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# Preparation of a Guide for Design and Analysis of Bolted Closures

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## Abstract

Radioactive material package designers are becoming more and more reliant on finite element analyses to determine the response of their packages to the normal, hypothetical accident, and other conditions. In the United States, closure designs have traditionally followed the methods of NUREG/CR-6007 [1], Stress Analysis of Closure Bolts for Shipping Casks. This document was prepared in 1992, when the state-of-the-art for finite element analyses was much less developed than it is today. For this reason, the National Nuclear Security Administration's Office of Packaging and Transportation commissioned a working group to develop an updated guidance document detailing today's best practice for design and analysis of bolted closures. This document is primarily concerned with fissile material packages that have relatively thin-wall containment vessels, whereas NUREG/CR-6007 was primarily concerned with cask-type packages with relatively thick-wall containment vessels. For some load conditions, this difference can have a dramatic effect on the stresses in the closure. The guidance document discusses the loadings that must be considered during the design, including preload (both tension and torsion), thermal loads, internal and external pressure loads, loads from normal conditions of transportation drops, shock and vibration loads, and the loads from the hypothetical accident sequence. Once the loading conditions have been determined, the transfer of the package loads to the closure bolts must be calculated. The guidance document discusses hand calculations for calculating bolt loads as well as finite element means of determining bolt loads and bolt stresses. Guidance is provided on comparison of these calculated loads/stresses with allowable stress limits. Finally, the document provides insight on interpretation of results, discussing the difference between a requirement for leak tightness with one for assuring pressure safety and the difference between peak stresses and average stresses.

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## Introduction

The design guidance document is intended to assist package designers, analysts, and reviewers when evaluating bolted connections for containment vessels (CVs) in radioactive material packages. It is especially intended for packages where the CV has relatively flexible walls and lids, in contrast to spent nuclear fuel casks which have much stiffer walls and lids. Current guidance for design of bolted closures in NUREG/CR-6007, *Stress Analysis of Closure Bolts for Shipping Casks*, was developed for casks with relatively stiff walls and lids using traditional hand calculation techniques. Since the time of NUREG/CR-6007 finite element analysis (FEA) tools have greatly improved and are frequently used by package designers and analysts; therefore, new guidance will provide information on the use of FEA for the design and analysis of bolted closures.

The assessment methods described are premised on the use of bolt and/or joint forces and moments to evaluate the joint in lieu of using FEA to directly determine the stresses in the bolts. It is assumed that designers, analysts, and reviewers will typically rely on forces and moments derived from FEA; however, this does not preclude using hand calculation methods to determine these forces and moments similar to those recommended in NUREG/CR-6007. Multiple methods for using FEA to determine bolt and/or joint forces and moments are provided. The methods discussed here are applicable for CV bolted closures when the bolt and joint materials are reasonably ductile and standard joint designs (i.e., the axes of the bolts are perpendicular to the mating surfaces that are being joined, such as those shown in Figures 1 and 2) are used.

## Packages and Bolted Closures

In many radioactive material packages, the containment vessel has thick steel walls and a thick lid that is joined with a series of bolts, such as shown in Figure 1. For these packages, the stiffness of the bolts is generally significantly less than the stiffness of the members they are joining, and the methods of NUREG/CR-6007 are usually applicable, practical, and lead to safe designs. For packages with flexible containment vessels, such as those shown in Figure 2, the bolts are of comparable stiffness to the members being joined and calculation of bolt forces and moments by hand calculation techniques is more difficult. It is for the design of this type of package that the guidance document was prepared.

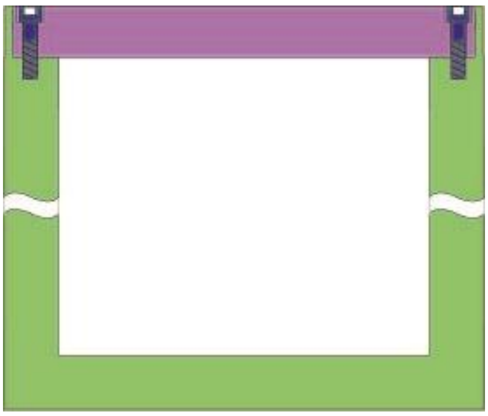
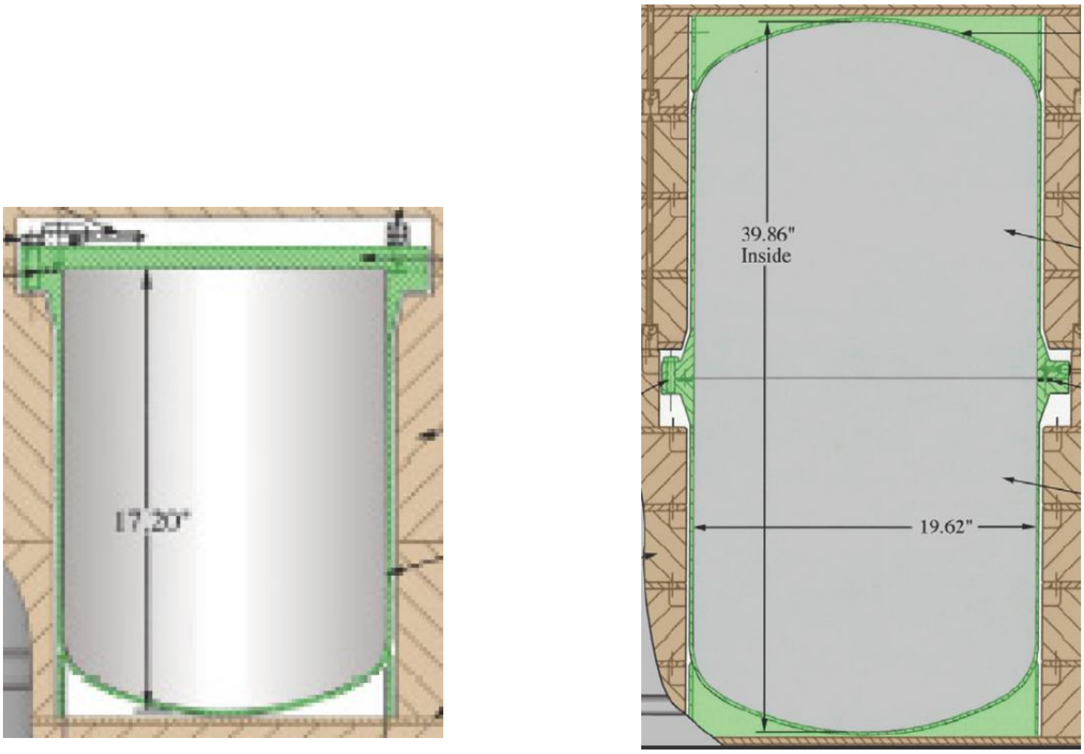


**Figure 1 – Stiff walled containment vessel design.**




a) Flat lid closure. b) Mid-body closure.

**Figure 2 – Flexible walled containment vessel designs.**

## Modeling Bolted Closures

The purpose of a bolted joint in a structure is to provide a connection between components of the structure that is capable of transmitting loads and is easily assembled and/or disassembled. Bolted joints typically make use of high strength metallic fasteners that act to clamp the various components of the joint together. The clamping action in the assembled joint is generated by elastically (sometimes plastically) stretching each bolt during its installation, producing an axial load in the bolt that remains after installation is complete. In a properly designed bolted joint, the preload improves the overall performance of the joint: the preload ensures contact is maintained between the joined components without over-stressing the bolt, reduces the axial load variation on the bolt improving its high cycle fatigue performance, and increases the frictional shear load capacity of the joint. The presence of preload, however, complicates the load transfer mechanisms of the joint.

Generally, it is not advisable to assume that finite element analyses are capable of accurately predicting the maximum stress/strain within a given bolt or bolted connection. In order to accomplish this, it would be necessary to accurately model the individual threads and any possible deviation between actual thread profile and the theoretical profile (e.g., deviations in thread angle and flatness, misfit between the external thread of the bolt or screw and the internal thread of the nut or threaded part), the fillet joining the bolt head to the shank, the residual stress state in the bolt, etc. Therefore, the use of finite element analyses should be restricted to predicting the loads/moments carried by each fastener within a bolted connection, and these loads/moments should be compared to acceptable levels in the same way that bolts are analyzed when using traditional hand calculations. The Sections below will describe various methods that can be used with finite element analyses to determine the loads carried by each fastener. Selecting which method to use will depend on the degree of accuracy required, the type of connection, the function that the bolts are playing within the connection (the type of loads acting on the bolt), the relative stiffness of the bolt vs. the connected parts, etc. Example meshes for a single bolt with the geometry shown in Figure 3 are given for each of the methods.

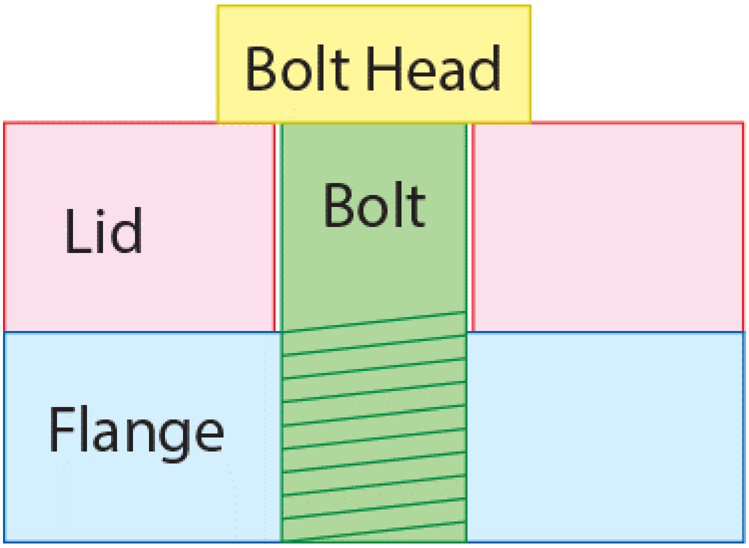



**Figure 3 – Simple bolt geometry to be used in examples.**

## Modelling bolts with beam or spring elements

Using beam or spring elements is probably the simplest way to model a bolt. The two ends of the beam or spring element are attached to opposite sides of the members that are being connected. With this simple formulation care must be taken that the loads at the contact locations are spread realistically. Besides its simplicity in implementation, another advantage of this method is that the bolt loads are directly output. Sometimes only part of the bolt will be modelled with a beam or spring element (e.g., the grip portion) and other portions (e.g., the bolt head and embedded region) will be modelled with solid elements. Figure 4 shows a simple mesh with the bolt represented by a beam element. In this example mesh the beam would be tied, either through shared nodes or constraint conditions, to the lid mesh at the top surface and to the flange mesh at the bottom surface (or along the entire embedment length). Tying the beam and hex meshes together this way will result in unrealistically large forces in the hex mesh at the tie point, and therefore stresses (and strains) in this vicinity will be overestimated.

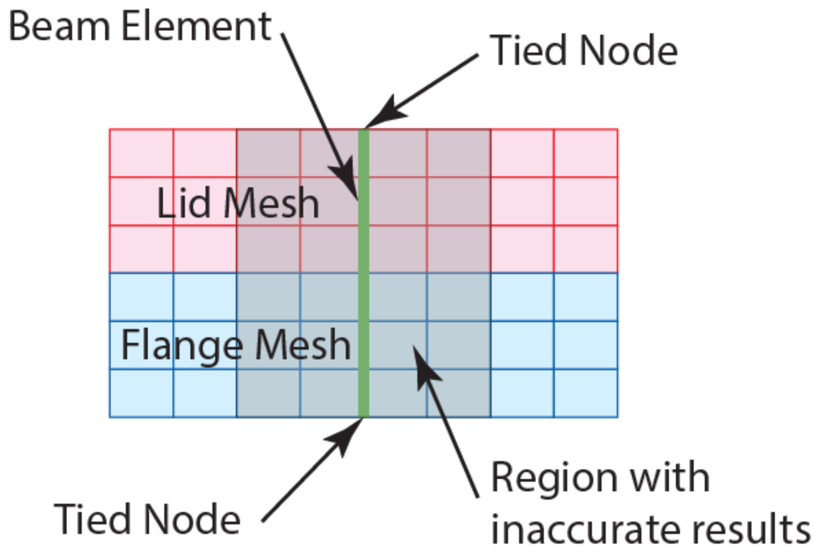



**Figure 4 – Example of modeling a bolt with a beam element.**

## Modelling bolts with constraint equations

The next degree of sophistication is to model the bolts using constraint equations to represent the forces being transmitted through the connection. This method is sometimes called "spot weld". In this method, a detailed finite element model is made of a single bolt and the tensile, shear, and moment carrying behavior is reduced to a set of constraint equations that are applied to the boundaries of the model. This is the method that was used in modelling aircraft crashes into vertical concrete spent fuel storage cask in [2]. When using this method, care must be taken to spread the load from the location of the constraint into the surrounding elements. Generally, it is not advisable to have the constraints applied only at a single node, as this causes all of the forces in the bolt to be transmitted to that node, resulting in artificially high stress and strains. The mating surfaces are meshed without the bolt hole or bolt embedded region and the nodes on the surface are joined with constraint equations. Figure 5 shows a mesh with the bolt represented with constraint equations. The manner of determining the bolt loads using this method will vary with the finite element program being used, but it is generally a direct output. In order to derive the proper constraint equations, a detailed finite element model of a single fastener using the method described below must be conducted. Constraint equations should also be carefully evaluated for package models that experience large rigid body rotations to ensure physically representative behavior is maintained. Some codes apply the constraint equations in the global coordinate system, which will have the relationships in the wrong direction if there are large rotations.

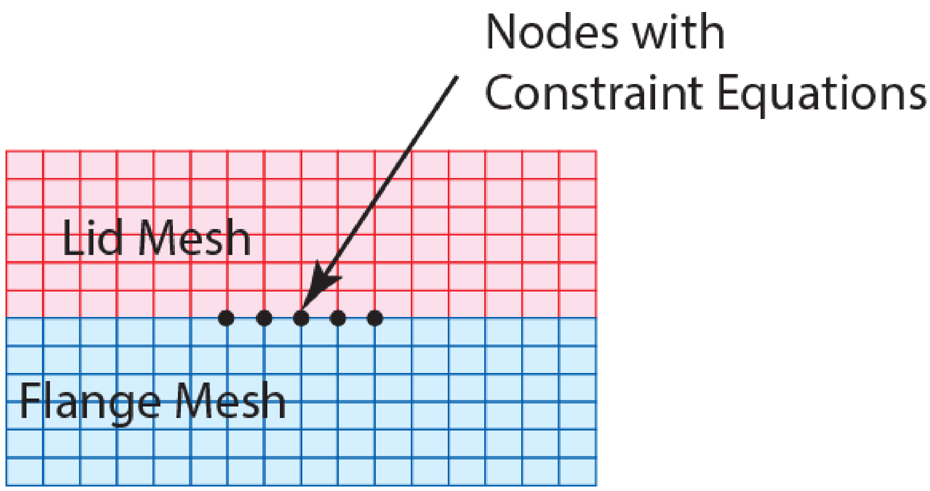



**Figure 5 – Example of modeling a bolt with constraint equations.**

## Modelling bolts with solid elements

Using solid elements to represent the bolt is the most detailed way to model bolted connections. This method of modelling allows bolt loads due to direct tension, shear and bending due to bearing contact on the bolt shaft, shear and bending due to friction under the bolt head, and prying due to rotation of the connected parts. The load path may change during the event. For example, as the connected parts slide relative to each other, initially the friction under the bolt head will lead to shear and bending within the shank of the bolt, but as sliding continues past the clearance hole, the bolt shank will come into direct contact with the part and be loaded in bearing (although good design practice for connections is to limit the possibility for bolts to be loaded by direct bearing). Considerable effort is required in post-processing to capture the tensile, shear, and bending loads in each bolt. Figure 6 shows a model of a bolt that was loaded in double shear (not quite the same geometry as Figure 3) that was used to capture bolt failure [3]. This problem had two planes of symmetry, one through the longitudinal center of the bolt and one through the transverse center of the bolt, so only ¼ of the geometry was modelled. For this analysis, the model was trying to replicate test results. The degree of refinement of the meshes is necessary to accurately portray the progressive failure of the bolt. In designs where there is a large margin to failure (as is the case for containment vessel bolts and design basis loads) this level of refinement would not be necessary.

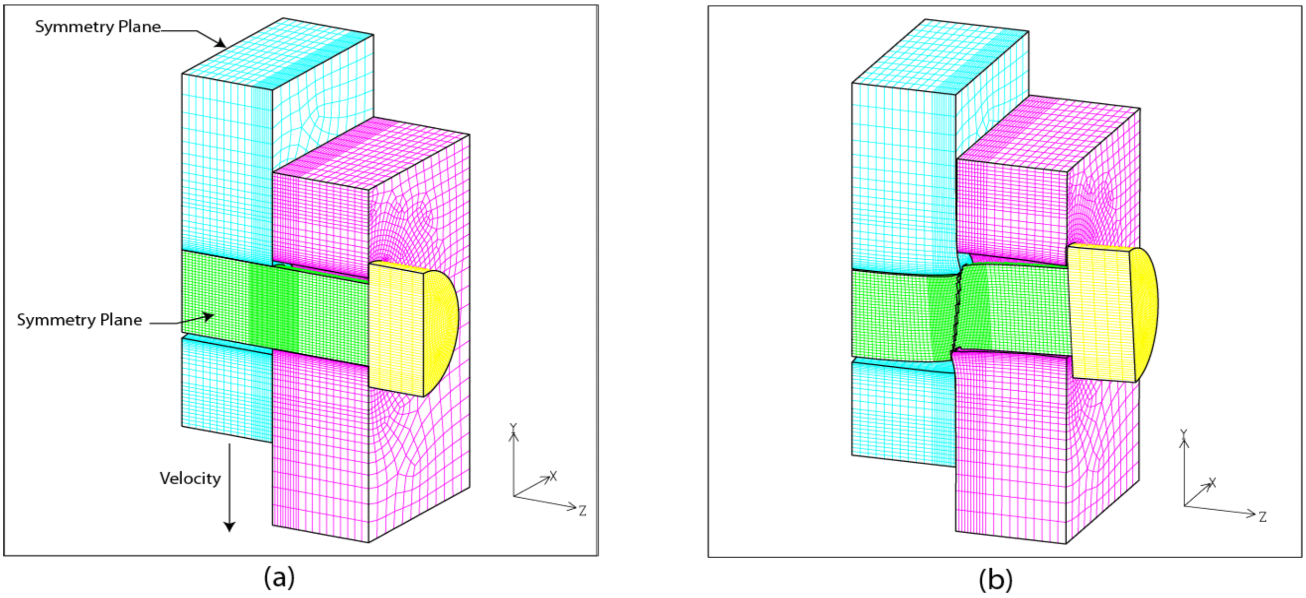



**Figure 6 – Example of modeling a bolt with solid elements, (a) undeformed mesh, (b) at moment of failure in shear.**

The bolt in this test was an A325 structural steel bolt and the blocks were A440 steel. Figure 7 shows a comparison between the test results and two cases for the analytical result. In the first case, the blocks were modelled using the A440 steel properties (SB). In this case the test and analytical results are a very close match. To see the effect of block material properties on the results, a second analysis was run with the block steel properties being the same as the bolt steel (HB). As can be seen from the figure, the displacement at failure is greatly reduced for the hard steel blocks, but the load at failure was nearly identical. This demonstrates the importance of accurately modelling all aspects of the joint in order to get the correct joint stiffness.

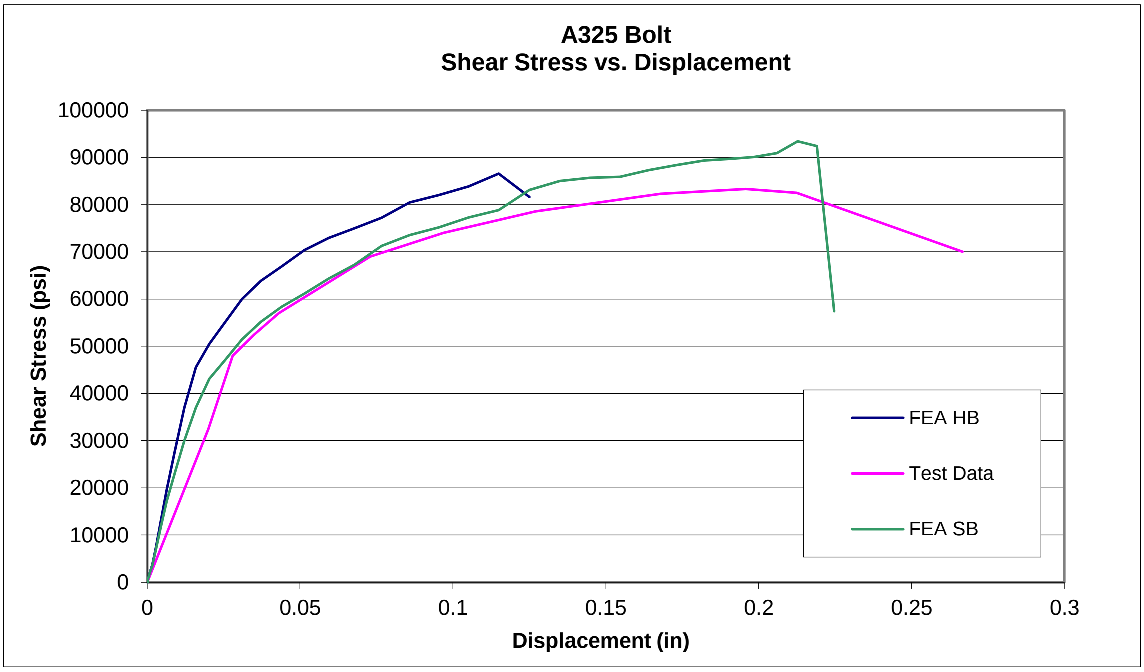



**Figure 7 – Bolt shear stress versus displacement of the shear block.**

## Conclusions

Using finite element analyses to design package closures is not a straight-forward task. Multiple methods, each with their own advantages and pitfalls, exist for leveraging advanced FEA analysis to evaluate bolt performance during package impact events. In recognition of this, the Office of Packaging and Transportation is sponsoring the preparation of a guidance document that will aid designers, analysts, and reviewers to ensure that numerical bolted closure analyses are performed adequately and correctly. It is estimated that this document will be available within one year.


## Acknowledgments

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