An Approach to Efficient Structural Analysis of Packaging

Gerald C. Mok, Lisle B .Hagler, and Brian L. Anderson
Packaging and Transportation Program
Lawrence Livermore National Laboratory, Livermore, CA , USA

Abstract

There is no established structural analysis procedure for radioactive material transportation packagings. This may be because the structural-design performance is specified in terms of package-design requirements of containment, shielding, and subcriticality rather than structural-design requirements of stress and strain limits. Thus, an approach to efficient structural analysis of packages would entail the following steps: (1) Obtain full understanding of the intended function of all packaging components; (2) Use this understanding and structural and nuclear engineering insight and, if necessary, simplified analyses, to identify potential packaging structural weaknesses which may lead to violation of the packaging regulatory requirements; (3) Analyze the weaknesses to establish the structural performance requirement based on the package requirements; and (4) Use appropriate structural analysis methods and models to determine the margin of safety of the package against these weaknesses or failure modes. This paper will give examples to demonstrate the application of the approach.

Introduction

Transportation regulations[e.g., 1 & 2] require thorough and convincing safety evaluation of packages for the transportation and storage of radioactive materials. This requirement and the lack of standard procedure makes structural evaluation difficult and laborious, despite help from powerful modern computational tools. Thus, it is natural to ask whether the process can be made more effective. This paper describes an approach which is outlined in the abstract. We believe that many structural analysts, especially the "old-timers" like us, have been knowingly or unknowingly practicing. We just attempt to organize and document the approach.

The Approach

The approach essentially calls for the return to basics in structural evaluation. Relying on his basic understanding and insight of the safety requirement and the behavior of structure and materials and on his basic skill of employing simplified models and methods, the structural analyst takes back the control of the evaluation process from the complex computational tools and tries to reach a rough but quick estimate of the conclusion. Based on the rough conclusion, the structural analyst can recommend the proper design, analysis model, or evaluation method (test or analysis) to use for successful and efficient completion of the evaluation task.

Table 1 shows the safety evaluation of containment vessels (CV) under impact conditions. Depending on the design, four failure modes are possible, and each failure mode requires special attention to modeling, analysis, and interpretation of results as described in the remainder of this paper. Thus, it is necessary for the structural analyst to reverse his normal analysis processes, i.e., to go backward from his crude determination of the safety evaluation outcome to the selection of evaluation method and model. The analyst will find this reverse approach helpful and efficient. The sections following Table 1 provide further details.

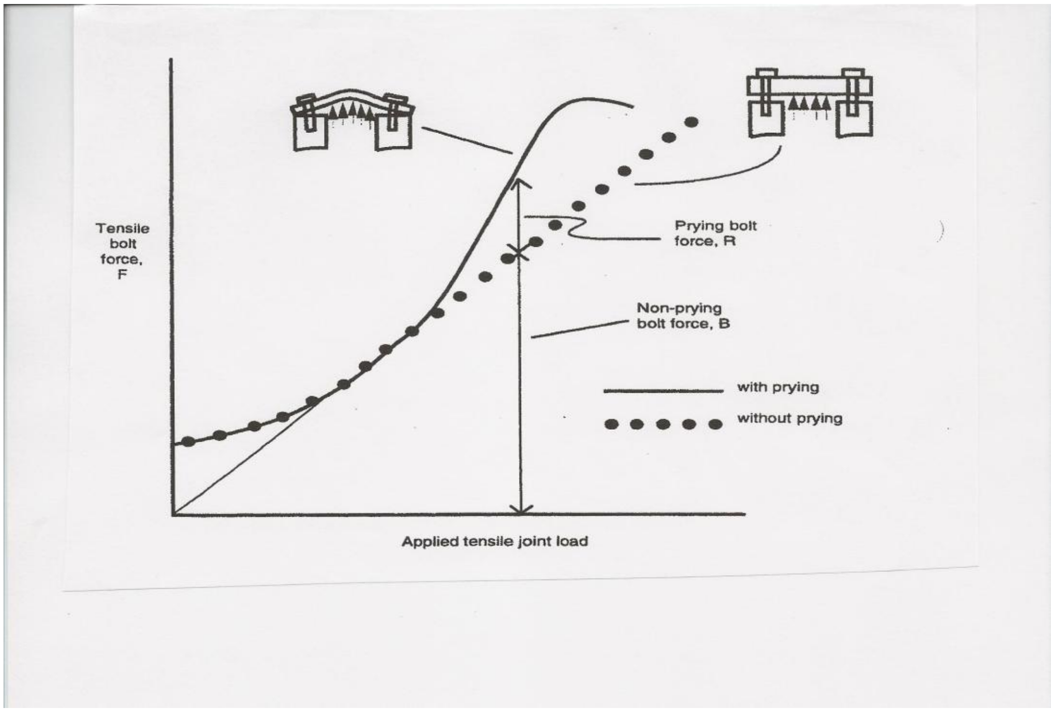
Table 1. Impact Safety Analysis of Containment Vessel

Failure Mode To Be Investigated	**Acceptance Criteria**	**Governing Factors**	**Required Analysis**
Leakage of Bolted Closure	Bolt stress	Flange rigidity, bolt preload, applied loads	Elastic stress analysis
Large Ductile Deformation of Containment Vessel	Deviatoric plastic strain	Yield condition, deviatoric plastic strains, applied loads	Elastic-plastic large-deformation stress strain analysis
Brittle Fracture of Containment Vessel Made of Ferritic St'ls	Nil ductility temperature and/or fracture toughness	Fracture toughness, cracks or flaws, tensile loads	Linear fracture mechanics analysis
Global Buckling of Containment Vessel	Buckling stress	Elastic buckling stress, imperfections. nonlinearities, and compressive loads	Elastic buckling analysis plus imperfection and nonlinearity analyses

Leakage of Bolted Closure

A bolted closure joint of a transportation cask usually consists of two matching annular flange surfaces compressed together using a number of bolts and sealed with an o-ring. To meet the containment requirement, all joint components, especially the closure bolts, must not experience permanent or plastic deformation during the impact. If a simplified evaluation indicates this to be impossible, then a redesign or additional impact limiter may be needed to protect the closure joint. If a detailed analysis is performed, the analysis must be an elastic analysis with the yield stress (not the shake-down stress) as the limit. Figure 1 shows the composition of a bolt force: the preload, the applied load, and the prying load.[3] The preload is a design load intended to keep the joint together until the external applied load exceeds it. The applied load is the external load in excess of the preload, and the prying load is due to the deformation of the flanges. Thus, the maximum bolt force is equal to the preload plus the prying load or the external applied load plus the prying load. It is essential to keep the applied load and the prying load under control.

Figure 1. Composition of Tensile Bolt Force



Large Ductile Deformation of Containment Vessel

Some shipping containers are designed without special impact limiters. They depend on the large plastic deformation of the metallic containment vessel to absorb the impact energy. The use of elastic analysis can never demonstrate the design to be acceptable. It can also show that using elastic-plastic analysis with a stress acceptance criteria may not always work either. This is because the stress criteria is not the strain-energy criteria. Thus, a special strain criteria in addition to the yield condition (i.e., stress criteria) need to be developed.[4]

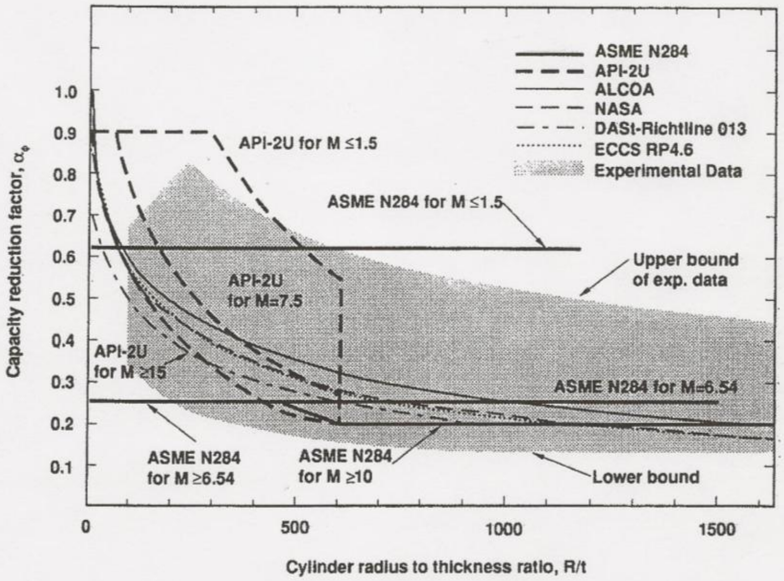
Brittle Fracture of Containment Vessel

Ferritic steels have two general level of toughness: an upper-shelf level at higher temperatures and a lower-shelf level at lower temperatures. The transition from the low to the high toughness begins at a temperature called nil ductility temperature (NDT). Using empirical data and linear fracture mechanics analysis, temperature criteria have been developed to select material and/or to limit lowest service temperature (LST) to protect shipping containers against failures by brittle fracture. The criteria relates the LST to NDT as LST = NDT + A, where A, obtained from a linear elastic crack analysis, is a function of container thickness, dynamic yield stress, and the impact stress.[5] In addition, there is a required minimum upper shelf toughness. If a simplified analysis indicates the container may not meet the criteria, a redesign is essential before additional evaluations are performed.

Global Buckling of Containment Vessel

Elastic buckling is an eigenvalue problem which can be solved. However, the actual buckling loads, especially those of a cylindrical shell under axial load, can be much lower than the elastic solution, due to the influence of geometric imperfections, etc. Thus the buckling loads used for safety evaluation are elastic buckling loads reduced using two multipliers: α and η. α, the capacity reduction factor, represents the geometric and constraint effects, while η, the plasticity reduction factor, represents the effect of material plasticity etc. α usually has a value less than 1.0 while η has a value less than 1.0 when the buckling stress exceeds the proportional limit.[6] Figure 2 from Reference 6 show how much the capacity reduction factor can vary. Thus, if a simplified buckling evaluation indicates a global buckling with significant safety implication can occur, it is prudent and efficient to initiate a redesign rather than to pursue an improved analysis.

Figure 2. Variation of Capacity Reduction Factor



Conclusions

Some structural analyses of packaging safety performance are inherently dominated by uncertainties. Using sophisticated modern computational tools and models may not be the most efficient way to accomplish the task. The structural analyst should always try to use simple methods/formulae and his basic understanding and insight to obtain an estimate of the solution first.

References

[1] Safety Requirements No. TS-R-1, *Regulations for the Safe Transport of Radioactive Material*, 2002 Edition, International Atomic Energy Agency, Vienna, 2002.

[2] *Packaging and Transportation of Radioactive Material*, Code of Federal Regulations, Title 10, Part 71, U.S. Government Printing Office, Washington, DC (January 2012).

[3] G. C. Mok, L. E. Fischer, and S. T. Hsu, *Stress Analysis for Closure Bolts of Shipping Casks*, Lawrence Livermore National Laboratory Report UCID-110637, prepared for the US Nuclear Regulatory Commission NUREG/CR 6007 (April, 1992).

[4] W. R. Holman and R. T. Lungland, *Recommendations for Protecting against Failure by Brittle Fracture in Ferritic Steel Shipping Containers up to 4 inches Thick*, Lawrence Livermore National Laboratory Report UCRL-53013, prepared for the US Nuclear Regulatory Commission NUREG/CR 1815 (April, 1992).

[5] M. West, D. R. Leduc, C. A. McKeel, L. B. Hagler, G. C. Mok, and G. S. Bjorkman, 2009 US DOE/EM/PCP *Structural Analysis and Acceptance Criteria Course*, Pleasanton, Ca, (Nov 17-18, 2009).

[6] T. Y. Lo, G. C. Mok, and D. J. Chinn, *SCANS Theory Manual Vol. 6, Buckling of Circular Cylindrical Shells*, Lawrence Livermore National Laboratory Report UCID-4554, Vol. 6 , prepared for the US Nuclear Regulatory Commission NUREG/CR 20674, Vol. 6 (April, 1989).