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SEISMIC ANALYSIS OF A PRESSURE VESSEL

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ABSTRACT

The seismic analysis of ASME Section VIII Div 1 [1] industrial pressure vessels has typically been accomplished using rather simplified “equivalent static force” procedures. As detailed by Bardia et al [2], the equivalent static force from an earthquake event is developed from tabular data in building codes. In general, these procedures have proven to be safe and effective. However, this method assumes that deformation may occur but containment will be maintained. A similar assumption of deformation is contained in the modification factor used in building codes. If the vessel is expected to function after a specific earthquake event, such methods are not adequate for design. This paper addresses a more detailed procedure of seismic analysis that involves a finite element analysis of the vessel incorporating the interaction of the piping and the vessel. This methodology provides a better understanding of the localized stresses, such those as at vessel nozzles with pipe attached. This methodology may be used to analyze a vessel for a design that can be subjected to a specific earthquake response spectrum with minimal deformation and probable return to operation status.

INTRODUCTION

In their 2005 paper [3], Kokavesis and Botsis state: “Pressure vessel codes such as ASME do not provide guidelines for the calculation of seismic loads.” However, the ASME Code does require that seismic loads be included in the evaluation of a vessel’s codeworthiness. The 2003 International Building Code [4] requires that mechanical equipment and nonbuilding structures comply with ASCE 7-02 [5]. ASCE 7-02 in turn refers back to the ASME Code. The ASCE standard does, however, provide guidance on evaluating the base shear and overturning moment requirement for the base. Gillengerten [6] provides an example of the analysis of a boiler for an earthquake event using the provisions of several code procedures. But again, the analysis is limited to shear and overturning moment design for the base.

There are two common procedures used to evaluate the response of structures and components to earthquake loading; the equivalent static force procedure and the dynamic analysis procedure. The equivalent static force method uses a static force developed from a seismic acceleration value applied at the center of gravity multiplied by the operating mass of the vessel and contents. This force is used to develop static moments and shear values for stress analysis. Typically the seismic acceleration value is based on methodology contained in consensus standards such as ASCE 7-02. The dynamic analysis method uses a seismic response spectrum that the vessel will be subjected to and is analyzed using a numerical methodology such as finite element (FE) codes. The seismic response spectrum is also based on consensus standards such as ASCE 7-20. The magnitude of the response spectrum is a function of the ground motion and the assumed damping value for the responding structure. The dynamic analysis methodology investigates the vessel response to the acceleration as a function of frequency as represented by the seismic response spectrum and allows the resulting stresses to be more rigorously investigated than the static methodology.

It is common practice in seismic analysis to consider that components or structures such as pressures vessels can be considered rigid if their fundamental period is less than 0.06

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seconds. In other words, if their first mode of vibration is above ~16.7 Hz they can be considered rigid and the base shear and overturning moment will suffice seismic considerations. Many vessels, especially low pressure service, thin walled vessels have a first mode of vibration well below 16 Hz. Thus, they cannot be considered rigid. The base shear and overturning moment of a vessel that is not rigid cannot be computed accurately without using the dynamic analysis procedure.

Furthermore, pressure vessels normally are connected to piping that can impose significant loads on the vessel due to seismic excitation. Typical piping systems will have numerous modes below the 16.7 Hz "rigid" cut-off. These piping loads must be considered for a valid evaluation of the vessel.

It is not always necessary to conduct a seismic analysis of a vessel. In many locations, the wind loading will have a much greater influence on the design than will the seismic loads.

EXAMPLE

Figure 1 illustrates the configuration of a vessel used as a process component in an LNG plant that will be assessed using Consensus Standard NFPA 59A [7]. The vessel is approximately 14 m between tangent lines and 4.1 m in diameter and has a shell thickness that varies from 23-27 mm and is designed to meet ASME Section VIII, Division 1. It is supported on a 3.5 m skirt that rests on an elevated platform. The design pressure is 1450 kpag and the operating pressure is about 380 kpag. The operating temperature is –158 ^{o}C.

As should be noted, the piping associated with this vessel is rather extensive. The point at which the piping system can be terminated without affecting the analysis results is very much an engineering judgment call. In this case, several runs were conducted to determine the sensitivity of the nozzle loads to the extent and termination of the piping. Although it would be ideal to include the whole piping system, doing so presents some practical analysis problems that will be discussed in a later section.

It should be noted that the piping system for this plant was analyzed separately from the vessel using a dedicated piping code. As will be noted later, the correlation between the nozzle loads computed with the vessel analysis and those derived from the piping analysis did not show a strong correlation.

ANALYSIS PROCEDURES

It is fairly clear just from observation that this vessel and piping system cannot be considered rigid. It would seem highly probable that there are vibration modes below 16.7 Hz in the system. Thus, the proscriptive equivalent static analysis procedures in ASCE 7-02 cannot be employed to accurately evaluate the stress in the vessel and nozzles. Due to the large amount of piping supported by the vessel, even the evaluation of the base shear and overturning moment via the equivalent static analysis procedures would be of questionable accuracy.

In order to evaluate the dynamic response of the vessel, an (FE) analysis of the system was conducted. The model for the system shown consisted of 85,334 nodes that defined 84,642 elements. The vast majority of these elements were plate elements used to define the vessel. 7,543 beam elements were used to model the piping. The piping supports and guides up to the first anchor were included in the model.

In general, there are two analysis procedures that can be used to evaluate the response of a system to seismic loads. One procedure is to compute the response of a structure to a time history of the seismic event. This can be accomplished using either direct integration or modal superposition techniques. A second procedure is to conduct a modal analysis of the system and then conduct a Response Spectrum (RS) analysis.

Given that this vessel rests on another structure, the base structure was first analyzed using the time history method and a RS was derived from this analysis as the input for an RS analysis of the vessel system. The mass of the vessel represents more that 25% of the structural mass. Thus, the mass of the vessel must be included in the modal analysis of the supporting structure. The vessel mass will affect the structure response to a seismic event. The development of a structure in floor response spectrum for the vessel location is typically conducted utilizing a commercial structural code such as GT Strudel. This uses a time history analysis methodology of the structure to develop a specific vessel location RS. This two-step procedure is typical in the seismic analysis of one system that is supported by another.

Typically, when one is interested in only the frequency and mode shapes associated with a system, a relatively coarse mesh can be employed without greatly affecting the results. In this case, however, we are interested in the stress. Thus, there needs to be enough detail in the mesh to accurately evaluate the stresses.

Figure 2 illustrates a typical portion of the mesh used for the model. In general, 64 elements were used around the circumference of all of the nozzles. The elements were sized so that the aspect ration was approximately 1:1 in the nozzle junction region. This mesh density has been shown to be adequate for the accurate evaluation of stress in vessel nozzles.

The piping and vessel were both analyzed for the same seismic event loadings

MODAL ANALYSIS

A modal analysis was conducted using a sparse solution technique employed in Algor Release 19.1 FE software. A total of 100 modes with a cut-off frequency of 33 Hz were requested. Due to the large size of the model and limitations in the software, it was only possible to compute the first 65 modes for the vessel. The modal mass values (as a percentage of the total mass) and the cumulative modal mass are illustrated in Figure 3. As is typical for vessels such as this, the primary modes are at a relatively low frequency (6-7 Hz).

Most of the code references have a requirement that "The analysis shall include a sufficient number of modes to obtain a combined modal mass participation of at least 90% of the actual mass in each of two orthogonal directions." e.g. [5]. In this example, Figure 3 indicates that the contribution of the higher order mode is relatively insignificant. Thus, using 65 modes up to a frequency of ~23 Hz adequately describes the system. Had the vessel been analyzed without the piping, it is likely that the 90% criteria could have been met.

LOADS

As has been stated, an RS was developed specifically for this vessel from a site-specific ground motion and the response of the supporting structure. In fact, two response spectra were developed. NFPA 59A requires that such vessels, used as process components in an LNG facility, be designed for an Operating Basis Earthquake (OBE). This is a load that the system is expected to survive with probable return to operational status.

The NFPA standard also defines a Safe Shutdown Earthquake (SSE). The requirement for this event is that the container has to maintain its integrity during the event. In other words, it can bend but not rupture. It is important to note that the SSE is not a required load under NFPA for process components.

The NFPA 59A seismic event design methodology for piping and components (which defines components to include process vessels) specifies an operating base earthquake (OBE) and references applicable ASME codes for methodology and design stresses. The ASME codes stress investigation methodology and design stresses are developed to address all operational loadings, including seismic, and maintenance of functionality.

ASCE 7-02 and typical building codes require that the structure be designed to a maximum considered earthquake (MCE) event in a life safe methodology that allows plastic deformation in the structure but not collapse. However, the structure is not expected to be functional after the seismic event. Therefore ASCE 7-02 provides methodology for significant reduction of the applied earthquake accelerations and provides design stresses to be used in a static analysis methodology.

The NFPA 59A OBE accelerations are approximately one half the ASCE 7-02 MCE accelerations. However, since the ASCE 7-02 methodology includes significant reduction factors for MCE acceleration for stress evaluation, the NFPA 59A OBE accelerations are typically significantly greater than those utilized for ASCE 7-02 purposes.

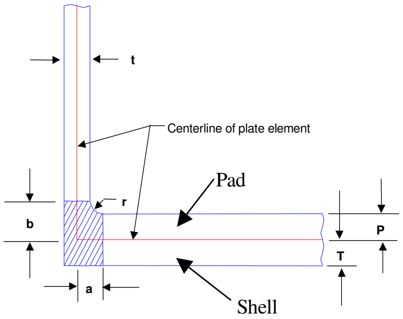
Figures 4 and 5 represent the OBE and SSE response spectra respectively for the elevated support location of the vessel. It is clear that the shapes of the spectra are influenced significantly by the direction of application. This is due to the response of the supporting structure to the ground excitation. In the FE code used for the analysis, only one spectrum shape was allowed. In order to conduct the analysis it was necessary to pick one spectrum shape and then use scaling factors to differentiate the directions, as noted on the figures.

OBE STRESS

Figure 6 illustrates the indicated Stress Intensity (SI) in the vessel due to the OBE load. As noted on the figure, the highest indicated SI is near the nozzle on the top of the vessel.

If we look at the geometry of this nozzle and apply a recommended evaluation procedure [8], the highest reported stress is not the correct stress level for evaluation. In Figure A, the shaded region is to be specifically excluded from the evaluation of a nozzle except for purposes of fatigue evaluation.

Nozzle Stress Evaluation Locations - N2



$P := 1.0\,\text{in}$ $\quad T := 1.0\,\text{in}$ $\quad t := 0.5\,\text{in}$ $\quad r := 0.5\,\text{in}$

$a := \frac{t}{2} + r$ $\quad a = 0.019\,\text{m}$ $\quad b := \left(\frac{P+T}{2}\right) + r$ $\quad b = 0.038\,\text{m}$

Figure A - Nozzle Evaluation

The distance b designates the distance from the intersection on the model to the point of evaluation. In Figure 7, only those elements in which the stress equals or exceeds 3S (413.7 MPa for the material used) are indicated. From Figure 78, it is clear that this stress level is exceeded only in the first row of elements next to the intersection. These elements extend 0.0351 m away from the intersection. Since this distance is less than b (0.038 m), it is clear that the evaluation level at this intersection is less than 3S.

The highest observed stress due to the seismic loading occurs at the junction between nozzle N3 and the top vessel head. The peak values observed are less that 3S for the material employed. Thus, based on the seismic loads alone, the vessel meets the requirements of ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 when Division 2 analysis methods are employed.

The anchor bolt and skirt stresses were also evaluated. The skirt stress and bolt loads were acceptable.

The effect of the liquid inventory sloshing on the skirt and support was evaluated using the procedure outline by Malhotra [9] and found to be acceptable.

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SSE STRESSES

As this vessel is a major component of the plant and contains significant liquid, prudent engineering judgment dictates that we examine the response of the vessel to the SSE. This is despite the fact that the NFPA 59A standard does not require that the SSE loads be evaluated. Figure 8 illustrates the stress at the nozzle intersection with only those elements in which the stress equals or exceeds Minimum Tensile Stress (517.1 MPa for the material used) are indicated. Reasonable engineering judgment would be that the SSE is a "deform but not break" event, similar to a Life Safety ASCE 7-02 design, and the Minimum Tensile Stress rather than 3S is deemed the appropriate criteria for evaluation. Using the same procedure that was used for the OBE evaluation, the nozzle stresses are found to be below the criteria level.

The anchor bolt and skirt stresses were also evaluated. The skirt stress and bolt loads were acceptable. Additionally, buckling in the skirt was also examined.

PIPING-DERIVED LOADS

As was noted at the beginning of the paper, the correlation between the nozzle loads developed in the vessel analysis and the piping analysis for the OBE was not good. The ratio between the loads derived by the two methods ranged from 0.14 to 3.37 as shown in the table below.

Ratio of FE RS to Piping RS							
		Force - N			**Moment - N-m**		
Node	**Nozzle**	**F1**	**F2**	**F3**	**M1**	**M2**	**M3**
15453	2	0.18	0.30	0.59	0.39	0.28	0.14
15529	7	0.83	0.42	0.43	0.32	0.05	2.83
21484	4	1.14	0.13	0.37	2.03	0.95	0.88
44611	3	2.34	0.68	2.24	2.28	1.58	1.74
58073	1	1.04	0.31	0.36	0.65	1.72	1.18
65847	6	3.37	0.42	0.43	0.67	2.36	2.33

No one particular reason was found for the lack of correlation. Rather, the different assumptions and boundary conditions used in the two analyses are assumed to be the culprit. Even though the nozzle spring rates developed in the vessel analysis were used in the piping analysis, there are enough differences in the procedures to produce different results. That is perhaps a good subject for another paper. As a practical matter, the vessel was examined using both sets of loads (vessel and piping derived) and had to meet the criteria for both cases.

CONCLUSIONS

Use of the static equivalent force technique is not adequate for the seismic analysis on many pressure vessels and systems. Response Spectrum analysis techniques provide more and better information. When the vessels and piping system are modeled separately, the nozzle loads produced can differ dramatically. Using both sets of loads to evaluate the vessel is prudent.

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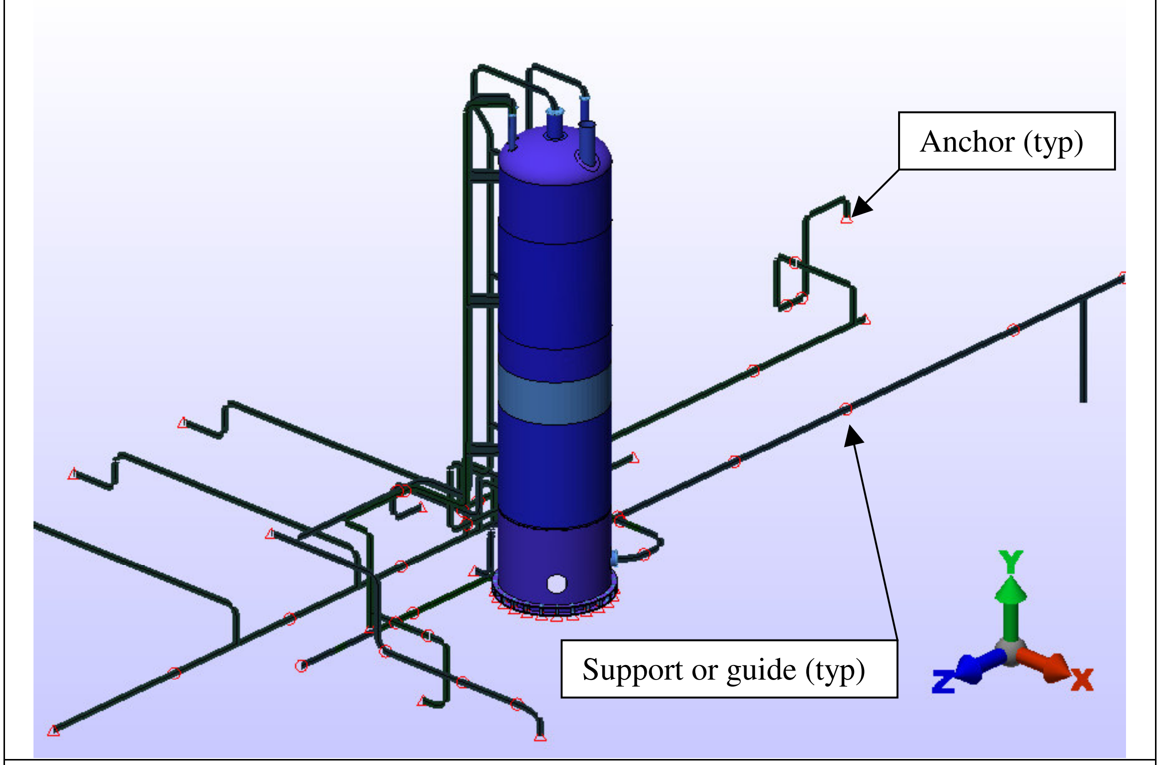

Figure 1 – Overall system configuration

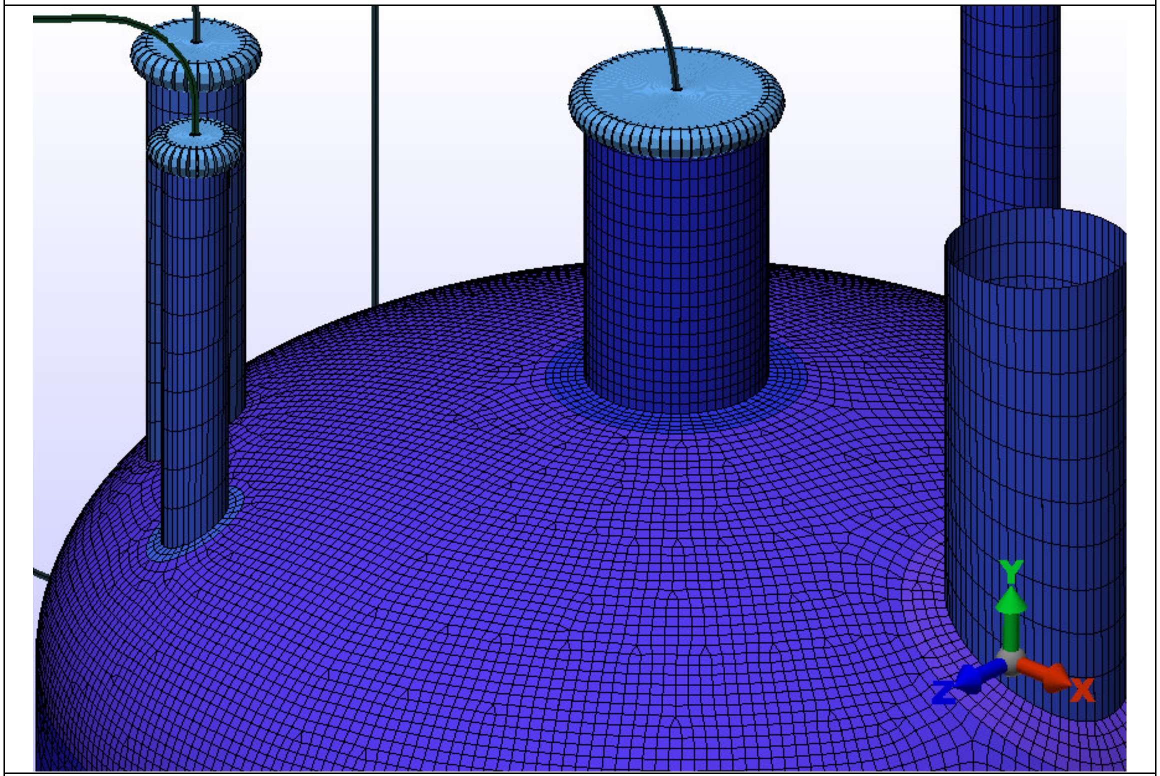

Figure 2 – Example of mesh

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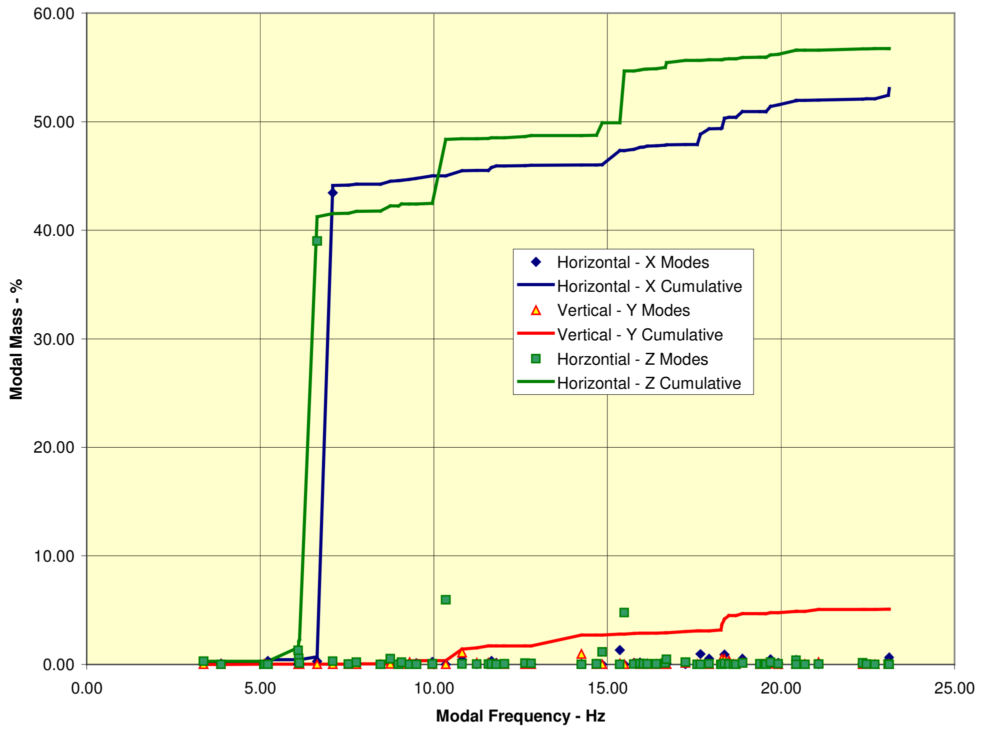
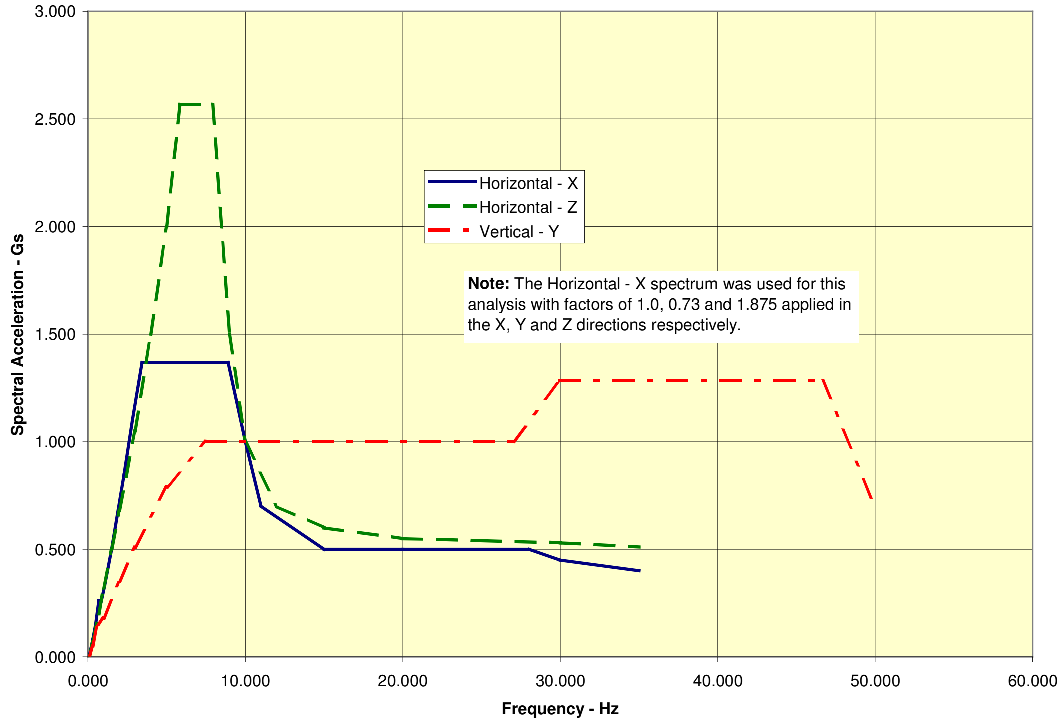


Figure 3 – Modal mass



Note: The Horizontal - X spectrum was used for this analysis with factors of 1.0, 0.73 and 1.875 applied in the X, Y and Z directions respectively.

Figure 4 – OBE response spectra

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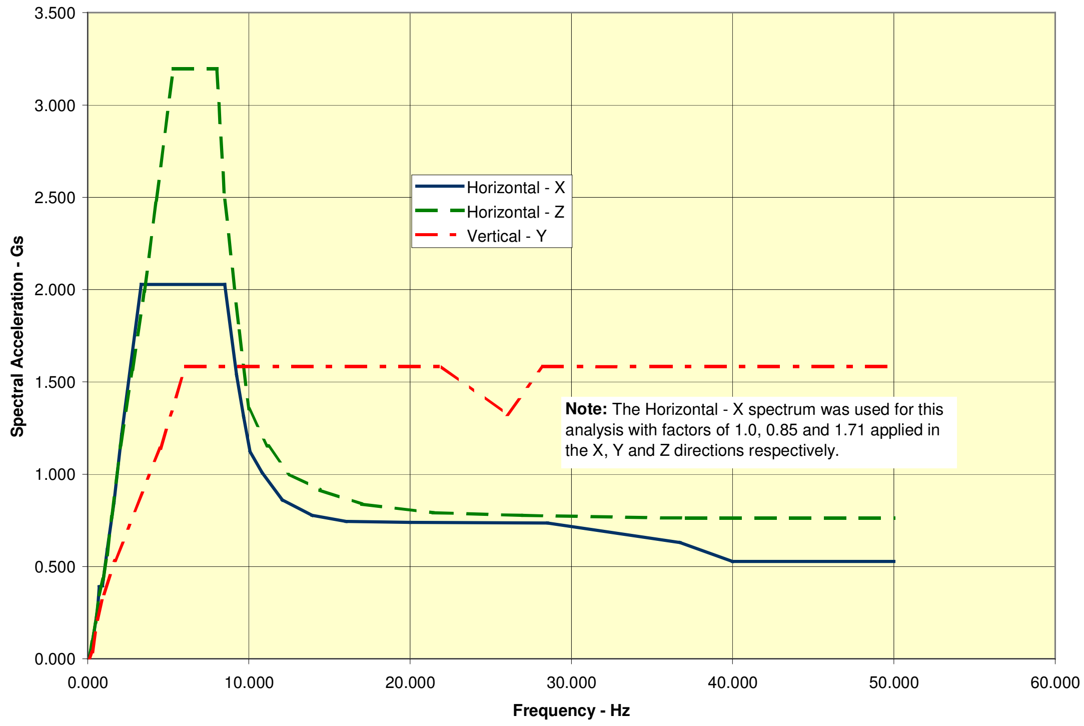
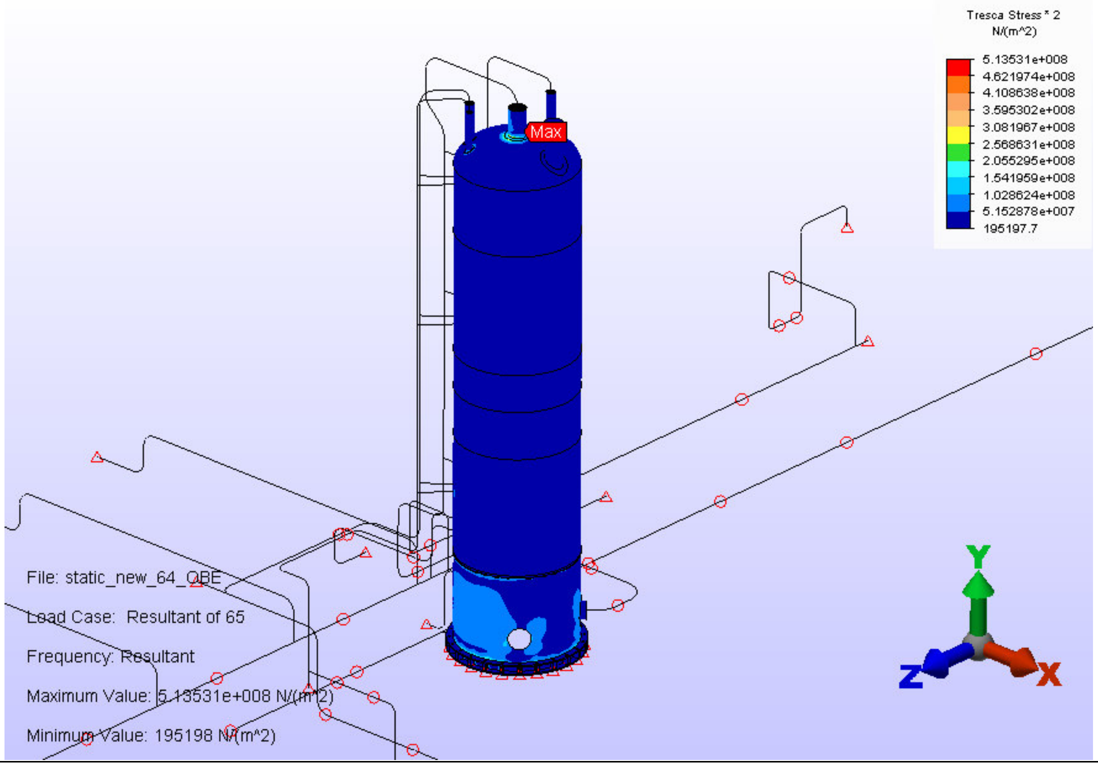


Note: The Horizontal - X spectrum was used for this analysis with factors of 1.0, 0.85 and 1.71 applied in the X, Y and Z directions respectively.

Figure 5 – SSE response spectra



File: static_new_64_OBE

Load Case: Resultant of 65

Frequency: Resultant

Maximum Value: 5.13531e+008 N/(m^2)

Minimum Value: 195198 N/(m^2)

Figure 6 – Plot of stress intensity due to OBE load

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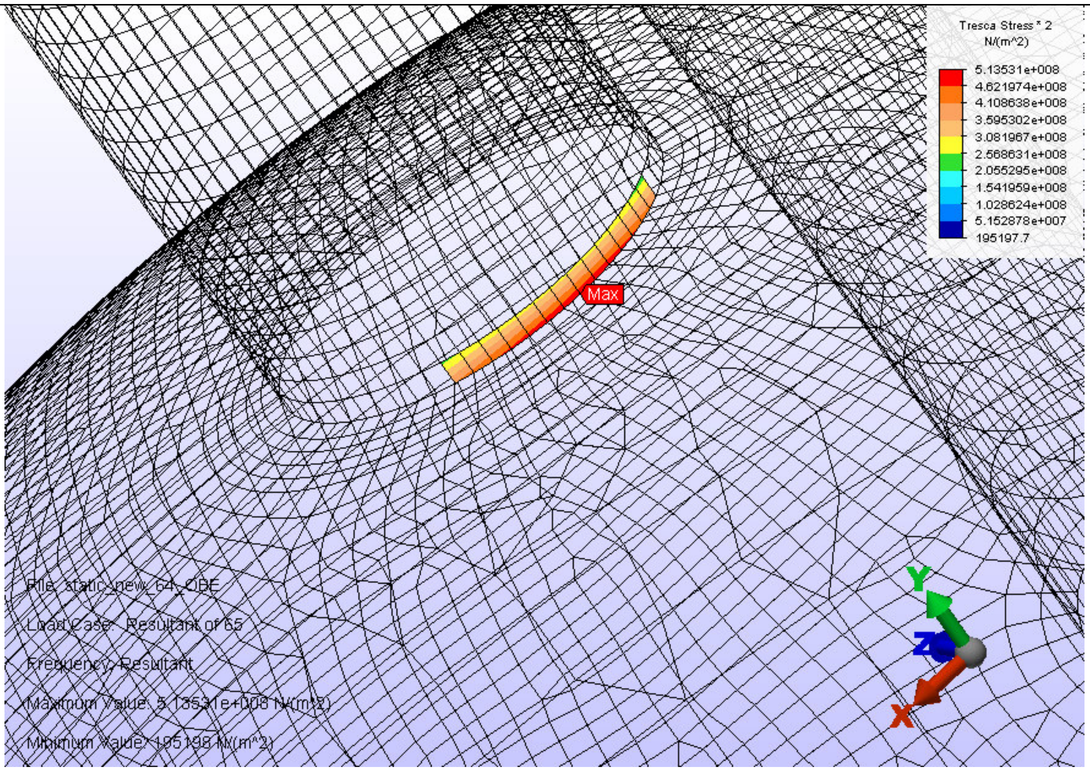

Figure 7 – Detail of stress intensity due to OBE load

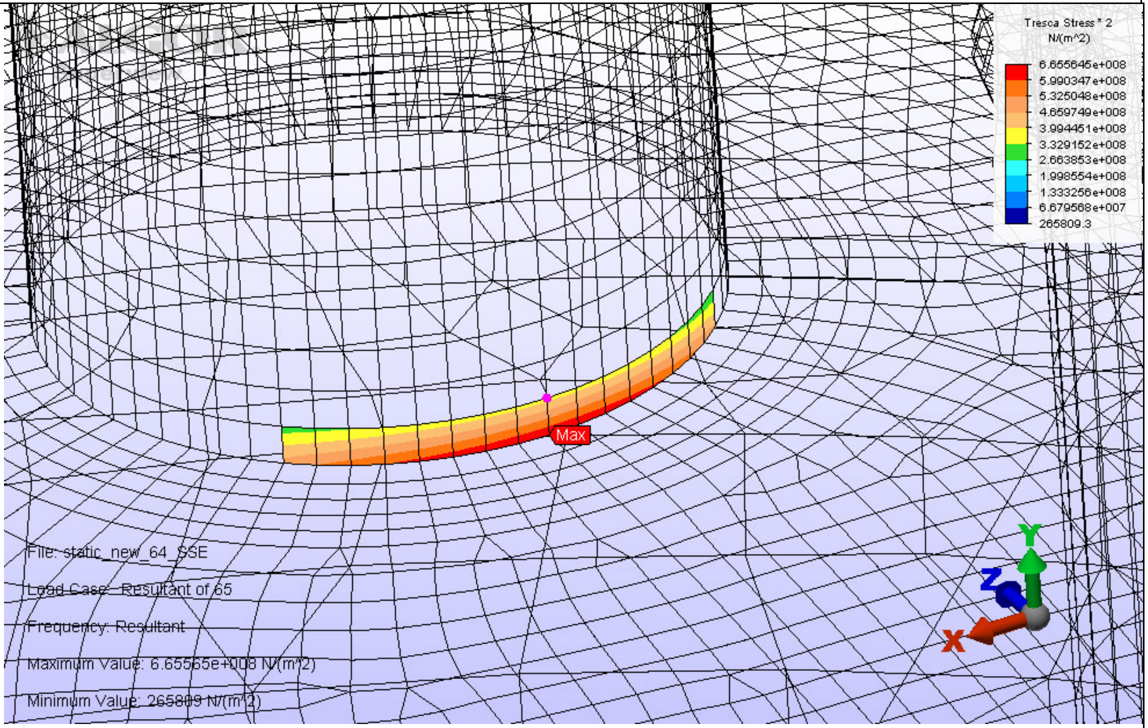

Figure 8 – Detail of stress intensity due to SSE load

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