The Development of an Aluminum Toroidal Shell-Type Impact Limiter

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INTRODUCTION

The impact limiters on a Type B transportation cask are designed to absorb the impact energy for the 9-meter (30 foot) drop accident conditions without bottoming out in order to limit deceleration loadings on the cask. Toroidal shell-type impact limiters made from stainless steel have been investigated in the past for transportation cask service in Japan (Y. Sugita and S. Mochizuki) and by the General Electric Company (R. J. Pomares, et al). These designs were relatively heavy and quite rigid causing high deceleration loads on the cask. This paper presents the results of an investigation to determine the feasibility of an aluminum Alloy 6061-T6 toroidal shell impact limiter for a Legal Weight Truck (LWT) cask being developed by the Westinghouse Corporation for the United States Department of Energy. The incentives for the study were the potential advantages such as a compact configuration, lightweight, durability, and essentially maintenance-free operation.

As shown in Figure 1, the impact limiter investigated consisted of a torus with a mean radius of 71.8 cm (28.25 inches), a circular cross section radius of 20.3 cm (8 inches) and a shell thickness of 2.22 cm (0.875 inches) which is welded to a relatively stiff support ring. The support ring in turn is fastened to the main body of the cask with a bolted connection.

The feasibility study focused on the performance of large deformation inelastic analysis of the toroidal shell using the ABAQUS finite element program to determine its load-deflection and energy absorbing characteristics. The toroidal shell impact limiter absorbs energy through large plastic deformations during impact. Therefore, a high priority was placed on the performance of detailed inelastic analysis of the toroidal shell to quantify the absorbed energy and strains in the toroid during impact. Quasi-static analyses were carried out with ABAQUS using 2D axisymmetric and 3D solid models for the various drop orientations.

Concurrently, an engineering test program was conducted on aluminum straight pipe and 180 degree pipe bend specimens to develop experimental data on the local crush rigidity, weld strength, and fracture strains for aluminum Alloy 6061-T6.

INELASTIC ANALYSIS

The solutions for the various finite element models were obtained using the ABAQUS computer code which is a general purpose non-linear structural analysis finite element program. The impact limiter analysis is highly non-linear due to the influence of large deformations, plastic material response, and the variable contact between the limiter and the rigid surface. The ABAQUS code has capability in all three of those areas.

Model Description

The geometry of the toroidal impact limiter is shown in Figure 1. The geometry of the impact limiter model that was analyzed is shown in Figure 2. Since the attachment ring is much stiffer than the toroidal shell, it is assumed infinitely stiff in the analysis and is not modeled. Therefore, the two circumferential edges of the shell model, which are the locations of the welds to the ring, are given fixed displacement boundary conditions.

The impact limiter is loaded by moving a rigid surface of given orientation, r, against the impact limiter as shown in Figure 2. The surface of the structure cannot penetrate the rigid surface, but it can separate freely from the loading surface after contact or slide freely along the rigid surface. The contact and separation which occur between the limiter and rigid surface is modeled by rigid surface interface elements which are attached to the outer radial edges of the solid elements. These elements transmit normal contact pressure between the imposed rigid surface and the outer surface of the impact limiter.

Since the end drop (rigid surface orientation, $r = 0$) solution is axisymmetric about the axis of revolution of the impact limiter, axisymmetric finite element models were used for end drop analysis. The axisymmetric model used, shown in Figure 3, consisted of 30 solid isoparametric 8-noded elements distributed in the meridional direction, and one element through the thickness. Other axisymmetric models similar to the model shown in Figure 3 except for a difference in the number of elements the meridional direction and through the thickness were used to assess the accuracy of the analytical results.

For all drop orientations except the end drop, the analysis problem is three dimensional in character, and thus require 3D finite element models. Since the rigid surface being imposed on the limiter is a flat plane, the solution will be symmetrical about the radial plane passing through the impact limiter at the point where contact is made. Thus, only half of the limiter needed to be modeled and analyzed. The 3D model used, shown in Figure 4, consisted of 225 solid 20-node brick elements. There were 15 elements in the circumferential and meridional directions, respectively, and one element through the thickness. The interactions between the imposed rigid surface and the 3D finite element mesh were modeled by rigid surface elements as was done for the 2D model.

The uniaxial stress-strain curve for the aluminum Alloy 6061-T6 used in the analysis was based on the manufacturer's published data for a stress-strain relationship in terms of true stress and true strain.

Analysis Results

The pertinent information from end drop solutions obtained from the inelastic analysis is presented in Figures 4 and 5. The load-deflection relationship and the absorbed energy E_a as a function of imposed rigid surface deflection are shown in Figure 4. The load deflection curve has a somewhat flat region just above the knee in the curve. This load plateau corresponds to the limit load which would be obtained in an infinitesimal displacement solution for an elastic-perfectly plastic material. An evaluation of the absorbed energy curve in Figure 4, shows that the impact limiter can absorb the required energy, 2.19×10^6 N.m (19.4×10^6 in-lbs), if it deflects about 16.5 cm (6.5 inches). However at this deflection, the maximum calculated effective plastic strain at the toroidal shell surface is of the order 100%. A displacement plot of the torcidal shell is shown in Figure for an imposed rigid surface displacement of 14.0 cm (5.5 inches). Maximum strains occur near the weld attachment.

The pertinent information obtained from the side drop solution (r = 90° in Figure 2) for the 225 element 3D model is shown in Figure 6. In this Figure both the applied rigid surface load and the absorbed energy are given as a function of the rigid surface deflection. For the limiter to absorb the required energy, 1.10×10^6 N.m (9.7×10^6 in-lbs), the shell must deflect approximately 17.8 cm (7 inches). As for the side drop, for such large deflections the strains in the toroidal shell were of the order of 100%.

ENGINEERING TEST PROGRAM

Static load-deflection tests on aluminum straight pipe sections and 180 degree pipe bends were conducted as part of an engineering test program to demonstrate the feasibility of the aluminum toroidal shell impact limiter. The tests were conducted to determine the energy absorption characteristics, the strain capability of the aluminum material used in the fabrication of the toroidal shell, and the effects of welding. The objectives of the testing were to: show that the aluminum straight pipe test specimens could deform to greater than 70 percent of the pipe diameter before the onset of cracking failure; show that the aluminum alloy could accommodate the high local strains predicted for energy absorption by the finite element analysis; measure the load-deflection/energy absorption characteristics of the specimens; and confirm that the energy absorption of the aluminum toroidal shells could be predicted by the finite element analysis methods.

Static load-deflection tests were conducted on 20.3 cm (8 inch) diameter, Schedule 40 straight pipe sections (approximately half-scale of the impact limiter cross-section) to evaluate the load-deflection/energy absorption characteristics of the aluminum pipe, and on a 20.3 cm (8 inch), Schedule 40, fabricated 180 degree pipe bend which simulated the impact limiter to evaluate the load-deflection/energy absorption characteristics for a side drop type loading. The test configurations of the straight pipe sections and the 180 degree pipe bend are shown in Figures 7 and 8, respectively. Seamless and welded straight pipe specimens were tested to evaluate the effect of weld joints which are required in the fabrication of toroidal shell impact limiters. The weld joints in the straight pipe sections were positioned in 0 degree, 45 degree, and 90 degree orientations during testing as shown in Figure 7.

The 180 degree pipe bend test was fabricated by welding together two 90 degree seamless, long radius elbows. To simulate actual impact limiter construction, the pipe was slit through the pipe wall along the toroidal radius, a weld prep machined, and the joint welded (see Figure 8). The pipe bend was also welded to a mounting ring to simulate the actual impact limiter. The welded assembly was then heat treated and aged to the requirements of specification MIL-H-6088F to restore the material properties to the original T6 condition.

Test Results

The seamless straight pipe specimens exhibited consistent load-deflection and energy absorption (in the range of 4,519 N.m (40,000 in-lb) to 4,784 N.m (42,344 in-lb) characteristics. The cross-section of the specimens deformed into a dog bone type shape. The load-deflection curves were knee-shaped with the bend coming at about 31,140 N (7,000 lbs), which corresponded to a limit type load, and then a somewhat flat region until failure at 44,480 N (10,000 lbs) and a cross-section deflection of approximately 65 percent of the diameter. Local strain measurements were obtained from photographs of the test specimens by measuring the separation between the scribe lines which had been etched on the specimens at the expected point of maximum stress. The maximum local strains observed were between 20 to 30 percent when noticeable cracking occurred along the pipe in the horizontal plane and failure occurred. These maximum strains at failure for the Alloy 6061-T6 aluminum were far below the required strain capability for the impact limiter established by the inelastic analysis results. In addition, the maximum cross-section deflection capacity was below the 70 percent estimated as required for impact limiter service.

The welded straight pipe specimens exhibited a wide range of energy absorption between 790 N.m (7,000 in-lb) and 5,444 N.m (48,187 in-lbs). The lower end of the range is attributed to failure of the weld when it was positioned directly under the load (0 degree orientation in Figure 7). The maximum cross-section deflections achieved with the welded straight pipe specimens were in the range of 15.6 to 58 percent. These test results showed that the weld strengths were reduced below that of the base material and the welds were less ductile.

During the test, it was observed that no cracking occurred until a load of 462,000 N (104,000 lbs) was achieved. Crackling sounds were heard starting at that load and a long horizontal crack appeared approximately 1.27 cm (0.5 inches) below the top surface. The test was stopped at a load of 889,650 N (200,000 lbs) which was the maximum capacity of the test machine. Upon retracting the machine ram, it was seen that the entire crown of the bend had caved in. It appeared that the circumferential weld on the specimen failed first, causing the upper rims of the two 90 degree elbows (from which the 180 degree bend was fabricated) to cave in. Based on analytical predictions, this test specimen would have had to carry a load of over 1.8×10^6N (400,000 lbs) and deflected more than 10.16 cm (4 inches) without failure for the toroidal shell impact limiter to be acceptable for the side drop impact. The very poor performance of this test specimen was attributed to the early failure of the circumferential weld joining the two elbows.

In summary, the test results showed that the local strain capacity of aluminum Alloy 6061-T6 was significantly less than the strains predicted in the finite element analysis required for energy absorption, and the presence of the weld joints significantly reduced the strength and ductility of the aluminum material.

CONCLUSIONS

The results of the inelastic analysis showed that the 9-meter (30 foot) drop energy could be absorbed by the toroidal shell, but very large local plastic strains (of the order of 100%) occurred in the toroidal shell. This was experimentally shown to be beyond the capability of the aluminum Alloy 6061-T6, because the tests of the straight pipe and 180 degree bend specimens showed that cracking of the test specimens occurred at strains of about 30 percent. Therefore, it was concluded that the aluminum toroidal shell impact limiter was not a viable approach for the LWT cask because of its limited ductility and poor weld strength. A more ductile alloy is needed in order for a toroidal shell impact limiter to accommodate large displacements and absorb the necessary energy without cracking.

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ACKNOWLEDGEMENT

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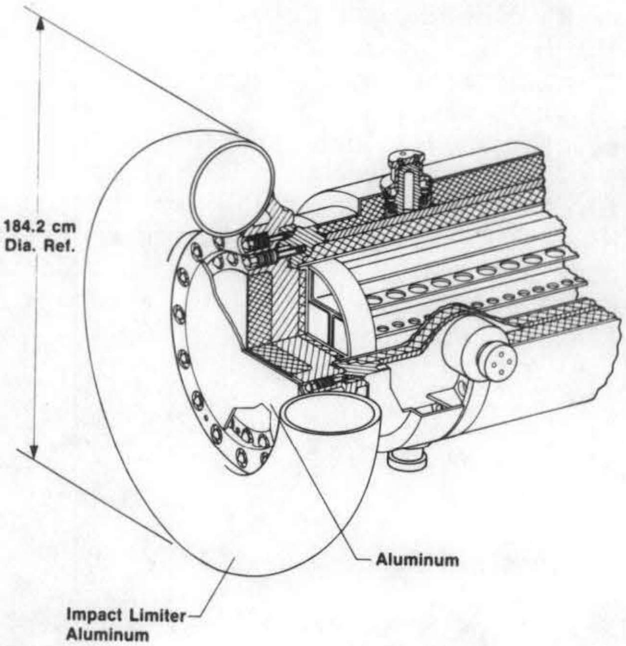

Figure 1
Impact Limiter for Legal Weight Truck Cask

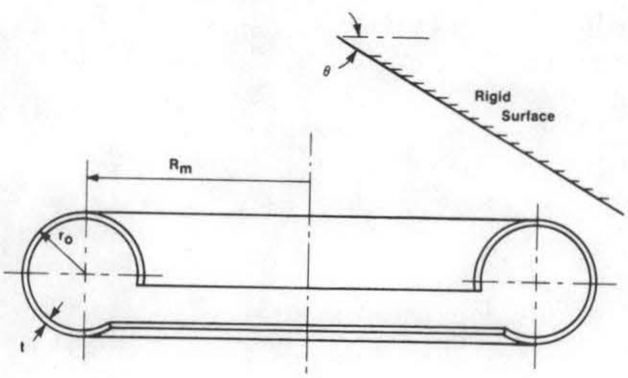

Figure 2.
Impact Limiter Model

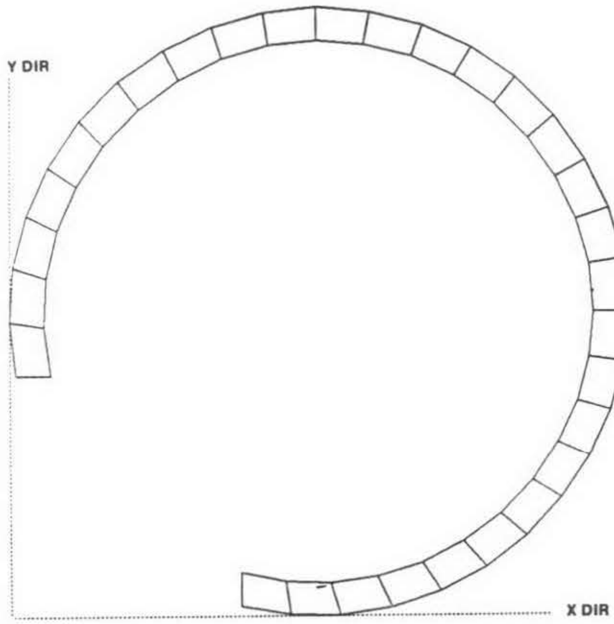

Figure 3
Axisymmetric End Drop Model

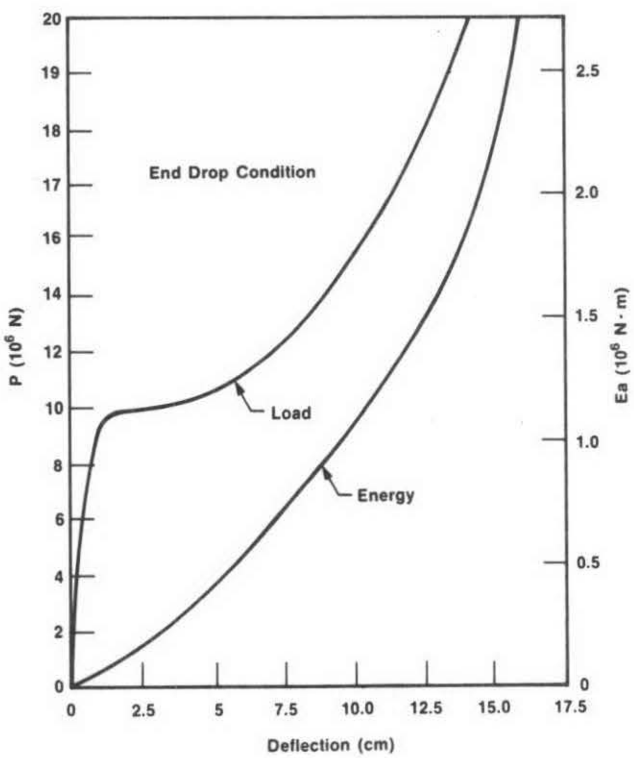

Figure 4 Load and Absorbed Energy as a Function of Deflection - End Drop

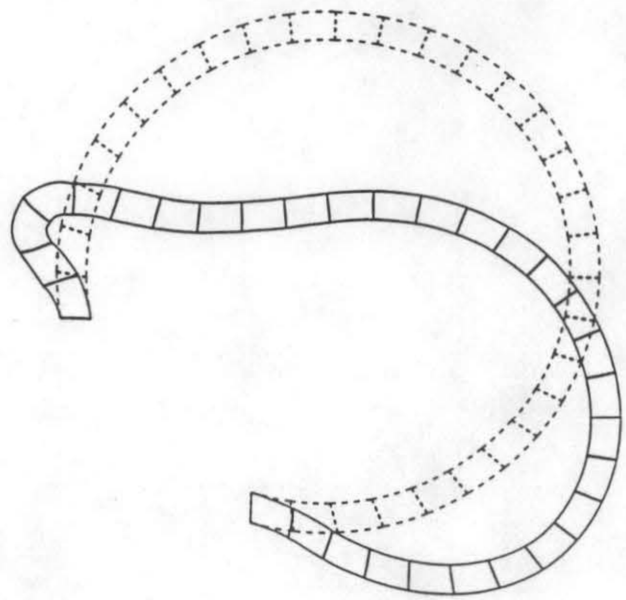

Figure 5 Displacement Plot for 14.0 cm Deflection - End Drop

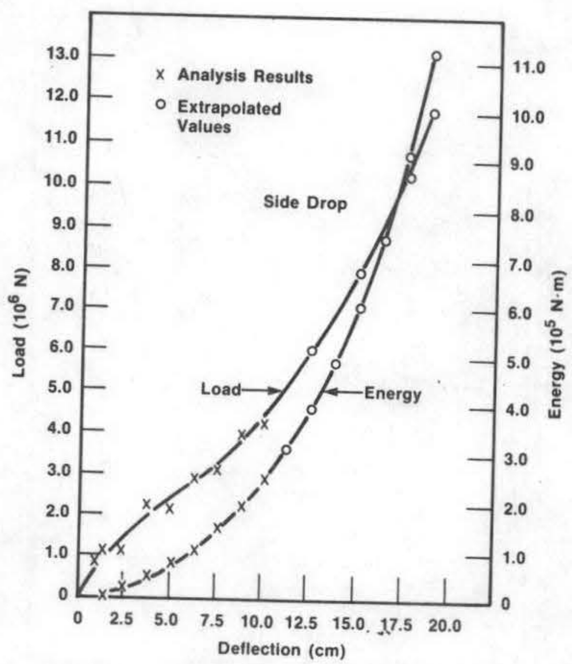

Figure 6 Load and Absorbed Energy as a Function of Deflection - Side Drop

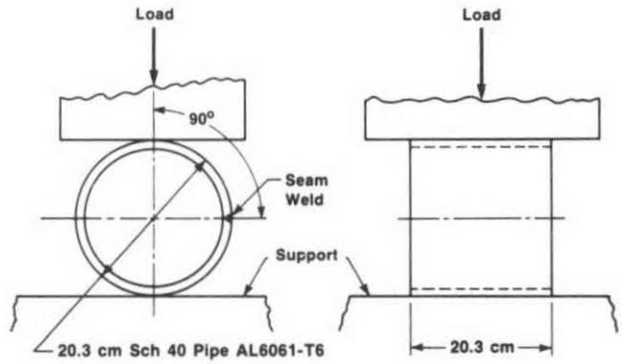

Figure 7 Test Configuration for Straight Pipe Sections

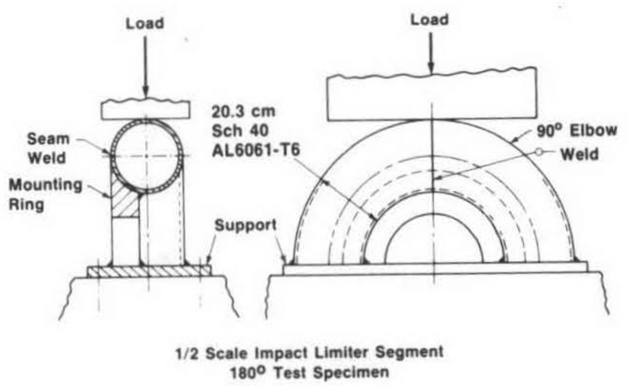

Figure 8 Test Configuration for 180° Pipe Segment