Improved Bolt Models for Use in Global Analyses of Storage and Transportation Casks Subject to Extra-Regulatory Loading.

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Abstract

Transportation and storage casks subjected to extra-regulatory loadings may experience large stresses and strains in key structural components. One of the areas susceptible to these large stresses and strains is the bolted joint retaining any closure lid on an overpack or a canister. Modeling this joint accurately is necessary in evaluating the performance of the cask under extreme loading conditions. However, developing detailed models of a bolt in a large cask finite element model can dramatically increase the computational time, making the analysis prohibitive.

Sandia National Laboratories used a series of calibrated, detailed, bolt finite element sub-models to develop a modified-beam bolt-model in order to examine the response of a storage cask and closure to severe accident loadings. The initial sub-models were calibrated for tension and shear loading using test data for large diameter bolts. Next, using the calibrated test model, sub-models of the actual joints were developed to obtain force-displacement curves and failure points for the bolted joint. These functions were used to develop a modified beam element representation of the bolted joint, which could be incorporated into the larger cask finite element model.

This paper will address the modeling and assumptions used for the development of the initial calibration models, the joint sub-models and the modified beam model.

Introduction

The lid-joint of a typical storage cask is presented in Figure 1. The lid of the typical cask is attached to the cask body with a set of studs, which are threaded into anchor blocks. The cask lid is held in place by nuts threaded on the lid studs. Determining the behavior of this connection is critical in evaluating the condition of the cask and any subsequent consequences from an extra-regulatory impact. Modeling this joint accurately is necessary in order to determine the performance of a cask subjected to such an extreme loading condition. However, developing detailed models of a bolted joint in such a large cask finite element model can dramatically reduce the critical time step, which increases the computational time and makes the analysis prohibitive.

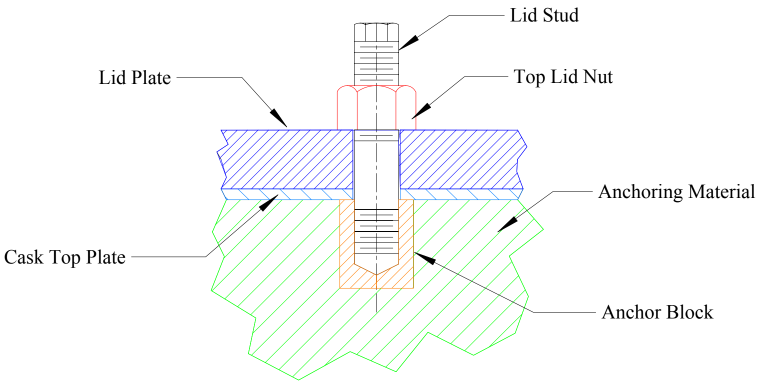

Figure 1. Schematic drawing of storage cask bolted joint.

To improve the modeling of a storage cask bolted joint, a rigorous stud model was developed for the storage cask finite element model that does not diminish the computational speed. The model uses a beam element (a one-dimensional element with bending, shear and axial stiffness) in which the force-displacement functions and the failure displacement, in shear and tension, have been determined using a series of detailed bolt finite element sub-models. The initial sub-models were calibrated for tension and shear loading using test data for large diameter (1.25 in) bolts. Next, using the calibrated sub-model, a sub-model of the actual bolt joint for the storage cask was developed to obtain force-displacement curves and the failure displacement for the storage cask stud. These force-displacement functions were used to develop a modified beam element representation of the stud that more accurately models the stud and lid behavior. This modified beam model was then incorporated into the larger cask finite element model.

A325 Bolt Force-Displacement Calculation

Before the detailed finite element sub-model for the storage cask stud was developed, a sub-model was developed for an A325 bolt. The purpose of this A325 bolt finite element sub-model was to verify that the models could reproduce the proper bolt response. Results from the A325 analysis were compared to test data [1] for double shear tests. The details of the A325 bolt model and the results are discussed below.

The finite element model of the A325 bolt is shown in Figure 2(a). This is a quarter-symmetry model in double shear, with 88,920 elements. ASTM Standard A325 specifies the bolt material as medium carbon steel. These requirements are met by a wide range of steels, from AISI 1030 to AISI 1055. AISI 1045 steel was used in this analysis since it meets the A325 specification requirements and stress-strain data for this material is readily available. A stress strain curve taken from Boyer [2] was used to develop the power law hardening constitutive model. Material parameters are given in Table 1.

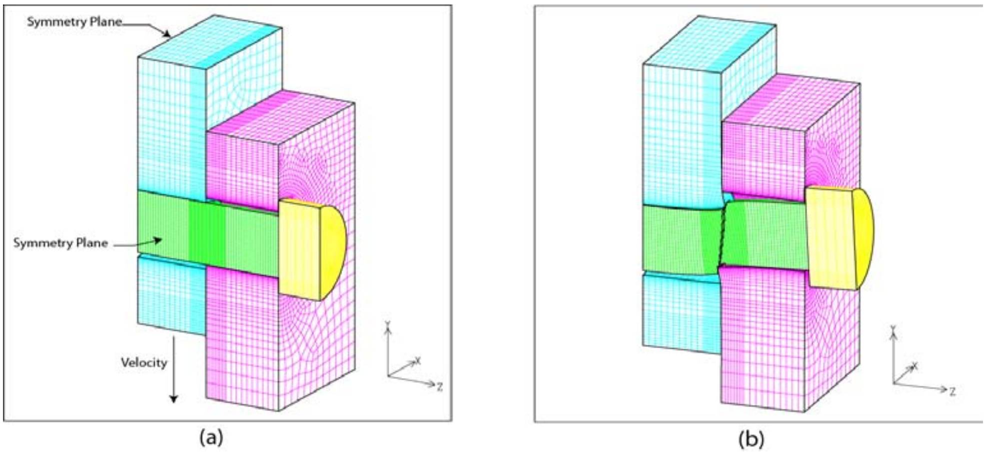

Figure 2. (a) A325 bolt finite element model; (b) Model at fracture

Table 1. Material parameters for AISI 1045 steel (Ref [2])

Elastic Modulus	28.9 E3 ksi
Yield Stress	90.2 ksi
Luder Strain	0.003
Hardening Constant	177.9 ksi
Hardening Exponent	0.456
Ultimate Strength (Engineering Stress)	132.7 ksi
Reduction in area	59.2%

The critical value of EQPS in pure shear was determined using the results reported by Wierzbicki [3]; under a state of zero hydrostatic stress (pure shear) the EQPS required to cause ductile tearing is approximately half of the value required in tension. For the AISI 1045 bolt steel, a value of 0.45 was used for the EQPS failure in shear.

Results from the shear analysis are presented in Figure 2 (b). This is for an A325 bolt with A440 shear blocks (used in the test); the figure shows the bolt just after it has fractured. The bolt elements were killed when the equivalent plastic strain reached 0.45.

Figure 3 gives the nominal shear stress versus block displacement for three separate cases: test data from Wallaert[1], results of a finite element analysis with the shear blocks having the same material as the bolt (hard shear blocks (HB)), and results from a finite element analysis with shear block having material properties softer than the bolt (soft shear blocks (SB); A440 steel). The figure clearly shows the effect of joint stiffness on the displacement of the bolted joint. The harder shear blocks (HB) fail the bolt in about half the displacement of the soft shear blocks (SB). This was observed in the tests by Wallaert. The curve for the softer shear blocks tracks the test data with the A440 block fairly well; the magnitude of the failure stress for both shear blocks and the test data are within 10% of each other.

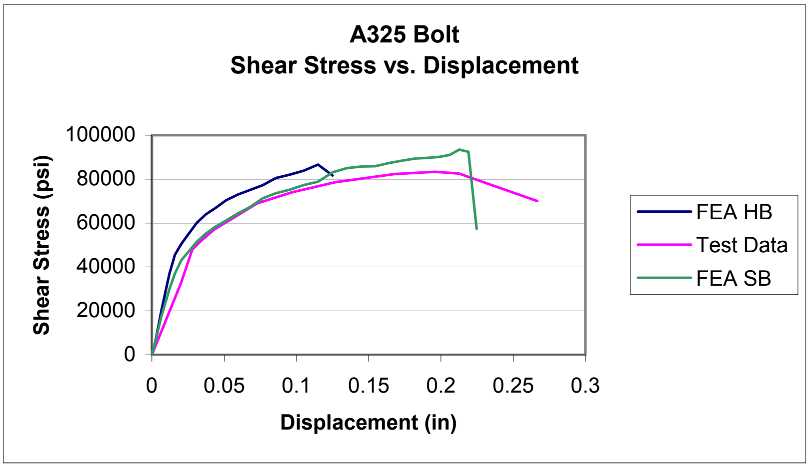

Figure 3. Bolt shear stress versus displacement of the shear block

Storage Cask Stud in Shear

The finite element model of the storage cask stud and lid section is presented in Figure 4(a). This is a single shear model with a plane of symmetry along the axis of the stud. The model includes the 3-inch stud and nut, the 4-inch thick lid plate, the cask top plate and the anchor block. There is a 1/16 inch radial clearance between the stud outside diameter and the lid hole inside diameter. This analysis establishes the pure shear behavior of the stud (this is necessary for the combined tension/shear capacity assessment). The lower section of the stud is attached to the anchor block using “tied surfaces” to simulate the threaded contact. The nodes on the upper surface (positive y face) of the anchor block were held fixed in the x, y, and z direction and the lower surface of the lid plate was given a velocity in the positive y direction.

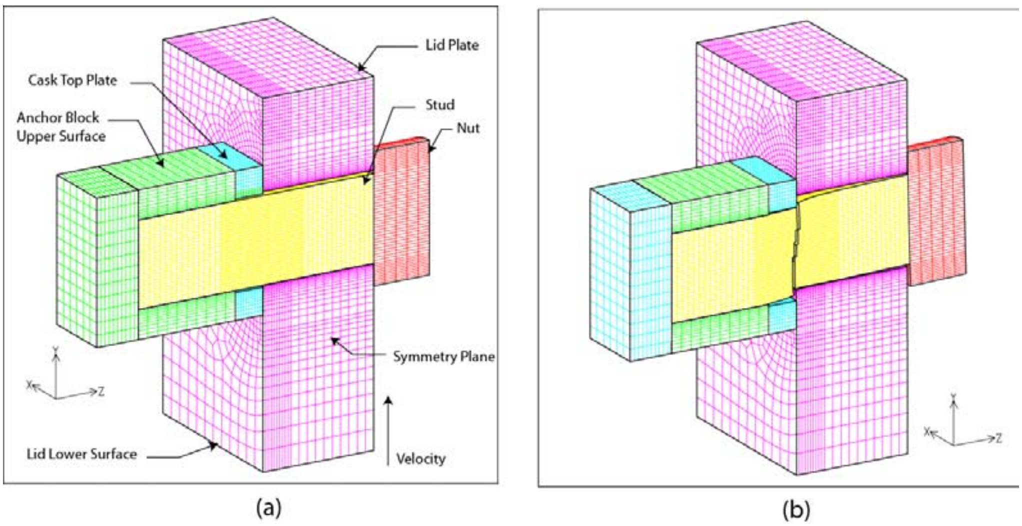

Figure 4. (a) Storage cask bolt model in shear; (b) Shear model results

The stud material is ASME SA564-630 stainless steel hardened at 1075 °F. The material parameters are presented in Table 2. The cask lid is made from ASME SA-516-70 and the anchor block is made from SA-350-LF3. Both of these materials were modeled using a power law constitutive model with the parameters given in Table 3.

Table 2. SA564-630 material parameters

Elastic Modulus	29.4 E3 ksi
Yield Stress	115 ksi
Luder Strain	0.00
Hardening Constant	111.5 ksi
Hardening Exponent	0.37
Ultimate Strength	145 ksi
Reduction in area	45%

Table 3. SA-516-70 and SA-350-LF3 material parameters

Elastic Modulus	30.0 E3 ksi
Yield Stress	52.2 ksi
Luder Strain	0.02
Hardening Constant	67.52 ksi
Hardening Exponent	0.339

The resulting displacements for the shear loading of this model are presented in Figure 4(b). This shows the fracture of the stud resulting from the sliding of the cask lid under the conditions postulated in the analysis. The reaction force on the anchor block is plotted as a function of the lid displacement in Figure 5. This gives a maximum lid displacement of 0.488 inches and a maximum force of 700,000 lbs. Using the forces shown in Figure 5, the nominal stress is calculated by dividing the reaction force in the anchor block by the nominal area of the stud, a maximum stress of 98 ksi is calculated in the stud; this is approximately 67% of the stud tensile strength and agrees well with published data [4], where the shear failure data is clustered around 62% of the tensile strength.

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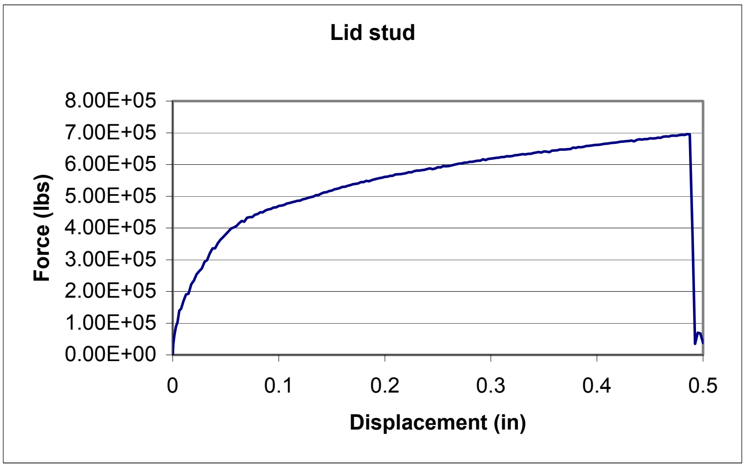


Figure 5. Lid stud shear force versus lid displacement

Storage Cask Stud in Tension

The finite element model for the storage cask stud and lid section in tension is shown in Figure 6(a). This is very similar to the shear model except that an undercut was made in the top portion of the thread area to represent a stress concentration that may develop at the base of the thread during the tensile loading. This detail is not important in the shear loaded model and therefore, it was only added to the tensile model. The diameter of the undercut is equal to the root diameter of the thread. Also, the bottom section of the anchor block was removed to simplify the model, and the thickness of the nut was increased to 3 inches to represent the true thickness of the nut. (Note that the height of the nut has no effect on the resulting stress field in the stud shank.) The lower surface (negative z face) of the block was fixed in the x, y, and z directions, and the lid block was given a velocity in the axial direction of the stud (positive z direction).

The results from the tension test are presented in Figure 6(b). Note that the stud failed in a necked region just above the cask top plate and not in the thread notched area. The stud force versus lid displacement is presented in Figure 7. The total elongation of the stud is about half of the diameter and the maximum force in the stud is about 1.03 million pounds. By dividing the force by the nominal area of the stud the engineering stress can be determined. The maximum nominal stress is approximately 146,000 psi.

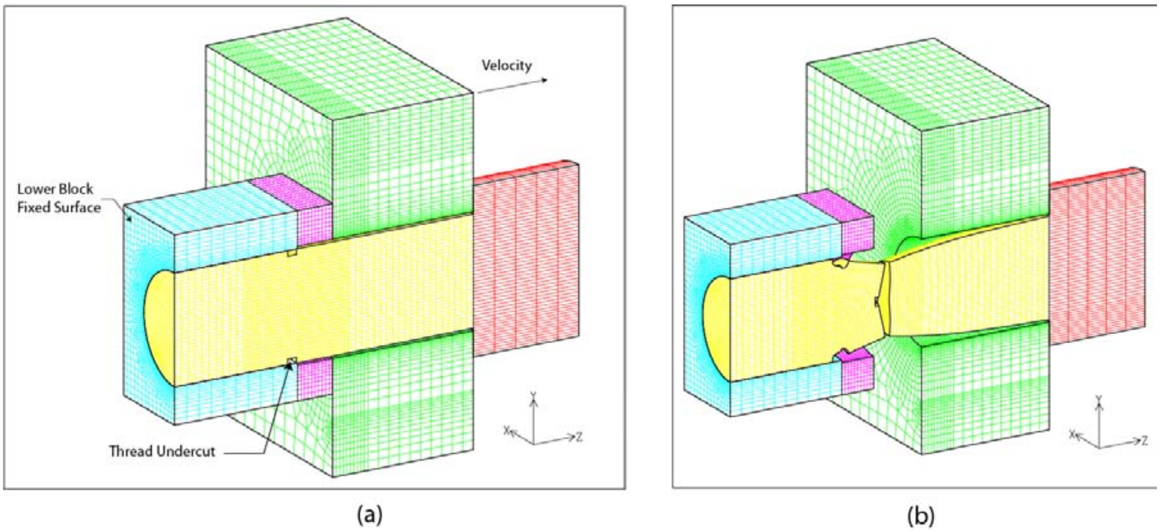


Figure 6. (a) Lid stud model for tension test; (b) Tension test results

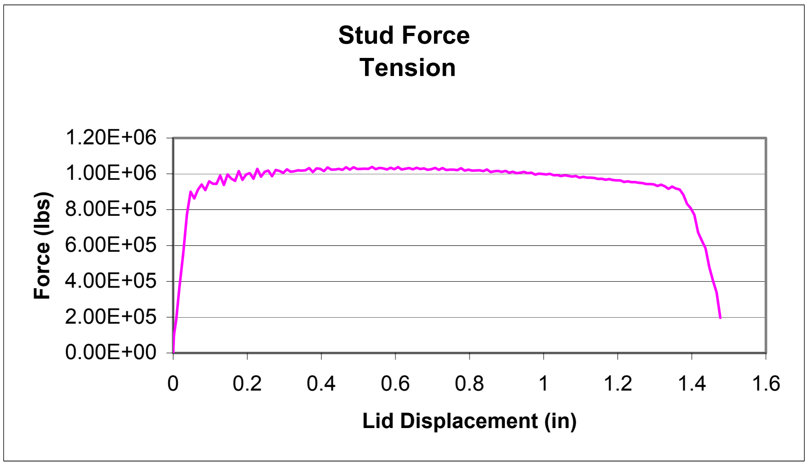


Figure 7. Force-displacement curve for a storage cask stud in tension

Modified Beam Model

The force-displacement curves generated using the detailed bolt sub-models are now used to develop a beam finite element model that is incorporated into the cask finite element model. Figure 8 shows the beam model incorporated in the cask finite element model. The model consists of three parts: the beam finite elements (shown in green in Figure 8), the two shear blocks used to model the single shear of the lid and mounting blocks, and the group of elements immediately surrounding the studs (dark blue elements). The mesh size used in this model is the same mesh size used in the cask finite element model.

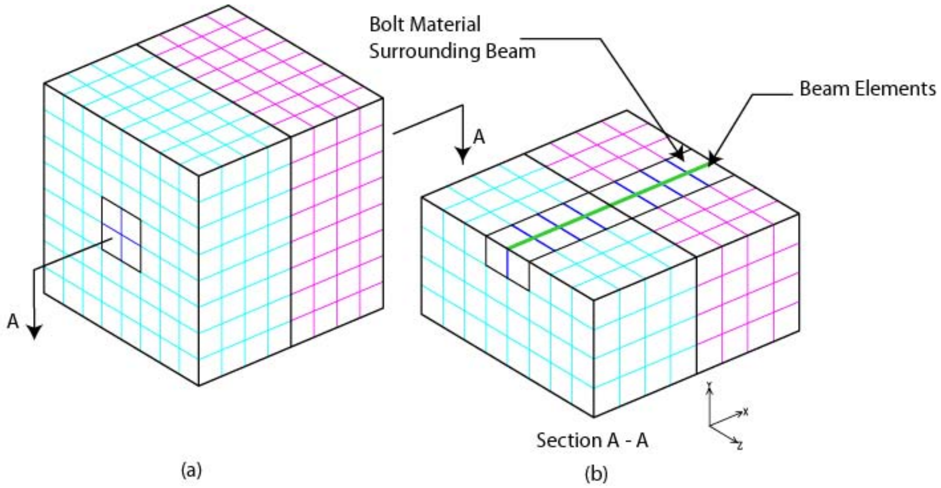
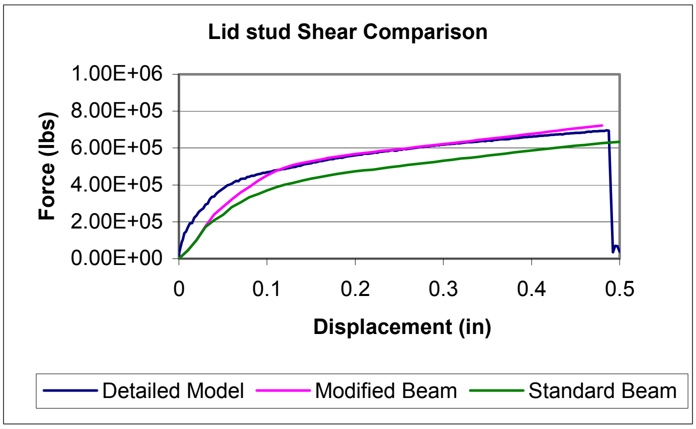


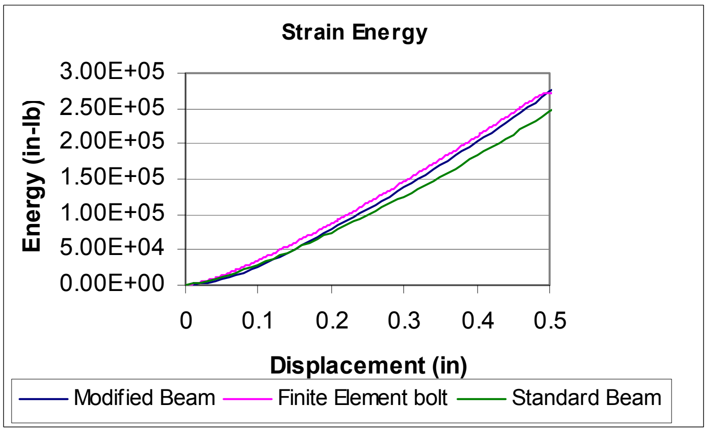
Figure 8. (a) Finite element of modified beam; (b) Section through modified beam model showing the beam elements

Using the beam model, a series of calculations were run to determine the stiffness of this joint. The first calculation is for the standard beam finite element model with a beam of the correct material and geometry, and with shear blocks of the correct lid material. The force displacement curve is shown in Figure 9(a) along with a curve from the detailed finite element stud sub-model. As indicated by this figure, the standard beam model is more compliant, i.e. more flexible, than the detailed finite element model. This is attributed to the difference in stiffness between the beam elements and the shear block elements, where the beam elements are attached. In this case, the shear block elements are made of a lower strength material and are 1-inch hexagons, while the beam elements are a higher strength material with an equivalent diameter of 3 inches. This results in a lot of deformation occurring locally in the material surrounding the stud (beam elements).

To increase the stiffness of the beam joint, the material of the elements surrounding the stud was changed to the same material as the beam. The shear force-deflection curve for this analysis of the modified beam model is also shown in Figure 9(a). By strengthening the surrounding material, the response of the beam model more closely mimics the response of the actual stud. The strain energy for each model is plotted in Figure 9(b). The strain energy of the modified beam model tracks very closely to the strain energy of the finite element stud model. The tensile force-deflection curve for the modified beam model is shown in Figure 10. This graph presents a total deflection of 0.3 in. In this range there is fairly good tracking between the two force curves, with the beam model having a higher stiffness than the stud model. However, the necking of the stud, which is accurately modeled in the sub-model, does not occur in the beam model. Therefore, at large displacements the force-displacement curve continues to rise in the beam model. Since the magnitude of the stud tensile displacements is expected to be small in the cask finite element model, this deviation is not important.



(a)



(b)

Figure 9. (a) Force deflection curve comparing original beam model, modified beam model, and detailed finite element model; (b) Strain energy in finite element models

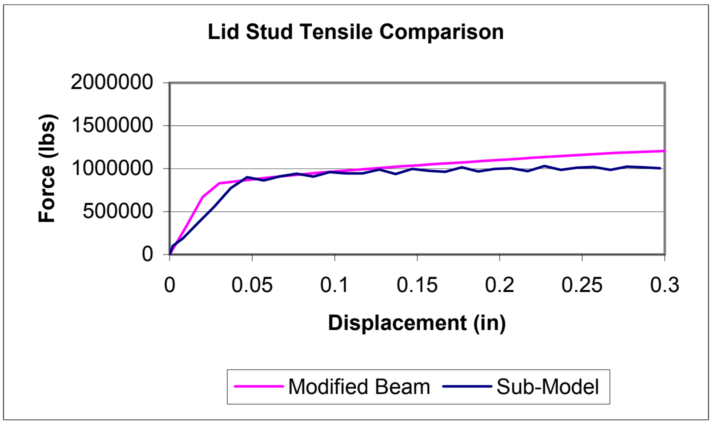


Figure 10. Force deflection curve comparing modified beam model, and finite element sub-model

Bolt Failure Determination

Using the displacements of the modified beam model obtained from the larger cask finite element model, the combined effect of tension and shear in producing stud failure is assessed using the following relationship

$$\left(\frac{u_n}{u_{n_{crit}}}\right)^p + \left(\frac{u_t}{u_{t_{crit}}}\right)^p < 1.0$$

where u_n is the normal or tensile directed lid displacement found in the analysis, $u_{n_{crit}}$ is the tensile deformation capacity (1.35 in from Figure 7), u_t is the tangential or shear deformation found in the analysis, and $u_{t_{crit}}$ is the shear deformation capacity (0.488 in from Figure 5). The value for the exponent *p* is typically 2.0.

Conclusion

To improve the modeling of bolted joints in large finite element models of shipping and storage casks, a modified beam modeled was developed using detailed bolt sub-model. The modified beam model develops the correct shear and tensile force characteristics as the actual joint without requiring the detailed modeling of the individual bolts. Failure of the joint is determined using a displacement criteria based on the combined shear and tensile displacements calculated in the larger finite element model.

References

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