these can be easy to interpret such as the weight of the firefighter in the basket at the end of the ladder, or the weight of the water being supplied to the nozzle. Other loads can be a little harder to quantify, such as how wind affects the ladder. There are several different ways to determine this effect, and two of those will be explored in this paper: the standard equation (ASCE 7-10), and CFD.

The most common way to compute pressure on a ladder is to use an equation from code ASCE 7-10. This equation finds an equivalent velocity pressure based on wind speed and ladder height. This pressure can be directly applied to the faces of the ladder perpendicular to the direction of the wind.

The CFD (computational fluid dynamics) method uses Acusolve to accurately determine the pressure field on all faces of the ladder. This pressure can be directly mapped onto the structural FEA (finite element analysis) model using Hypermesh to predict the stress and displacement in the model. Combining these loads with other loading such as gravity and water pressure, the engineer can make a final judgment on the design.

Using Standard Method to Apply Wind Loads- ASCE 7-10

Currently our aerial ladder customers use a standard equation from code ASCE 7-10 (figure 1) to determine the proper wind loads to apply to the FEA model to determine structural integrity. There can be quite a few factors used in determining the final wind loading to use, but this project's customer simplifies it by only focusing on the desired wind speed and overall ladder height

26.1.1 Scope

Buildings and other structures, including the Main Wind-Force Resisting System (MWFRS) and all components and cladding (C&C) thereof, shall be designed and constructed to resist the wind loads determined in accordance with Chapters 26 through 31. The provisions of this chapter define basic wind parameters for use with other provisions contained in this standard.

Figure 1 code ASCE 7-10

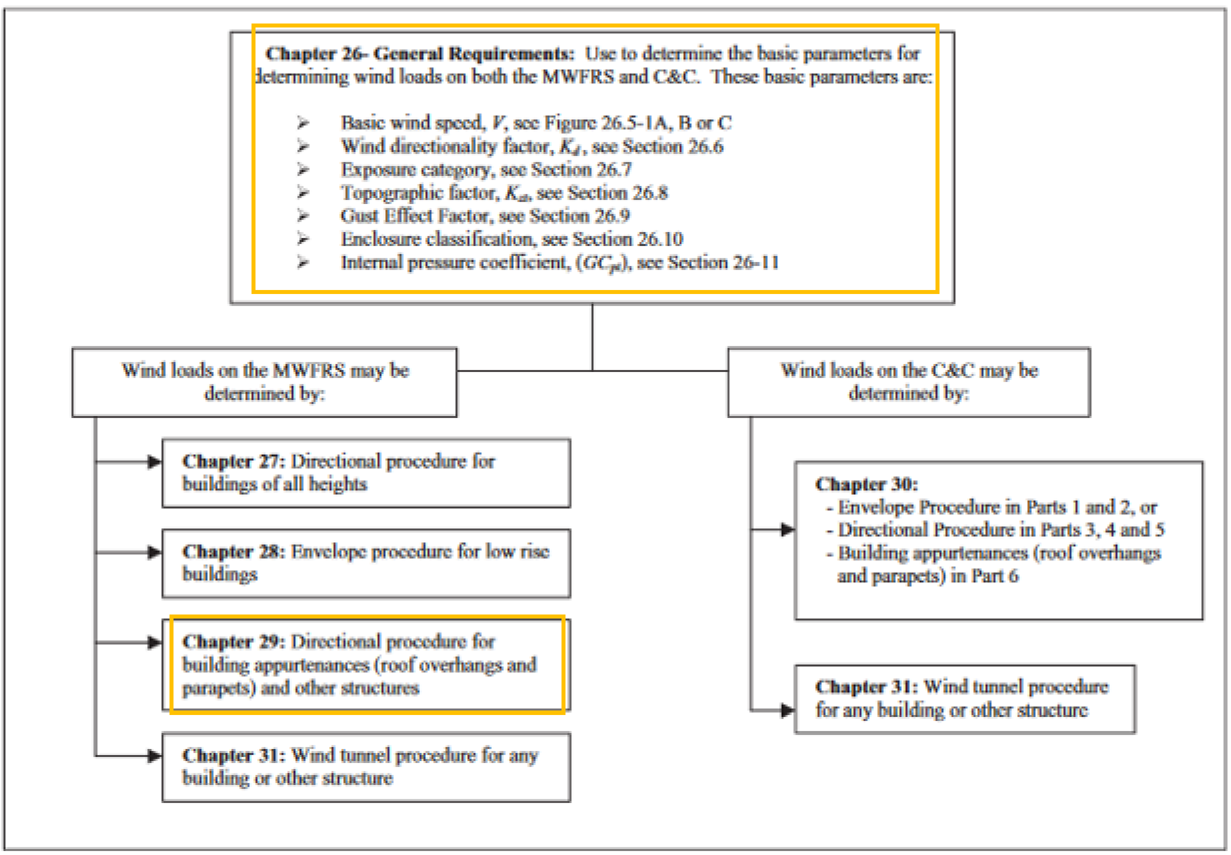


Figure 2. Wind load provisions

ASCE 7-10 Wind Equation

The final velocity wind pressure equation is simplified to determine the correct wind velocity pressure where V is the desired wind velocity and K_z is the velocity pressure exposure coefficient determined from figure 3:

$$q_z = 0.00256\, K_z\, V^2\ (\text{lb/ft}^2)$$

Velocity Pressure Exposure Coefficients, K_h and K_z

Table 6-3

Height above ground level, z		Exposure (Note 1)			
		B		C	D
ft	(m)	Case 1	Case 2	Cases 1 & 2	Cases 1 & 2
0-15	(0-4.6)	0.70	0.57	0.85	1.03
20	(6.1)	0.70	0.62	0.90	1.08
25	(7.6)	0.70	0.66	0.94	1.12
30	(9.1)	0.70	0.70	0.98	1.16
40	(12.2)	0.76	0.76	1.04	1.22
50	(15.2)	0.81	0.81	1.09	1.27
60	(18)	0.85	0.85	1.13	1.31
70	(21.3)	0.89	0.89	1.17	1.34
80	(24.4)	0.93	0.93	1.21	1.38
90	(27.4)	0.96	0.96	1.24	1.40
100	(30.5)	0.99	0.99	1.26	1.43
120	(36.6)	1.04	1.04	1.31	1.48
140	(42.7)	1.09	1.09	1.36	1.52
160	(48.8)	1.13	1.13	1.39	1.55
180	(54.9)	1.17	1.17	1.43	1.58
200	(61.0)	1.20	1.20	1.46	1.61
250	(76.2)	1.28	1.28	1.53	1.68
300	(91.4)	1.35	1.35	1.59	1.73
350	(106.7)	1.41	1.41	1.64	1.78
400	(121.9)	1.47	1.47	1.69	1.82
450	(137.2)	1.52	1.52	1.73	1.86
500	(152.4)	1.56	1.56	1.77	1.89

Figure 3. Determination of velocity pressure exposure coefficient

The velocity pressure exposure coefficient increases the applied pressure according to incremental heights of the ladder.

Once the velocity pressure q_z is determined, the computed pressure is applied to all faces of the ladder in the FEA model that are perpendicular to the direction of the wind. (Note that the pressure changes with height according to the K_z value). This can be a tedious process and faces can be easily missed or unwanted faces inadvertently included. This process is typically done by isolating elements by window and/or going part by part selecting elements on each face. If a mesh is changed, the process of re-creating pressures without duplicates is very time consuming. Manually selecting elements is time consuming and potentially less accurate.

Equation Wind Pressures applied to Ladder

The wind loads are currently modeled as pressures on the exposed faces of the FEA model. The pressure is only a function of height, and does not vary across the ladder (figure 4). These loads will be combined with gravity and other loads to determine the final structural integrity of the ladder.

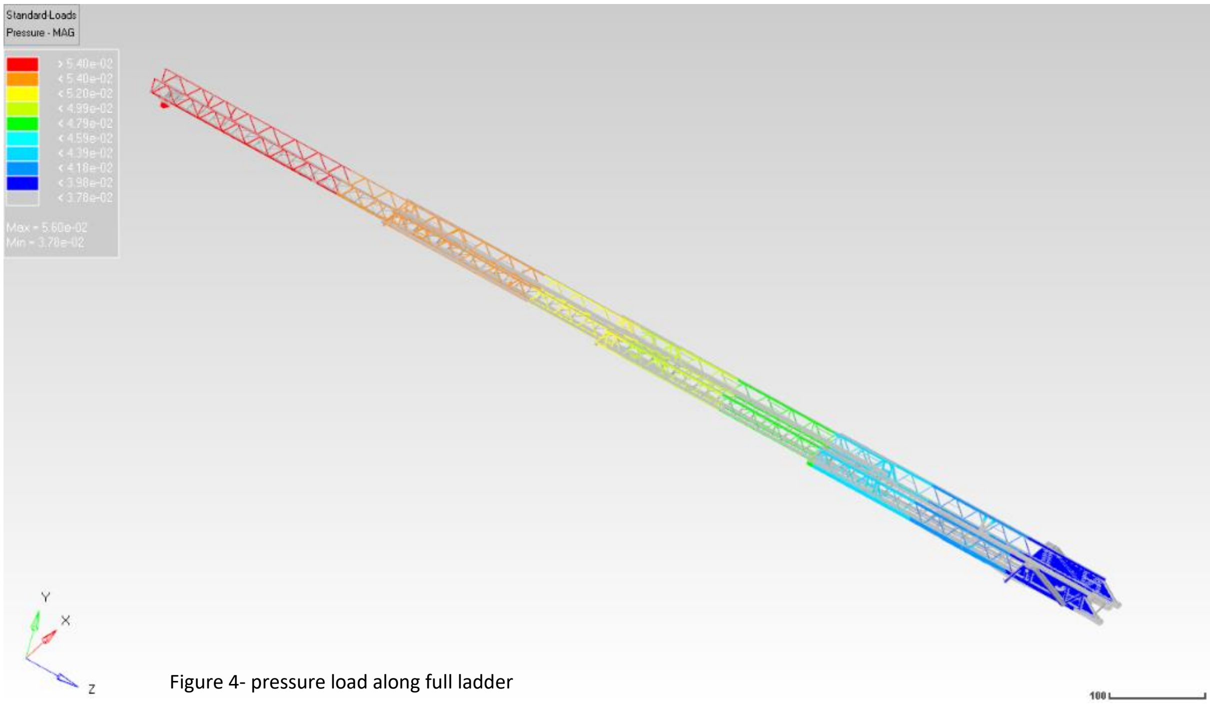


Figure 4- pressure load along full ladder

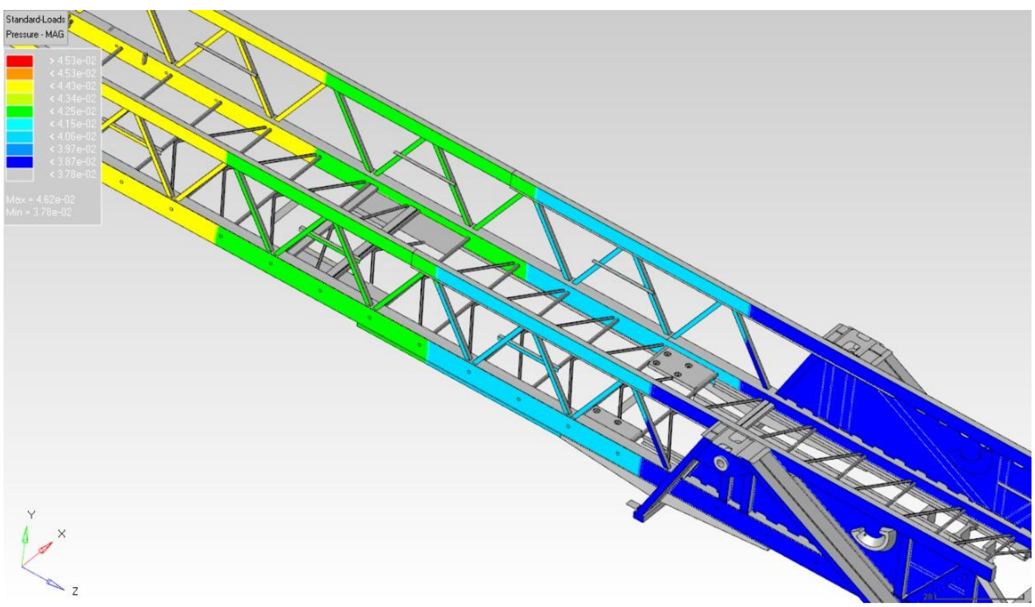


Figure 5- Detail of Base Section

Standard Method Benefits & Challenges Summary

Benefits to the application of the Standard method are:

- Use one structural mesh for all loading
- Design changes wouldn't require updating both the structural and CFD models.
- Relatively straightforward linear static analysis

Challenges to the application of the Standard method are:

- Tedious to select faces and based on judgement
- Wind profile is assumed to be in one direction only
- Wind turbulence is neglected

Using CFD wind tunnel analysis to apply wind loads to FEA model

An alternate method is to use CFD in a virtual wind tunnel to directly determine the wind pressure on the ladder.

A simplified CFD mesh is created from the ladder geometry or existing structural mesh. The shell mesh on the outside of the ladder needs to be air-tight since we will be modeling the air around the structure. Small parts and gaps need not be included in the mesh, but special focus needs to be on the exposed faces of the structure.

Next a virtual wind tunnel is created and meshed. The volume between the virtual wind tunnel and the outside surface of the ladder is meshed with 3-d elements to create the CFD mesh. Appropriate boundary conditions are then applied for a CFD analysis.

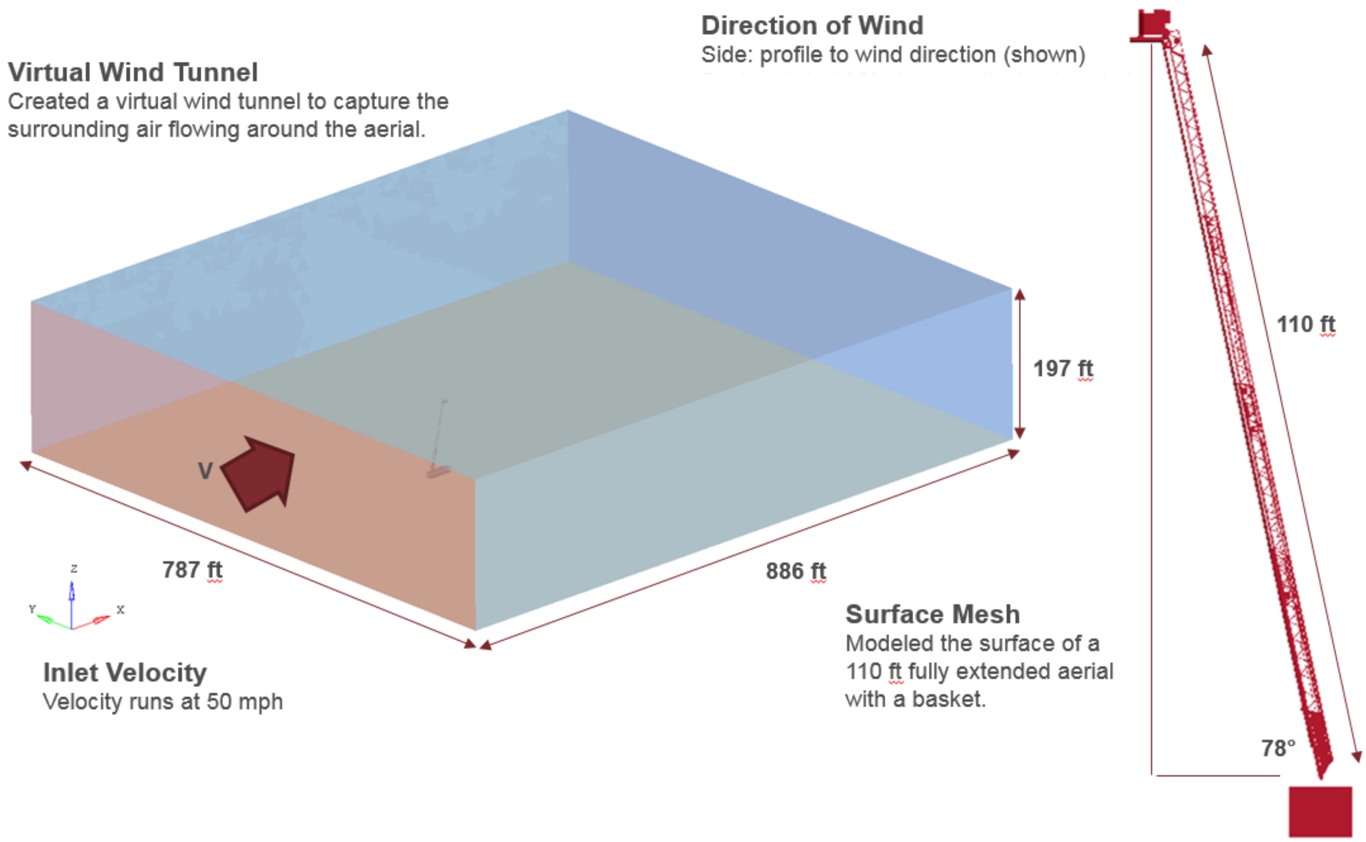


Figure7- CFD mesh and wind tunnel set up

The three contour plots of air pressure in the wind direction are shown in figure 8. The first plot shows a section taken just in front of the ladder; the second shows a section inside the ladder and the third shows a section past the ladder. Positive pressure is shown in red, negative in blue. Notice the negative pressure field that surrounds the ladder. This negative pressure is a key driver for the displacement and stress differences between the pressures derived from CFD and the pressures derived from the standard wind pressure equation.

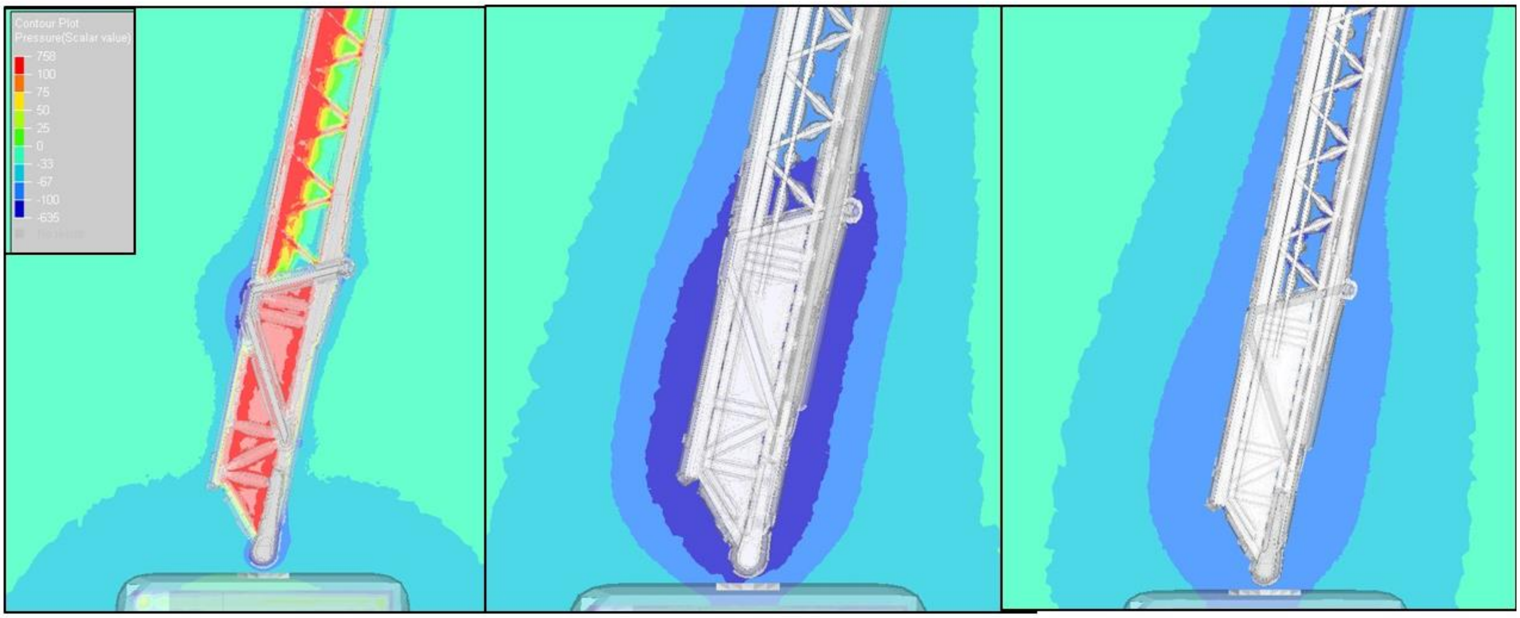


Figure 8- CFD pressures

Figure 9 shows a combination of a section cut just in front of the ladder and a second perpendicular section cut at the top of the ladder. Again, notice the high pressure on the faces of the ladder, but also the negative pressure field downwind that surrounds the ladder.

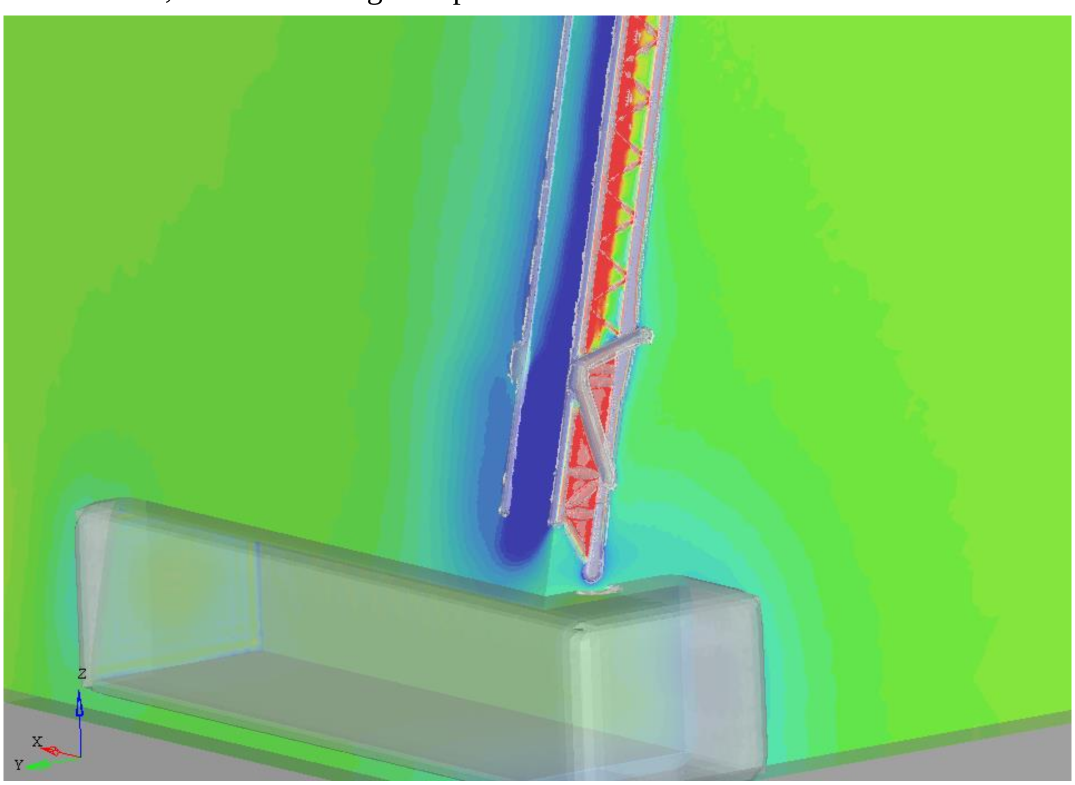


Figure 9- section cut

Convert CFD Results to Structural Pressures

Once the analysis has been completed in Acusolve, the computed nodal pressures are converted to element pressures on the structural model using the fields tool in hypermesh (see appendix for full process).

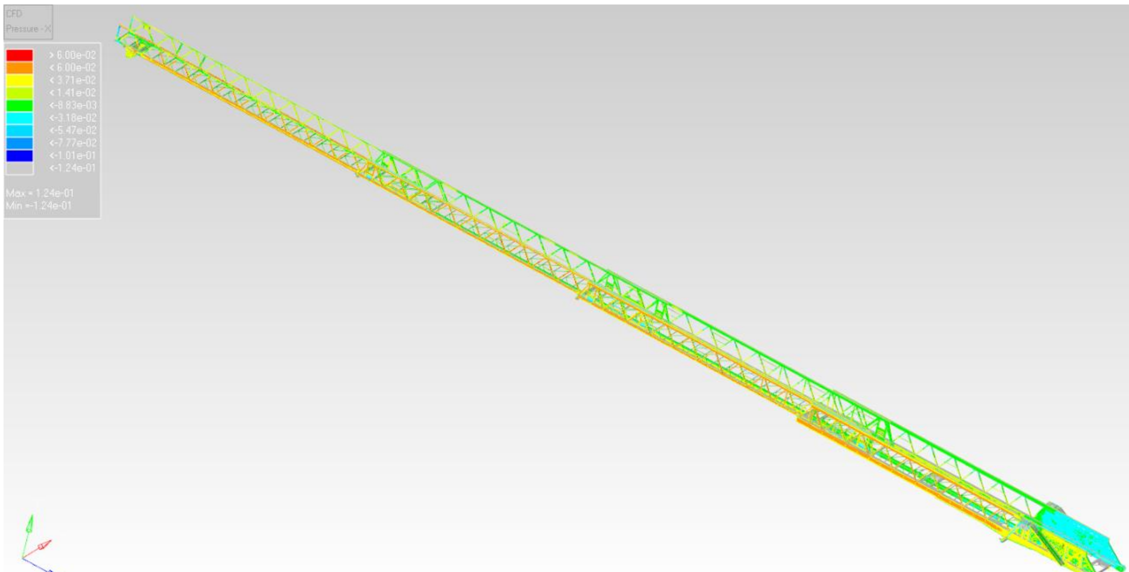


Figure 9- Full ladder pressures

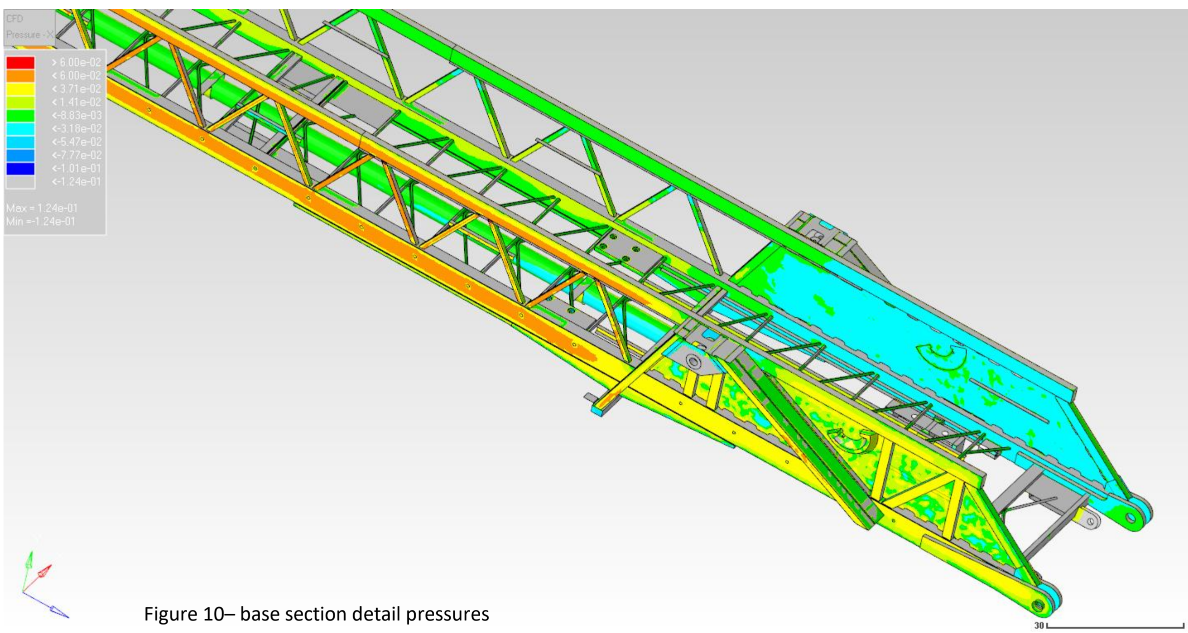


Figure 10– base section detail pressures

Pressure results on the base section of the ladder show higher pressures on the front face of the ladder compared to the standard pressures. In addition, there are negative pressures on the adjacent side of the ladder. These pressures are significantly different from the standard loading and should be included in the analysis of the ladder.

CFD Method Benefits & Challenges Summary

Benefits of the CFD method are:

- The pressures applied and their locations are a more accurate approximation of what the ladder will be subjected to for a given wind speed.
- Pressures due to turbulence are considered
- Pressures are applied to all faces/parts by using the Fields tool

Challenges to the application of the CFD method are:

- Two meshes are required – CFD and structural
- At least a limited knowledge of CFD is required
- Updating the mesh and analysis for design modifications is more involved.

Comparing Standard Equation and CFD Methods

Pressure Contour Comparison

The pressure contours show significant differences between the CFD field pressures and the standard wind equation pressures, particularly in the base section (figure 11).

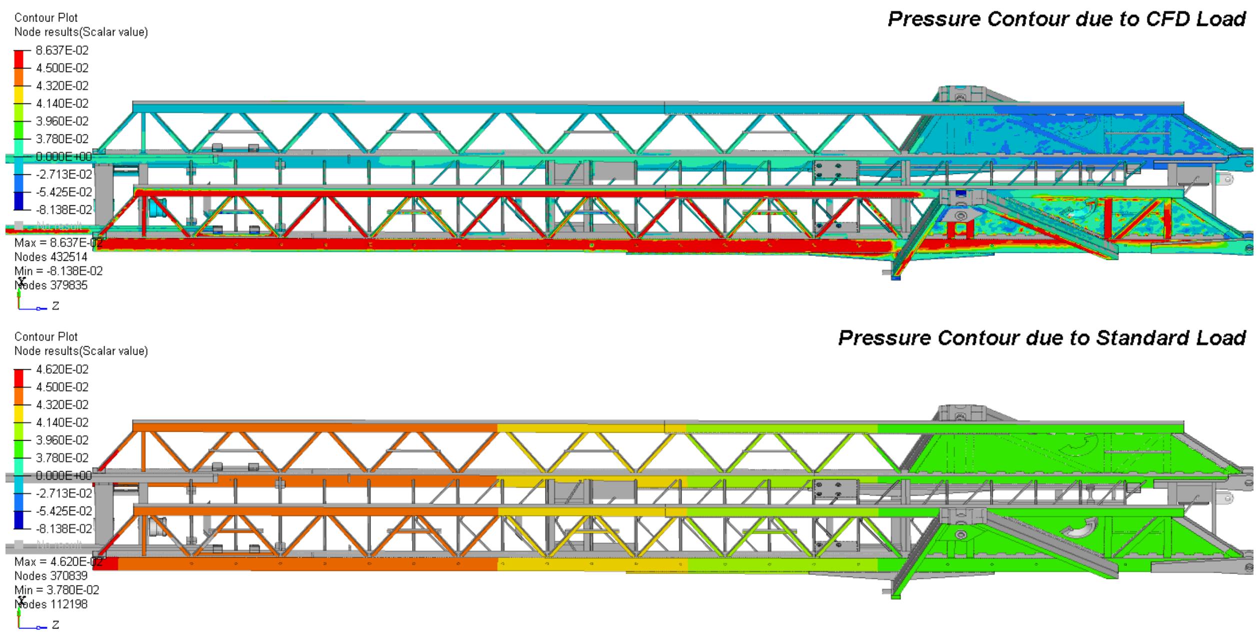


Figure 11 pressure contour of CFD (top) v Standard (bottom)

Reaction Force Comparison

The pressures from the CFD analysis and the ASCE code were applied to the structural mesh and analyzed using OptiStruct. Using Hypermesh's Free Body Tool to compute resultant force and moments, the shear force and moments at various sections of each model were determined. Four section cuts at the base, lower mid, upper mid and fly sections were used to compare the results.

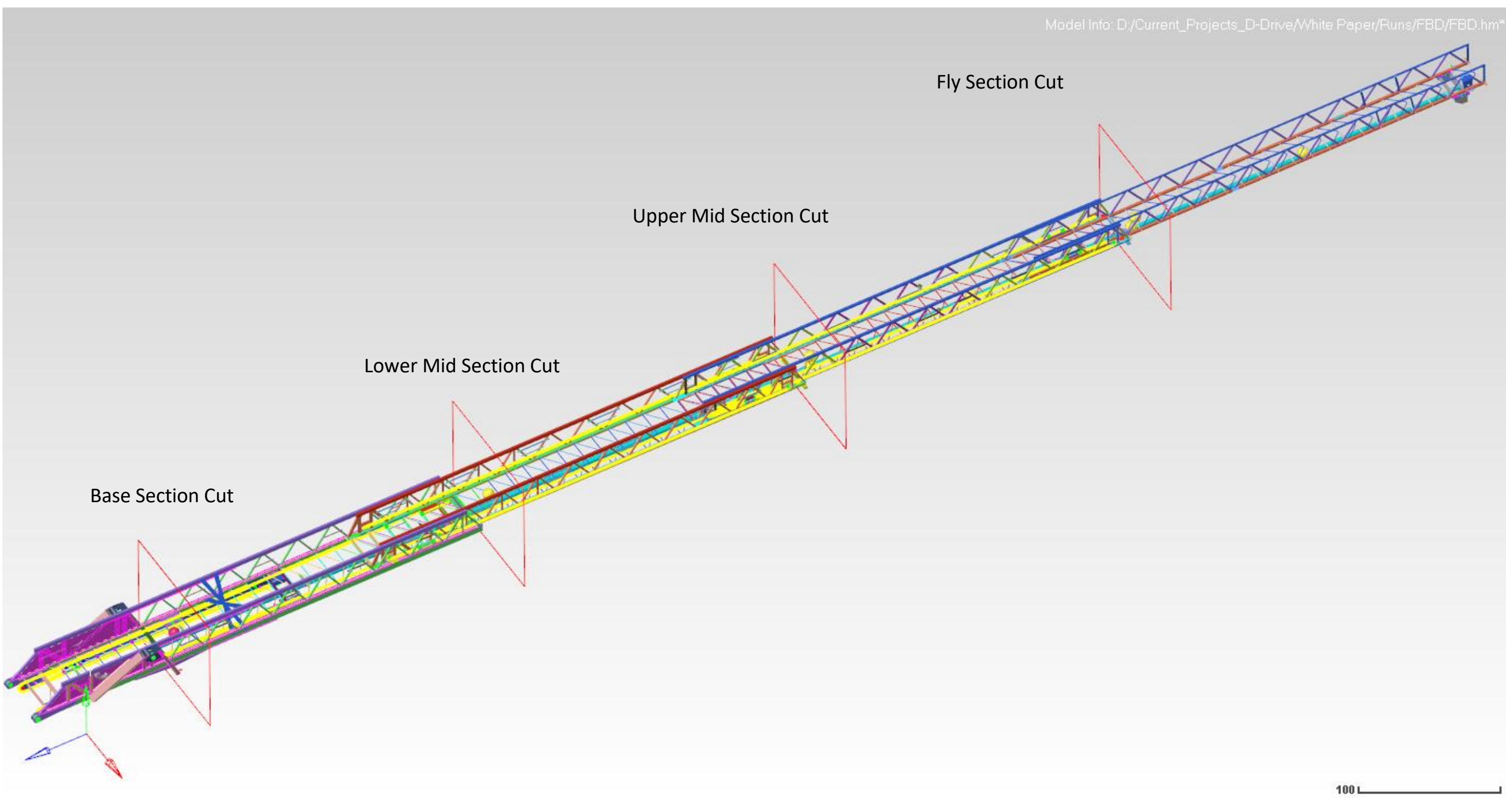


Figure 12 Cross section of ladder for force/moment calculations.

Shear Forces

The plots in figure 13 show the shear force components and the resultant shear at the four section cuts for the pressures derived from CFD and the ASCE equation. The shear force in the X direction (wind direction) correlates well with a small deviation of approximately 50 lbf higher in the CFD analysis at the fly (upper) section cut. The shear force in the directions perpendicular to the wind (F_y and F_z) are zero for the ASCE equation. The magnitude of shear at the base section is significant, although the importance decreases with the height of the ladder. The pressures from the CFD analysis are applied to all elements while the pressures from the ACSE equation are applied only to elements perpendicular to the wind. This difference is reflected in the magnitude of the shear.

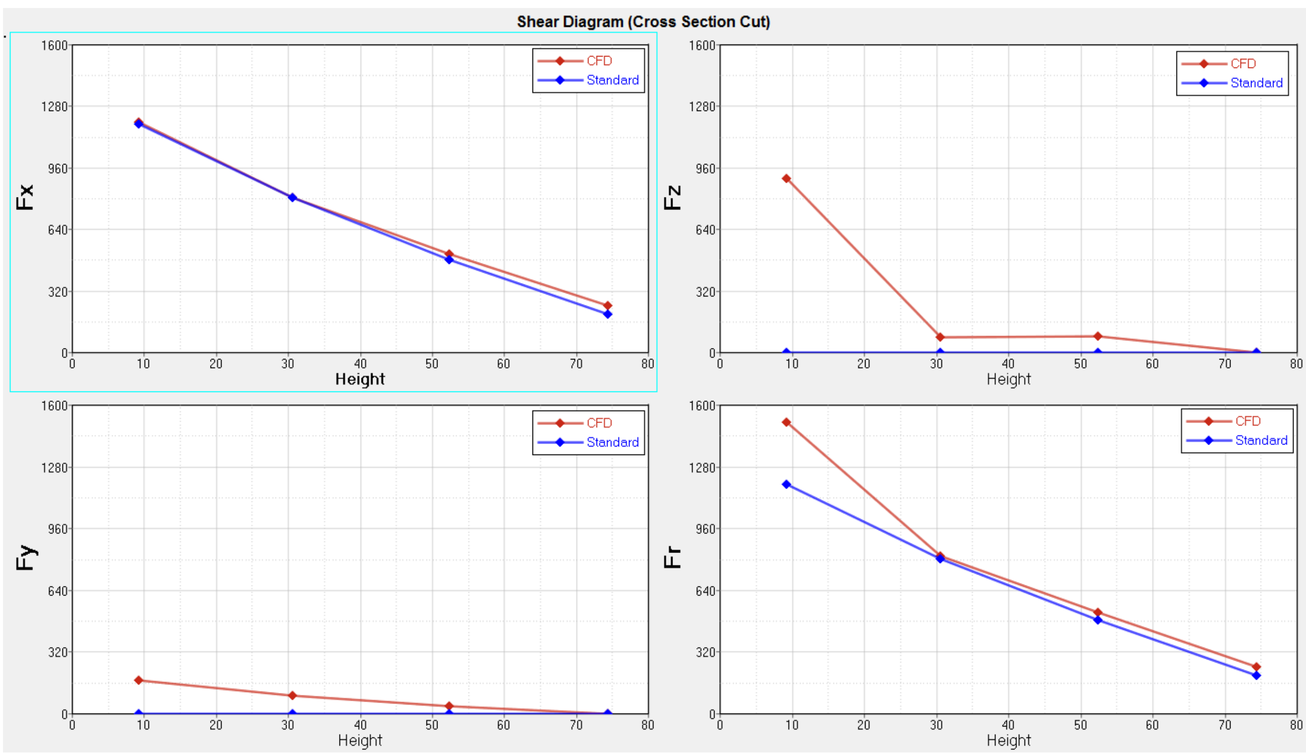


Figure 13 Shear forces at four cross sections of ladder

Moments

Figure 14 shows the moment components and the resultant moment at the four section cuts for the pressures derived from CFD and the ASCE equation. The pressures computed from the ASCE equation generate forces in the x-direction and moments in the y- and z-directions.

The moment about the y-axis due to the wind direction correlates extremely well between the two analyses. However, the moment about the x-axis (rotation about the mount axis) shows significant difference, although the difference decreases with height. This moment is generated by non-uniform wind pressure applied to the underside of the ladder, causing a twist. This difference is greatest at the base section and decreases with height.

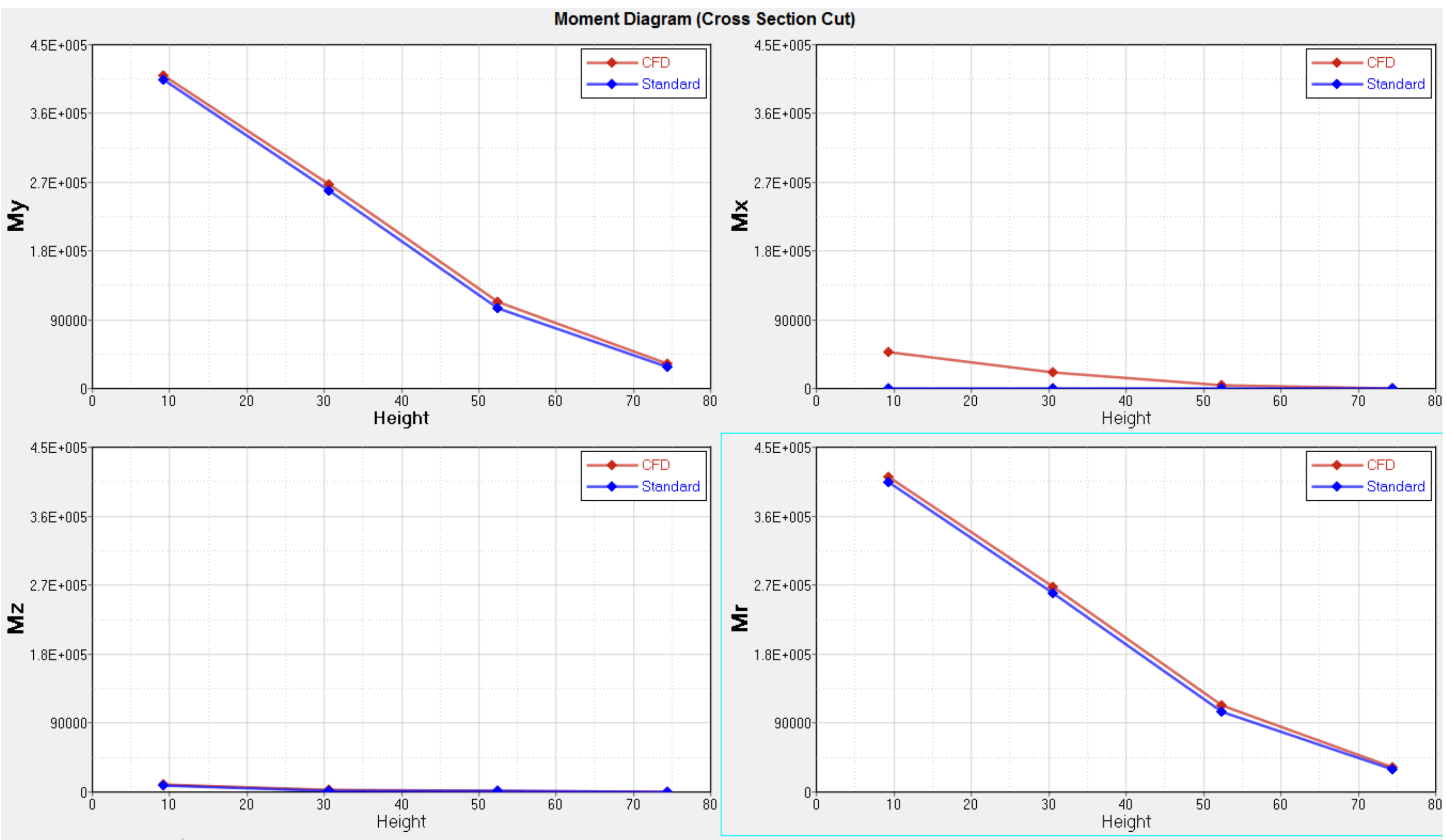


Figure 14 Moments at four cross sections of ladder

Displacement and Stress Comparisons

The displacement and stress are compared for the base section only, since the largest differences between the two methods of analysis are seen at this location.

Displacement: Contour

The models match in the X (wind) direction showing the same contour and magnitude for displacement. In the Y (vertical) direction, however, we see a large difference and that the ladder is rotating about the mounts in the vertical direction.

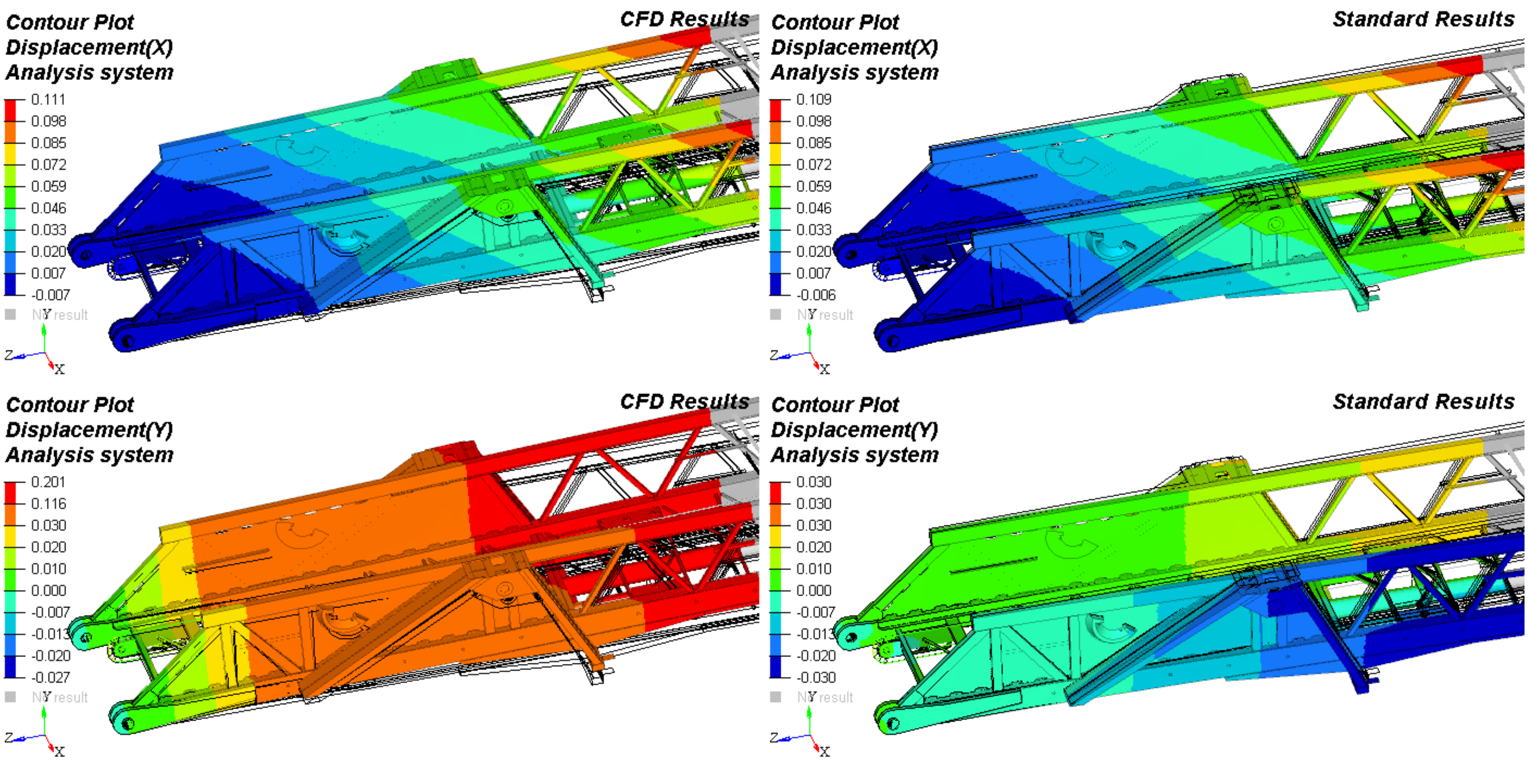


Figure 15 Displacement contour difference at base between CFD (left) and standard (right)

Displacement: Deformed Shape

The biggest difference in the total magnitude between the two loading methods is due to the upward rotation in the CFD model. We see similar displacement behavior in the wind direction showing the same bend about the Y and a bit of a twist about the Z. But in the CFD results, we get a rotation about the X at the mounts due to wind forces on faces other than in the wind direction, such as from underneath wind shear.

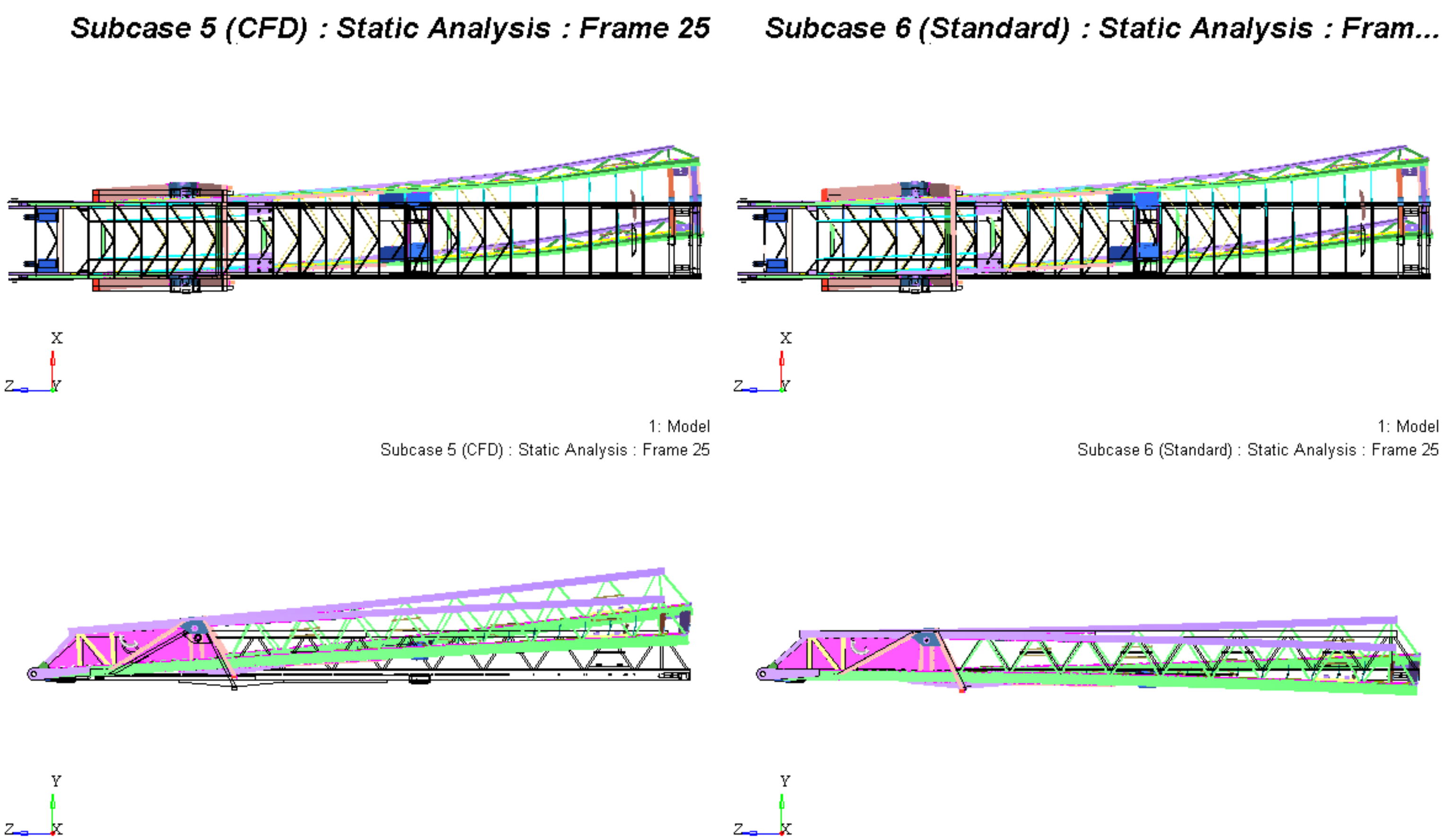


Figure 16 deformed shape difference between CFD (left) and standard (right)

Stress Contour Comparison

With the increased displacement in the CFD results, higher stress in the base section near the mount plates is expected. There is a significant enough difference between the CFD and standard equation stress results to warrant using the CFD method, especially when looking at the base section of the ladder.

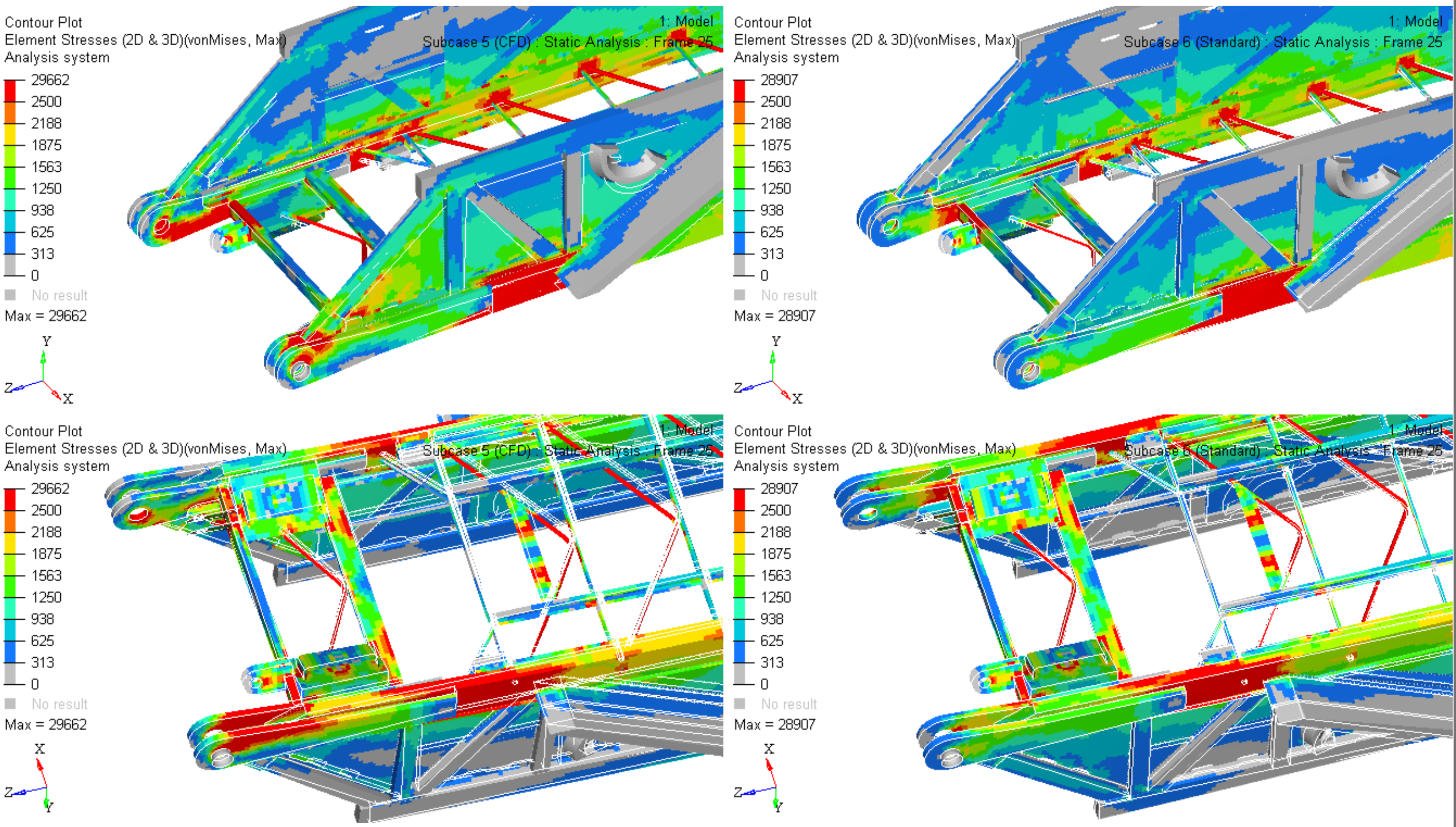


Figure 17 stress contour difference between CFD (left) and standard (right)

Conclusion

Using the equations from code ASCE 7-10 to determine pressures on the ladder is a good approximation when looking along the upper sections of the ladder. The results from both the CFD and standard equation methods correlate at the midsections and the fly, but there are large discrepancies at the base section of the ladder. This indicates that the standard equation is missing some significant loading at the base of the ladder, and that CFD analysis should be considered to fully capture the wind loading behavior of the ladder.

Appendix

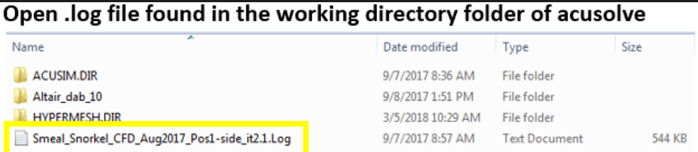
Converting Acusolve nodal pressures to element pressures in Hypermesh using the Fields option

Steps

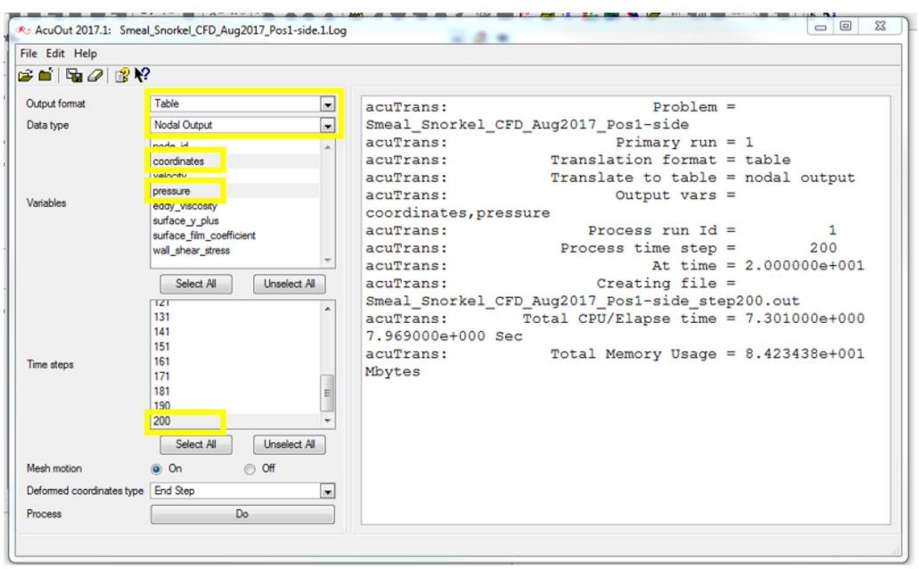
1. **Convert results from acusolve into a text file that Hypermesh can read using pressures and nodal coordinates**
2. **Create a field in Hypermesh with the pressures and nodal data**
3. **Map the pressures onto a structural mesh by realizing the field data**

- **Open acuconsole and launch acuout**

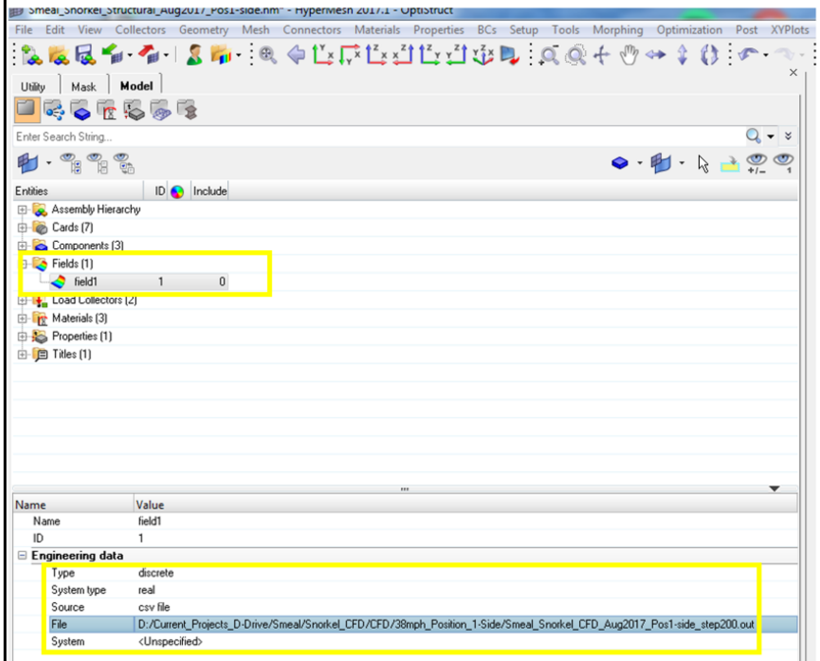
- **Open .log file found in the working directory folder of acusolve**



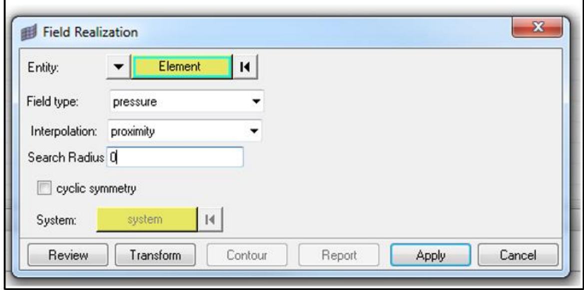
- **Create a .out file (will create in same folder as log file) of form:**
  - **Output format of Table (rows and columns separated by a space)**
  - **Nodal output (x,y,z coordinates)**
  - **Pressure results**
  - **Final Time step only**



- **Open your structural model**
  - **Note: model needs to be in same coordinate system and model units as your cfd model**
- **Create field with data shown below referencing file .out that you created and corresponds to this loadcase**



- **Realize field on all elements with properties shown**



– Realizing (Mapping) Fields

Field realization creates pressures and temperature loads, and maps properties IDs. In order to map the spatially varying values stored in a field entity to the element and node data of the new target mesh you must realize the field entity.

The following types of mapping are supported: node temperature loads, node displacement, element pressure, element property IDs and indirect thickness, and element material orientation.

1. In the **Model** browser, right-click on the field to realize and select ***Realize*** from the context menu.
2. In the **Field Realization** dialog, define realization settings accordingly.
   a. Using the **Entity** selector, select elements or nodes to be realized.
   b. Select a **Field** type.
   c. Select the type of **Interpolation** to perform.
      - **shape function** (based on mapping)
      - **proximity** (based on close point evaluation)
      - **linear interpolation** (based on inverse distance)
   d. Click ***Apply***.

Once the field has been realized, the new mapped values can be visualized using contour or they can be exported to solver decks. When a solver deck is exported, mapped loads will be available on the new mesh.