Dynamic and Static Behavior of Metal Gussets in Cask Impact Limiters

S.W. Attaway and H.R. Yoshimura

Sandia National Laboratories, Albuquerque, New Mexico, United States of America

INTRODUCTION

Static and dynamic analyses of an impact limiter for a spent fuel cask have been performed using the finite element analysis code PRONTO2D (Taylor and Flanagan, 1987). The impact limiter contained wood as the energy absorbing material, with the wood confined by a cylindrical metal outer skin and sixteen metal stiffeners (gussets). The object of these analyses was to determine how the wood interacts with the metal stiffeners and to determine if the impact limiter would behave differently under static versus dynamic loading conditions.

Originally, the metal gusset strength was assumed to be limited by the elastic Euler buckling load. Further analysis showed that the gusset strength was not limited to the elastic buckling load and that each gusset contributed significantly to the impact limiter's strength. The current analyses investigated the strength of a flat plate or gusset used in impact limiter systems.

IMPACT LIMITER DESIGN CRITERIA

Transport casks for spent nuclear fuel must demonstrate the capacity to survive, without release of contents, a hypothetical severe accident consisting of a 9-m (30-ft) fall onto an unyielding surface, in accordance with 10 CFR 71. Impact limiters attached to the cask ends are designed to absorb the energy from the fall by crushing and deforming. The impact limiters directly control the deceleration the cask experiences during the 9-m drop scenario.

The impact limiter response in the 9-m accident drop places limitations on the transport cask design. The impact limiter behavior affects both the forces acting at the cask/impact limiter interface, the inertial forces in the cask, and the forces in the bolts that hold the impact limiter in place.

An error in the predicted deceleration from the impact limiter analysis will propagate throughout the cask design. Therefore, impact limiter behavior is an essential part of a transportation cask design. If the limiter is too stiff, then the cask will decelerate rapidly, generating large inertial loads in the cask. If the limiter is too soft, then it can bottom out and generate high decelerations toward the end

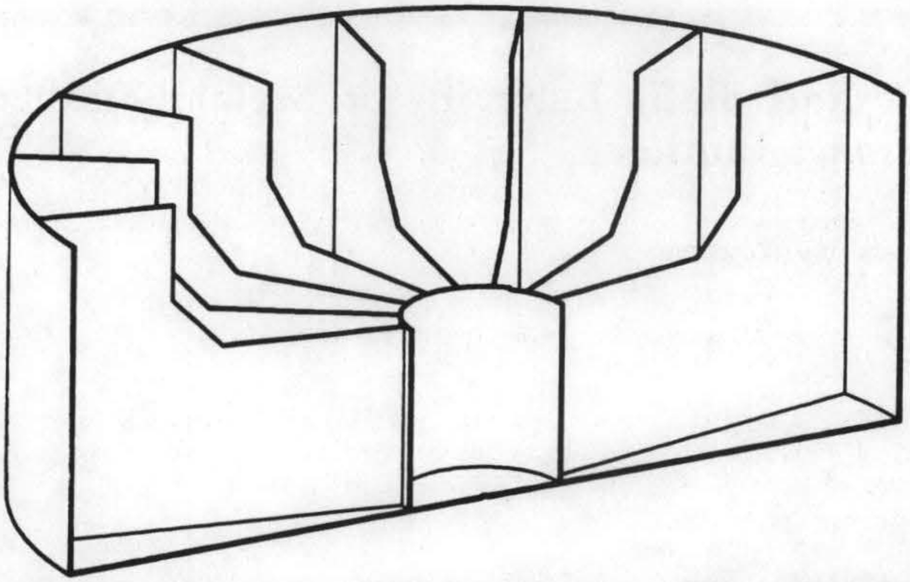

Figure 1: *Location of 16 metal gussets within the impact limiter. Sheathing material is not shown for clarity along the top of the limiter and along the load bearing surface at the cask/impact limiter interface.*

of the impact.

IMPACT LIMITER DESCRIPTION

The impact limiters under study were constructed from balsa and redwood, with an outer steel jacket provided for external support and confinement of the impact-absorbing material. Sixteen steel gussets, or stiffeners, provide additional internal support and confinement. Each gusset plate is 26 in. long by 53.5 in. wide and 3/16 in. thick. Gusset locations within the impact limiter are shown in Figure 1. The gussets are welded on all sides to the outer skin and inner annulus of the impact limiter. Balsa and redwood fill the space between the gussets.

IMPACT LIMITER ANALYSIS

Static and dynamic analyses of an impact limiter were performed using the finite element analysis code PRONTO2D. The object of these analyses was to determine if the wood, used as an energy-absorber, interacts with the metal stiffeners to increase the stability and strength of the gusset in a manner similar to a beam on an elastic foundation. The strength of the flat plates or gussets used in impact limiter systems could be significantly higher than the elastic buckling load, due to the boundary conditions.

This study also examined gusset behavior under dynamic loading conditions. The behavior of the gusset/wood impact limiter system can depend upon the rate at which the impact limiter is loaded. Three factors might contribute to this rate-dependent impact limiter behavior: rate-dependent yield strength of the metal gusset, rate-dependent yield strength of the wood, and rate-dependent buckling mode of the metal gussets. The rate-dependent buckling of the metal gusset was the only rate effect considered in this study.

The behavior of the gussets in the end-on drop was of primary concern. The complex geometry of the impact limiter prohibited a full three dimensional analysis. For this comparative study, a two dimensional analysis was performed by considering a plane strain idealization representing a $\frac{1}{16}$ slice (wedge) of the impact limiter. The plane strain slice is shown graphically in Figure 2. This "I"-shaped cross section column represents the gusset and outer skin. The gusset cross section was assumed to be placed between two platens. The gusset material was modeled using an elastic-plastic constitutive relation.

STATIC POST-BUCKLING ANALYSIS

To estimate the static gusset behavior in the post-buckled state, the finite element analysis code PRONTO2D was used to simulate the nonlinear gusset behavior. The analysis assumed that the one end of the cross section was fixed while the other end moved slowly with a prescribed velocity.

If softening behavior occurred as soon as the gusset buckled elastically, then the force from the gussets would be small relative to the wood strength. The finite element calculations predicted rather that the gussets harden until yielding spreads through the entire thickness, resulting in a much higher gusset force.

The static post-buckled shape is shown in Figure 3. The load deflection curve is also shown in this figure. A differential pressure (total load = 100 lbs) was applied to one side of the cross section to numerically initiate the buckling behavior.

DYNAMIC LOADING

In general, the buckling behavior of beams and columns under dynamic loading is different from the static loading behavior (Johnson, 1972). Typically, dynamically loaded beams and columns buckle at loads higher than the static buckling load due to lateral inertia. When buckling does occur, the mode shape and the post-buckled behavior of the dynamically loaded beam/column will differ from the statically loaded beam/column.

Gusset behavior under dynamic loading was computed using a transient, nonlinear, dynamic analysis. The finite element analysis code PRONTO2D was used for the computations. The finite element model used the same mesh, the same material properties, and the same "I"-shaped cross section as the static buckling calculations. However, the boundary conditions were defined to approximate the dynamic loading that the gussets experience when the cask impacts an unyielding surface in a 9-m drop. A rigid surface was used to simulate the unyielding surface along the bottom of the "I". A plate with an equivalent mass representative of the cask was in contact with the top of the cross section. Both the equivalent mass and the cross section were given an initial velocity of 13.2 m/sec (43.5 ft/sec), representing the 9-m drop test.

The finite element calculations confirmed that the dynamic loading was different from the static loading; the gussets did not have time to deform into the lowest buckling mode. Instead, the lowest order buckling mode was passed, and an instability developed at a higher load, causing a higher order buckled shape. The computed deformed shape and the associated loading curve from the dynamic analysis is shown in Figure 4. Because the maximum load was controlled by a plastic instability, the maximum load for the dynamic and static gusset crush was

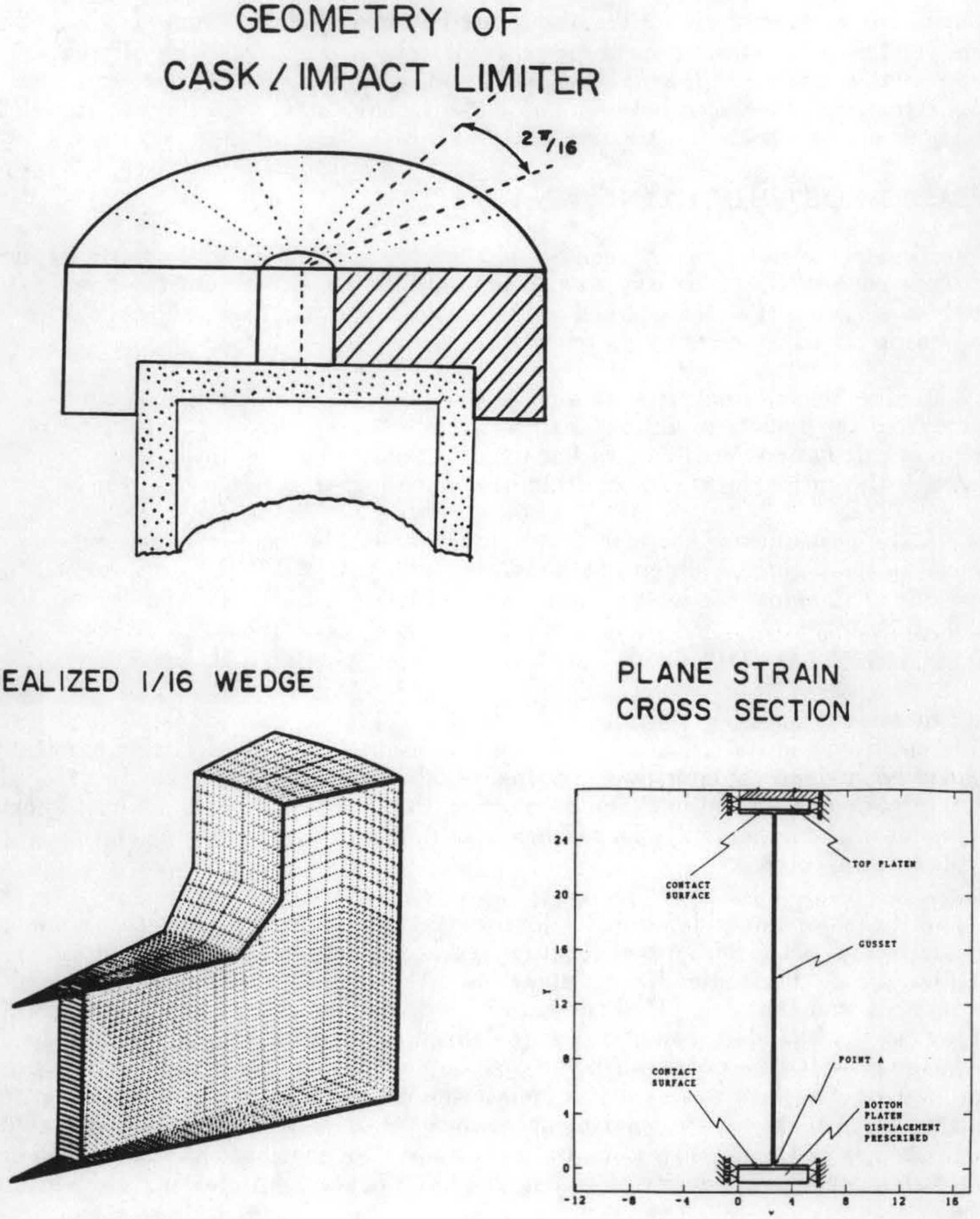

Figure 2: *Idealized plane strain slice.*

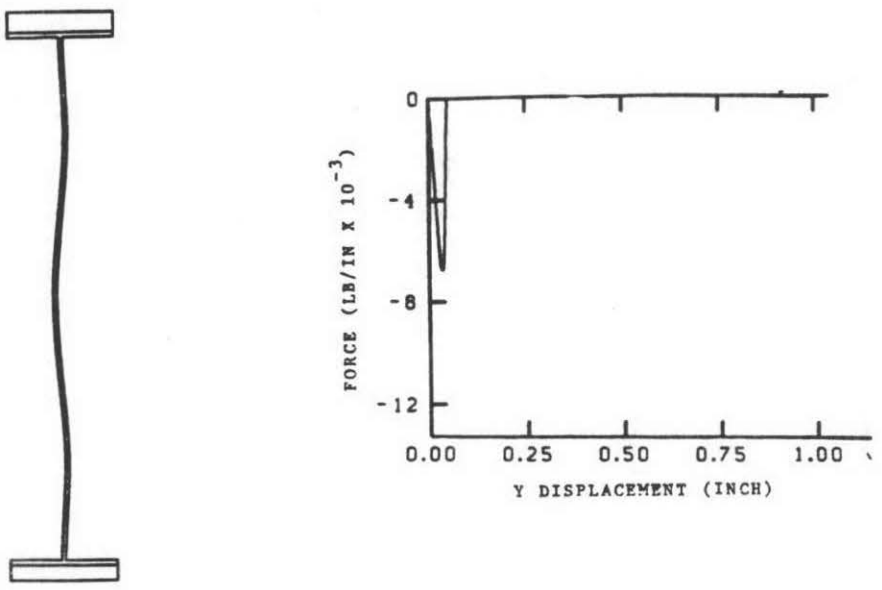

Figure 3: *Static post-buckled shape and associated load deflection curve.*

about the same. The duration of the load was not the same, however.

Because the load-deflection curve and the deformed shape differed for static and dynamic loading, a dynamic analysis or impact test must be used to realistically model the impact limiter behavior. More energy is absorbed by dynamic loading than by static loading.

GUSSET/WOOD COMBINATION

The gussets and outer skin were not designed to be the primary energy-absorbing material in the impact limiter; the balsa and redwood were to be the two primary energy-absorbing materials. The metal gussets and outer skin were intended to confine the wood and support the structure during normal shipping and handling and to provide confinement of the impact absorbing material under accident conditions.

Gusset behavior is not independent of the surrounding wood. The balsa resting between the gusset plates will provide extra out-of-plane support for the gussets tending to restrain the gusset from assuming its lowest mode shape and lowest buckling load. The gusset/wood system is similar to a beam on an elastic foundation, where the buckling load of the beam increases with the modulus of the foundation (Timoshenko and Gear, 1961). Thus, gussets laterally supported by the balsa will be stronger than the gussets alone, while redwood will provide even more support than the balsa.

The finite element calculations showed that the gusset force is over 1.5 times the balsa crush force. After the gusset became unstable, the dynamic analysis indicated it still supported approximately the same load as the balsa. The higher strength of the gusset/wood system calculated in this study will lead to greater levels of acceleration than previously predicted; this will cause higher stresses in the cask.

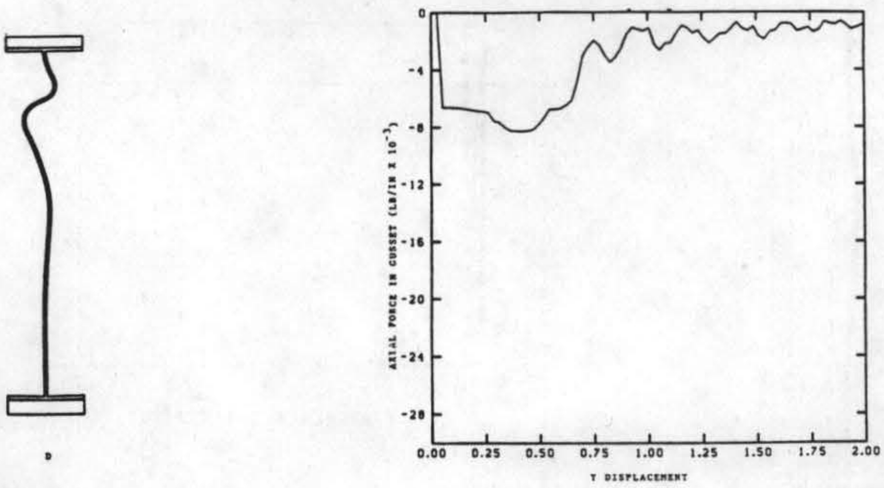

Figure 4: *Dynamic post-buckled shape and associated load-deflection curve.*

Figure 5 shows the deformed gusset/wood combination that resulted when the gusset was backed on each side by balsa wood. The wood was treated as an isotropic crushable material. Also shown in Figure 5 is the load deflection curve that resulted from the impact. The contribution of the gussets to the total crush forces was of the same order of magnitude as the wood crush force.

For the gusset/wood system, the dynamic and static load deflection curves are inherently different. To demonstrate the difference between the static and dynamic loading, the gusset/wood system was modeled at a slower impact velocity ($v = 37$ inch/sec). The resulting load-deflection curve is plotted in Figure 6. The load in the gusset falls off quicker in the slower impact. A true static load deflection curve should generate an even faster fall-off in load, as no inertial effects would be present.

CONCLUSIONS

The 16 metal gussets in the spent fuel cask impact limiters supported much greater loads than predicted by an elastic buckling analysis. In the initial design process, the strength of the metal gussets were considered to be limited by their elastic buckling load. This analysis showed that the limiting force in the gussets is controlled not by their elastic buckling load, but rather by their nonlinear behavior in the post-buckled range. The force in the gussets increased after the initial elastic buckle and did not decrease until the full thickness of the gusset had yielded. Additional gusset strength in the post-buckled range was derived from the lateral support provided by the balsa and redwood. Hence, the gussets' strength must be included in the design of the impact limiter. An error in estimating of the impact limiter stiffness leads directly to an incorrect estimate of the cask's deceleration with possible serious consequences.

The dynamic and static response of the cask impact limiters are different. Three factors contribute to the variation between the static and dynamic response: the metal gussets behave differently under dynamic impact than under static loading,

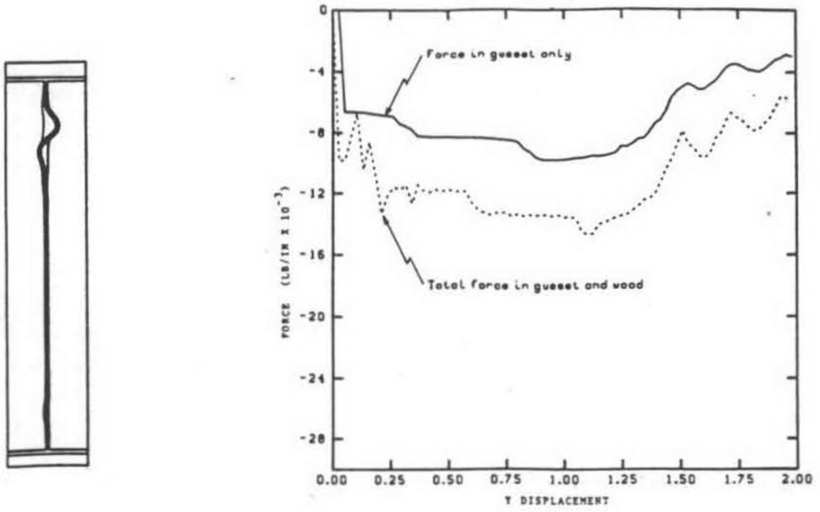

Figure 5: *Dynamic crush of wood/gusset combination.*

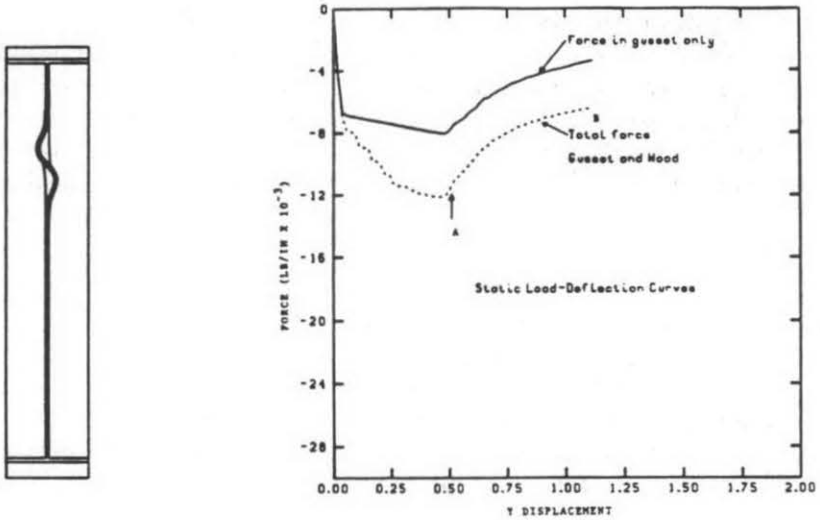

Figure 6: *Near static crush of wood/gusset combination.*

the strength of the wood depends on the rate and duration of its loading, and the yield strength of the mild steel gussets is strain-rate dependent. This study only considered rate effects from gusset buckling. Rate dependent wood behavior and rate dependent steel behavior will further increase the rate dependent impact loads.

The importance of loading rates must also be recognized in impact limiter testing methods. A static load test will yield a much softer impact limiter response than a dynamic drop test. A soft impact limiter response could make a good impact limiter look bad by predicting early crush lockup or false trunnion impacts. Conversely, a static load test could make an impact limiter that is too stiff under actual use (*i.e.,* dynamic loading) appear acceptable.

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