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# The Effect of Gap Size and g-Loading from Real Transportation Accidents On the Response of Closure Lid Bolts

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## Abstract

After a spent fuel transportation package is loaded, a gap will exist between the package contents and the bolted closure lid. When the package is rotated from a vertical position to a horizontal position and attached to the conveyance in preparation for transport the gap between the contents and lid will be aligned with the direction of transport.

During transport different accident scenarios could impose g-loads (deceleration loads) on the package while it is restrained by the restraint system that attaches the package to the conveyance. Even if the g-loads from an accident remain within the capacity limits of the restraint system, the presence of a gap between the package contents and closure lid may result in an impact of the contents onto the closure lid that could impose potentially large loads on the closure lid bolts. For certain combinations of g-loading and gap size the response could exceed the response of the hypothetical accident condition (HAC) 30 foot drop with a zero gap.

This paper explores the relationship between the gap size and the g-loading that produces the same stress level in all the closure lid bolts as would have been produced in the HAC regulatory drop test with a zero gap.

## Introduction and Problem Definition

Spent fuel transportation packages are typically loaded with their contents while in a vertical position. After the package is loaded, a gap will exist between the package contents and the bolted closure lid. When the package is rotated from a vertical position to a horizontal position and attached to the conveyance in preparation for transport the gap between the contents and lid will be aligned with the direction of transport.

During transport the package is restrained on the conveyance. The design of the portion of the restraint system that is a structural part of the package must conform to the tie-down standards in 10 CFR 71.45(b)(1), which requires that in the direction of travel the portion of the restraint system that is a structural part of the package must be capable of withstanding a static force applied at the center of gravity of the package equal to 10 times the weight of the package without generating stresses in any material in excess of the yield strength. Given the fact that; 1) minimum material properties would have been used in the design of the restraint system, 2) the ultimate strength is greater than the yield strength, and 3) the dynamic loading will increase the static strength of the material, it is reasonable to assume that the restraint system could easily support a 15g loading in the direction of travel prior to releasing the package from the conveyance.

During the transport of the spent fuel package by truck or rail conveyance a large number of different accident scenarios could be postulated. Each scenario will impose a different g-loading sequence on the package while it is restrained by the conveyance. For a significant number of these scenarios, the dominant loading during the accident, at least initially, would be expected to be in the direction of travel. During such an accident event the conveyance will decelerate and the gap between the contents and closure lid will quickly close due to the g-loads generated in the direction of travel while the package is still restrained by the conveyance. Even if the g-loads remain within the capacity limits of the restraint system, the presence of a gap will result in an impact of the contents onto the closure lid and impose potentially large loads on the bolts. For certain combinations of g-loading and gap size the response could exceed the response for the hypothetical accident condition (HAC) 30 foot drop with a zero gap.

This paper explores the relationship between the gap size and the g-loading that produces the same stress in the closure lid bolts as would be produced in the HAC regulatory drop test with a zero gap.

## Analysis Methodology

*A Simple Dynamic Model*

In Reference 4 (Bjorkman 2010) a simple dynamic model was developed to estimate the influence of gaps and various other parameters on closure lid response during a drop impact event. This was accomplished by creating an equivalent single degree of freedom idealization of a transportation package with a gap between the contents and closure lid subject to a constant deceleration. Such an approach is a well established technique for the approximate solution of dynamic problems involving impact and impulse loading (Biggs 1964).

*Solution*

The lid closure system is assumed to remain elastic during the impact event. This allows the equivalent single degree of freedom model of the lid closure system to be treated as a free vibration problem with initial conditions. The equivalent spring mass system is shown in Figure 1, where $M_{ec}$ and $M_{el}$ are the equivalent masses of the contents and lid respectively and constitute the total equivalent mass of the system, $M_e$ ($M_e = M_{ec} + M_{el}$). The spring stiffness, $K_e$, is the equivalent stiffness of the closure lid idealized as a simply supported circular plate.

For this case, the vibratory motion of the total equivalent mass, $M_e$, about the static equilibrium position is given by the equation (Timoshenko 1955)

$$x = x_o \cos(\omega t) + \left(\frac{v_o}{\omega}\right)\sin(\omega t) \quad (1)$$

where $x_o$ is the initial displacement of the mass from the static equilibrium position, x = 0, $v_o$ is the initial velocity of the total mass ($M_e$) at $x_o$ after impact of the contents with the closure lid, and ω is the natural frequency of the equivalent system.

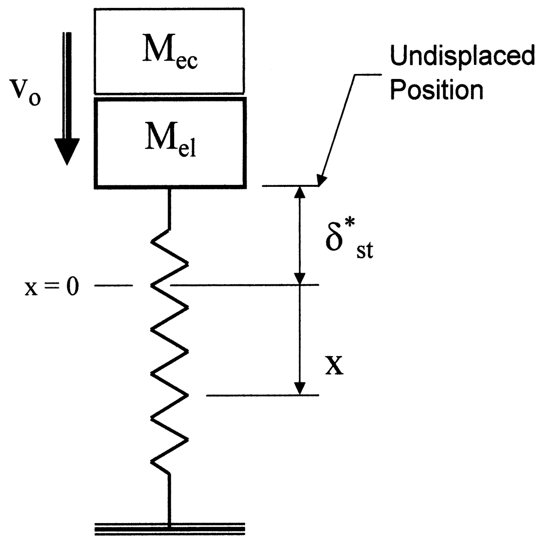


**Figure 1: The equivalent spring mass system**

The initial displacement, as measured from the static equilibrium position, is

$$x_o = \delta_{st}* = \alpha\delta_{st} \quad (2)$$

where $\delta_{st}^*$ is the static displacement of the mass, $M_e$, acted upon by a constant deceleration, αg, and, $\delta_{st}$ is the static displacement of the total mass, $M_e$, in a normal gravitational field, g.

The initial velocity, $v_o$, of the mass, $M_e$, is the resultant velocity of masses $M_{ec}$ and $M_{el}$ after the fully plastic impact of the contents with the lid, and is given by the equation (Den Hartog 1948)

$$v_o = v_i \frac{M_{ec}}{M_{ec} + M_{el}} \quad (3)$$

where $v_i$ is the relative impact velocity between the contents and lid.

From the solution of the initial value problem (Bjorkman 2010) one obtains the Dynamic Load Factor, DLF, for the response of the closure lid due to the presence of a gap between the package contents and the closure lid as

$$DLF = 1 + \sqrt{1 + \left(\frac{2\Delta}{\alpha\delta_{st}}\right)\left(\frac{M_{ec}}{M_{ec} + M_{el}}\right)^2} \qquad (4)$$

which is the desired result.

### Illustration of Equation (4) Results

To illustrate the result presented in Equation (4) a generic spent fuel transportation package and drop scenario is selected. Assume that when the package is dropped from 30 feet and strikes an unyielding target the impact limiter applies a constant crush force to the package that decelerates the package at a constant rate of 50g's. Let the package itself have the following properties:

| | |
|---|---|
| Lid: | Steel Material: E = 28,000,000 psi, ν = 0.3, Density = 495 lbs/ft$^3$ |
| | Radius = 34 inches; Thickness = 2, 4 and 8 inches |
| Contents: | Total weight = 40,000 lbs |
| Gap Size : | Gap = 0 to 2.5 inches |

*Lid Response*

In Figure 2 the Dynamic Load Factor (DLF) in Equation (4) is plotted as a function of gap size for three lid thicknesses. The results show the influence of gap size and lid stiffness on the displacement response of the lid.

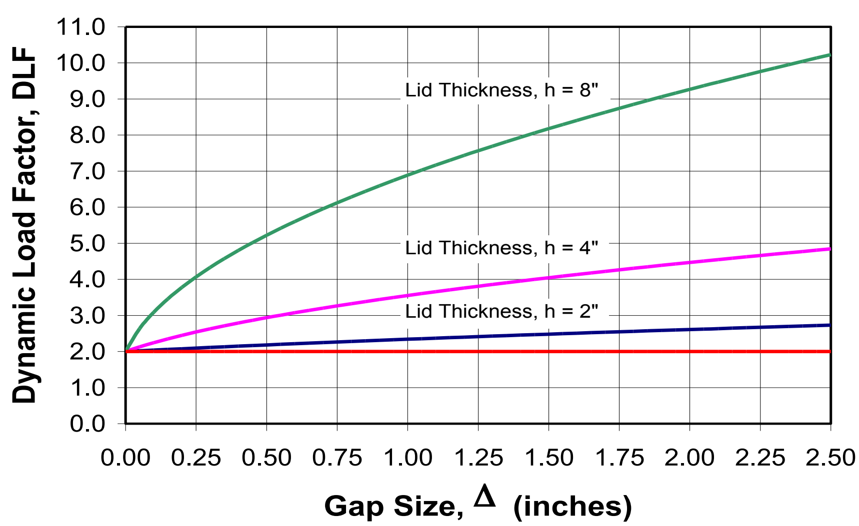


**Figure 2: Dynamic Load Factor plotted as a function of gap size for three lid thicknesses**

To put the results in context, a DLF = 1.0 represents the static displacement of the lid loaded by the contents under the influence of a gravity field of $\alpha$g. A DLF = 2.0 represents the total displacement of the lid and contents due to the instantaneous application of a gravity field of $\alpha$g, and is the maximum response of the lid and contents for the case of a zero gap.

*Support Reactions (Bolt Loads)*

For the case of a closure lid loaded impulsively (i.e., by a force F(t)), the dynamic reactions of the real structure would have no direct counterpart in the equivalent one-degree system, since the reaction (spring force) of the equivalent system is not the same as the real reaction. This is because the equivalent system was deliberately selected so as to have the same dynamic deflection as the real structure. For this case, the resultant reaction would be obtained by considering the dynamic equilibrium of the system where the inertia force of the mass, $M_e$, resists (opposes) the impulsive force. However, this is not the situation in our case.

In our case, as represented in Figure 1, it is the inertia force of the lid and contents that are directly causing the displacement and loading of the spring. The lid and contents inertia forces do not resist the motion; they cause the motion. Therefore, the displacement response, DLF, shown in Figure 2 is directly proportional to the support reactions (i.e., the lid bolt forces).

## Results

To determine the combination of gap size and g-loading that will produce the same response in the closure lid bolts as the HAC with a zero gap, one proceeds as follows. For the case of a zero gap ($\Delta = 0$) and constant deceleration, $\alpha$, the DLF is 2.0. The total reaction on all lid bolts is

$$\text{Total Reaction on all Bolts} = (2.0)(\alpha)(Me)(g) \qquad (5)$$

Based on the total number of bolts and their cross-sectional area, determine the value of $\alpha$ from Equation (5) for which all the bolts reach the yield stress (say 100,000 psi for high strength bolts). This is the $\alpha$ for the zero gap condition. The general equation is

$$\text{Total Reaction on all Bolts} = (DLF)(\alpha)(Me)(g) \qquad (6)$$

Now reduce $\alpha$ in Equation (6) and determine the DLF necessary to achieve the total reaction that would be produced by a stress of 100,000 psi in all bolts. With this value of $\alpha$ and the calculated DLF substitute into Equation (4) and solve for the gap size, $\Delta$.

Figure 3 is the result of such a series of calculations and shows the relationship between the deceleration g-load acting on a transportation package during an impact event and gap size for combinations of g-load and gap size for which the average tensile stress in all the closure lid bolts is equal to 100,000 psi, which is approximately the yield stress of a typical high strength bolt. Combinations of g-load and gap size that are above the curve produce bolt stresses greater than 100,000 psi. [The curve in Figure 3 has been calibrated to reflect the bolt response results obtained from a detailed LS-DYNA finite element analysis of a cask and its contents during a drop impact. The calibration coefficient is 0.58 reflecting the fact that the secondary impact between the contents and lid is not fully plastic as assumed in the derivation of Equation 4.]

## Conclusion

A simple dynamic model has been used to estimate the effect of a gap between a spent fuel transportation package's contents and closure lid on the response of the closure lid bolts to an accident event where the package remains attached to the conveyance. Figure 3 shows that when gaps are sufficiently large, a relatively small sustained g-load can produce stress levels in all the closure lid bolts that are the same as those that would have occurred during a HAC drop impact event with a zero gap. Figure 3 also shows that at the ultimate capacity of the restraint system (15g) a gap of less than 1 inch will produce a response equal to the HAC 30 foot drop with a zero gap.

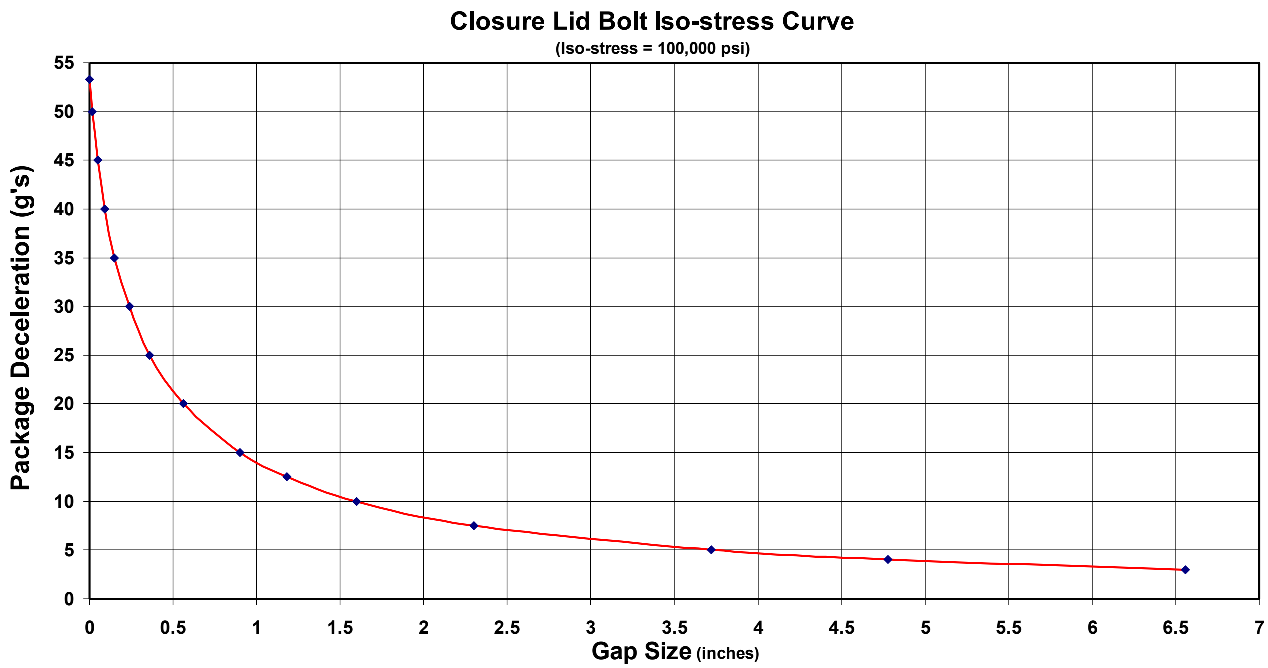


**Figure 3: Relationship between the deceleration g-load acting on a typical transportation package and gap size such that for each combination of g-load and gap size the average tensile stress in all the lid closure bolts is equal to 100,000 psi.**

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