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Axial crushing of frusta between two parallel plates

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Axial crushing of frusta as impact energy absorbers has been investigated by researchers for decades [1-3]. However, effort is made in this paper to classify the modes of deformation of frusta when crushed axially between two parallel plates. Tens of Aluminum spun capped end frusta of different semi-apex angles (15° to 60°) and thicknesses (1 mm to 3 mm) are crushed at quasi static loading conditions using Universal Instron Machine. The resulting modes of deformation can be classified into: 1) Outward-inversion, 2) Limited inward-inversion and outward-inversion, 3) Full inward-inversion and outward-inversion, 4) Limited extensible crumpling and outward-inversion, and 5) Full extensible crumpling. An explicit version of ABAQUS 5.8 Finite Element (FE) program is used to model the crushing modes. Good agreement between the FE predictions and the experimental work is obtained.

1. INTRODUCTION

Energy absorbers are systems that convert kinetic energy into other forms of energy, such as plastic deformation energy in deformable solids. The process of conversion in plastic deformation depends, among other factors, on the magnitude and method of application of loads, transmission rates, deformation displacement patterns and material properties.

The predominant domain of applications of collapsible energy absorbers is that of crash protection. Such systems are installed in high-risk environments with potential injury to humans or damage to property. The active absorbing element of an energy absorption system can assume several common shapes such as circular tubes [4], square tubes [5] and frusta [2].

Axisymmetrical and circular shapes provide perhaps the widest range of all choices for use as absorbing elements because of their favorable plastic behavior under axial forces, as well as their common occurrence as structural elements. In this paper the selected absorber has a truncated capped frustum shape which is employed over a wide range of applications.

2. AXIAL LOADING OF THIN FRUSTA

Johnson and Reid [6] identified the dominant modes of deformation in simple structural elements in the form of circular and hexagonal cross-section tubes when these elements are subjected to various forms of quasi-static loading. They described the load-deformation characteristics of a number of these elements.

Thin-walled tubes absorbers having symmetrical cross sections may collapse in concertina or diamond mode when subjected to axial loads. The collapsing of such components by splitting or by inversion is also reported [5].

The behavior of thin tubes (large diameter D/ thickness t), with circular and square cross sections, when subjected to axial loads, has been of particular interest since the pioneering works of Alexander [4]. One of the first study of frustum (truncated circular cone) was carried out by Postlethwaite and Mills [1] in 1970. In their study of axial crushing of conical shells they used Alexander's extensible collapse analysis [4] to predict the mean crushing force for the concertina mode of deformation for frusta made of mild steel.

Mamalis et al. [2] investigated experimentally the crumbling of aluminum and mild steel frusta of small semi apical angle (5° and 10°) when subjected to axial compression load under quasi-static conditions. They proposed empirical relationships for both the concertina and the diamond modes of deformation. They concluded that the deformation modes of frusta can be classified as a) concertina, b) concertina-diamond, and c) diamond. Mamalis and associates in a number of papers, published between 1983 and 1997, refined the work of Postlethwaite and Mills [1] in using the extensible collapse analysis for predicting the mean and the progressive crushing loads, and fair agreement with the experimental results was reported. Axial crushing of thin PVC frusta of square cross-section and thin-walled fiberglass composite [3] is reported by them.

The above studies deal with axial crushing (or crumbling) of frusta with small semi apical angle (15° maximum) between two parallel plates. However, this paper investigates the quasi-static crushing of aluminum frusta with large range of semi apical angles (15° to 60°) and classifies the deformation modes into 5 categories.

3. FINITE ELEMENT MODELING

In the present study, ABAQUS Explicit FE code (version 5.8) [7] is employed to investigate the axial deformation modes of frusta under quasi-static loading. An axisymmetric four-nodded element, CAX4R, is used for modeling the frustum shown in Fig. 1. About 300 elements are used for the model. Material properties of the model were taken as rigid perfectly plastic with yield strength S_y=125MPa, and density ρ=2800 Kg/m^3. All nodes at the centerline of symmetry were selected to move only in the vertical direction.

Both upper and lower surfaces were set in contact with rigid body surfaces. These rigid surfaces were modeled using two nodal axisymmetric rigid elements, RAX2. A coefficient of friction of μ=0.15 was incorporated between the contact surfaces. A reference node was introduced at the top end surface of the model. This node was set to move at a velocity of 0.01m/s representing quasi-static case.

The upper small capped end of the frustum was in contact with a rigid body moving at a constant velocity. The lower end was restrained from moving in vertical direction as shown in Fig. 1. The axisymmetric elements were chosen to model the axisymmetric collapse of the frusta, and most of the experimentally observed deformation modes were of this type especially at large semi apical angle and/or large thickness.

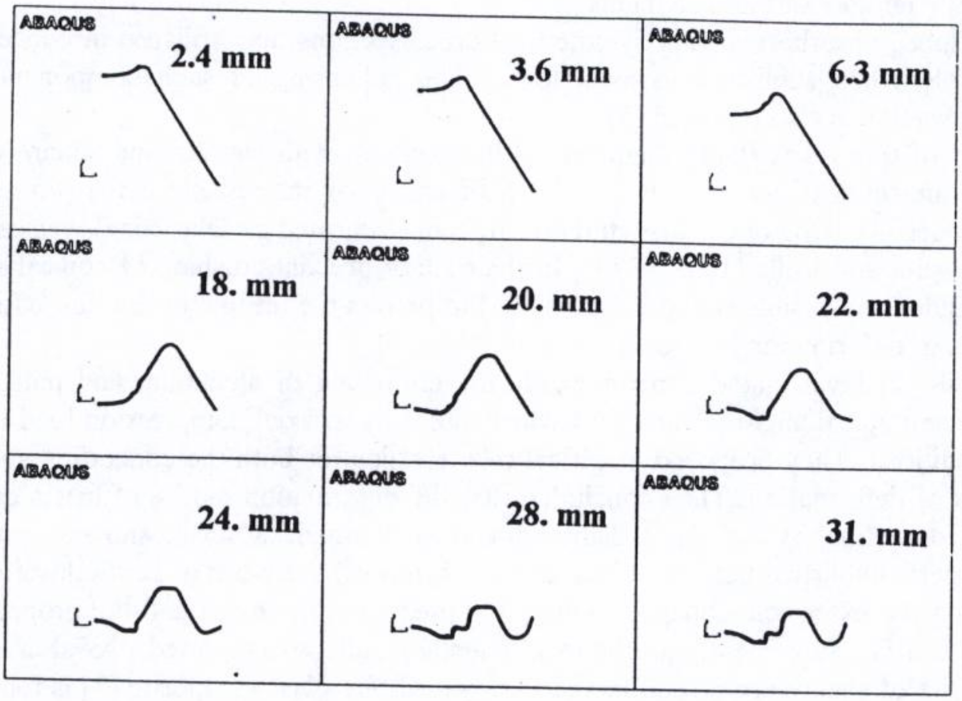

Figure 1: ABAQUS deformed plots for crushing of aluminum frustum (Specimen 60101).

4. RESULTS AND DISCUSSIONS

A large number of frusta, featuring different thicknesses and semi-apex angles were subjected to various loading conditions. The program involved the use of 50 different sizes of aluminum frusta (10 different semi-apex angles and 5 different thicknesses) in crushing tests. Tests were conducted by the use of a 10-ton Instron Universal Testing Machine (UTM).

Table 1 gives the details of the crushing tests. The table lists experiment number, specimen number, semi-apical angle (α) in degrees, thickness (t) in mm, mass (m) in kg, average crushing force (P_{av}) in Newton, absorbed energy (E) in Joule, energy density (E*) in Joule/kg and the deformation mode. The large and small diameters of the frusta were kept constant and equal to 75mm and 20mm, respectively. The average force is calculated over the whole range of the displacement and the elastic contribution is ignored as a common practice in metallic energy absorbers [7]. It was noticed that the deformation modes can be classified into:

i) Flattening the lower end of the frusta and then curling up or upward inversion of the lower end (FLE then UI). This mode is limited to frusta with semi-apical angle = 60°.

b) Partial inward inversion of the upper capped end followed by flattening of the lower end and then curling up or upward inversion of the lower end (PII and FLE then UI). This mode is observed to cover wide range of angles from 55° to 30°.

c) Full inversion of the upper capped end till the small end touches the lower plate. Then the deformation mode changes into flattening of the lower end and then curling up or upward inversion of the lower end (FII and FLE then UI). This mode is limited to few cases, mainly specimen 55101, 60101 and 60151.

d) Limited extensible collapse mode followed by flattening of the lower end and then curling up or upward inversion of the lower end (LEC and FLE then UI). This mode is limited to angles 25° and thick 30°.

e) Full extensible collapse mode. This mode is the only mode investigated in details in the open literature, see for example [2,3]. This mode is seen at small semi apical angles 20° and 15°.

Table 1: Details of the Experimental Work.

No.	Sp. No.	Semi apical angle (deg)	t (mm)	mass (kg)	P_{av} (N)	E (J)	E* (J/kg)	Mode
1	30101	60	1	0.013	1590	22.3	1710	FLE then UI
2	30151	60	1.4	0.016	2903	40.6	2540	FLE then UI
3	30201	60	2	0.024	4433	57.6	2400	FLE then UI
4	30251	60	2.6	0.030	4904	58.8	1960	FLE then UI
5	30301	60	3.2	0.035	5394	64.7	1850	FLE then UI
6	35101	55	1	0.012	2696	40.5	3370	PII then FLE & UI
7	35151	55	1.4	0.016	3432	51.5	3220	PII then FLE & UI
8	35201	55	2	0.022	5394	80.9	3680	PII then FLE & UI
9	35251	55	2.6	0.030	6080	91.2	3040	PII then FLE & UI
10	35301	55	3	0.038	7747	124	3260	PII then FLE & UI
11	40101	50	1	0.012	3040	54.7	4560	PII then FLE & UI
12	40151	50	1.4	0.018	4217	80.1	4450	PII then FLE & UI
13	40201	50	2	0.026	6845	130	5000	PII then FLE & UI
14	40251	50	2.4	0.030	8140	147	4880	PII then FLE & UI
15	40301	50	2.9	0.037	9679	194	5230	PII then FLE & UI
16	45101	45	1	0.013	4070	89.5	6890	PII then FLE & UI
17	45151	45	1.3	0.019	4952	109	5730	PII then FLE & UI
18	45201	45	1.9	0.028	9316	224	7990	PII then FLE & UI
19	45251	45	2.4	0.035	11278	271	7730	PII then FLE & UI
20	45301	45	3	0.044	12160	293	6630	PII then FLE & UI
21	50101	40	0.9	0.014	4217	114	8130	PII then FLE & UI
22	50151	40	1.3	0.020	6178	173	8650	PII then FLE & UI
23	50201	40	1.8	0.030	8826	229	7650	PII then FLE & UI
24	50251	40	2.2	0.037	11277	316	8530	PII then FLE & UI
25	50301	40	2.7	0.045	14710	412	9150	PII then FLE & UI
26	55101	35	0.9	0.017	4315	130	7610	FII then FLE & UI
27	55151	35	1.2	0.022	6914	201	9110	PII then FLE & UI
28	55201	35	1.8	0.032	7992	216	6740	PII then FLE & UI
29	55251	35	2.1	0.039	11180	335	8600	PII then FLE & UI
30	55301	35	2.6	0.047	14318	430	9140	PII then FLE & UI
31	60101	30	0.9	0.018	4903	177	9810	FII then FLE & UI
32	60151	30	1.1	0.024	7159	229	9550	FII then FLE & UI
33	60201	30	1.6	0.033	10689	353	1070	PII then FLE & UI
34	60251	30	2	0.045	11886	452	1000	LEC then FLE & UI
35	60301	30	2.4	0.055	14494	551	1000	LEC then FLE & UI
36	65101	25	0.8	0.019	2962	142	7480	LEC then FLE & UI
37	65151	25	1.1	0.027	4707	217	8020	LEC then FLE & UI
38	65201	25	1.4	0.035	7169	315	9010	LEC then FLE & UI
39	65251	25	1.9	0.048	10297	474	9870	LEC then FLE & UI
40	65301	25	2.3	0.058	14867	684	1180	LEC then FLE & UI
41	70101	20	0.7	0.020	2520	151	7560	FEC
42	70151	20	1	0.030	4364	262	8730	FEC
43	70201	20	1.3	0.038	5796	319	8390	FEC
44	75101	15	0.7	0.026	2373	197	7580	FEC
45	75151	15	0.9	0.037	3638	302	8160	FEC
46	75201	15	1.3	0.053	7061	586	11100	FEC

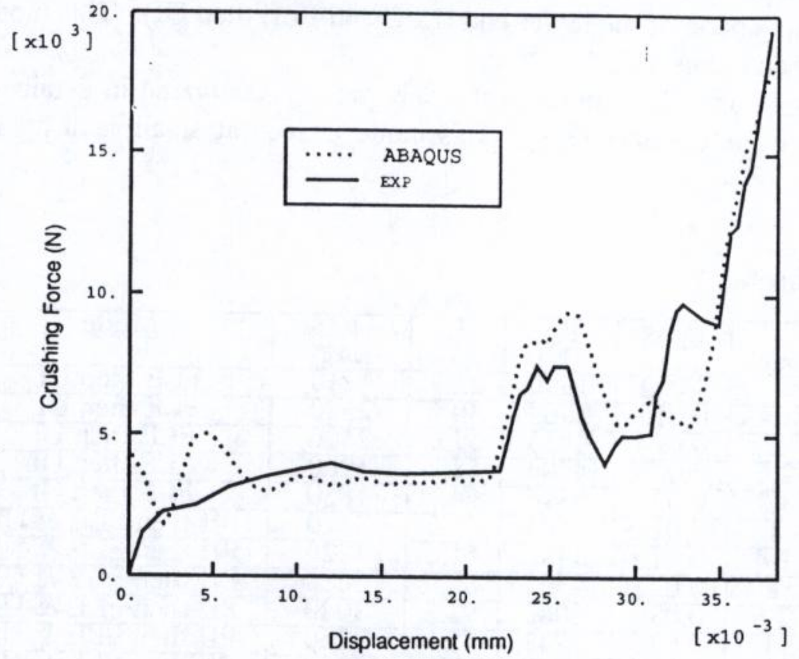

Figure 2: Experimental and FE load-displacement curves for Specimen 60101.

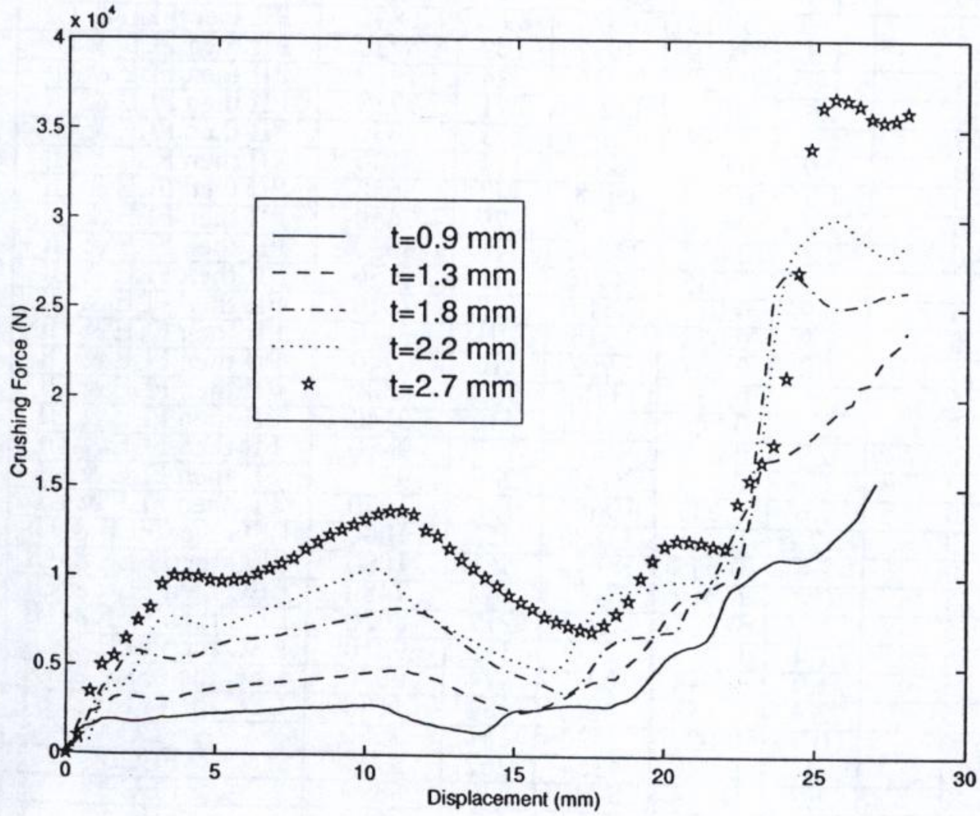

Figure 3: Effect of thickness change on the crushing force.

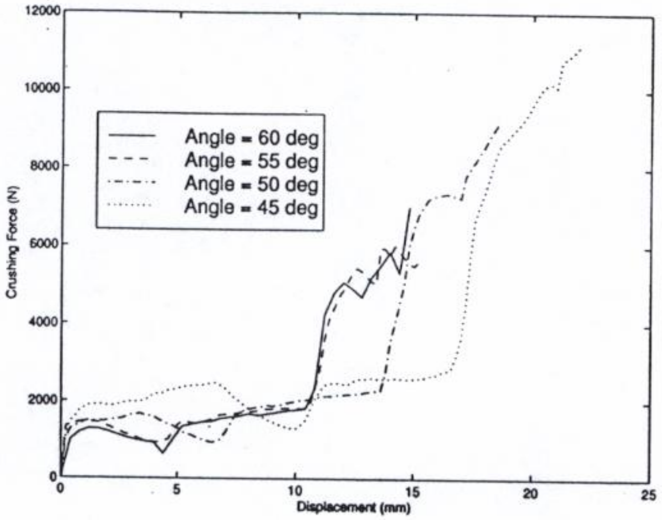

Figure 4: Effect of semi-apical angle change on the crushing force.

The FE details of the crushing process can be seen in Fig. 1 that gives the crushing mode of specimen 60101 in 9 stages. These stages were captured at the following axial intervals: 2.4, 3.6, 6.3, 18, 20, 22, 24, 28 and 31 mm. The first stage shows the initiation of the inward inversion, and the fourth one shows the upper end touching the lower plate. Flattening of the lower end is illustrated in the sixth stage. Figure 2 gives the experimental and the finite element load-displacement curves for specimen 60101. Fair agreement between the two curves is shown.

Figure 3 and 4 show the effect of changing the thickness and the semi apical angle of the frusta on the experimental progressive crushing load, respectively.

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