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EXPERIMENTAL VALIDATION OF ANALYTICAL MODELS FOR MEAN CRUSH LOAD UNDER QUASI-STATIC AND DYNAMIC COMPRESSION OF THIN-WALLED ALUMINIUM TUBES

Mujeeb Pasha[1] & B.G. Vijayasimha Reddy[2]

Department of Mechanical Engineering, Vemana Institute of Technology, Koramangala, Bengaluru, Karnataka, India

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ABSTRACT

Determination of mean crush and flow stressis essential to understand the plastic behaviour of materials subjected to impact loading. This study presents the experimental validation of 6 established analytical models for the mean crushing load of thin-walled circular aluminium tubes; AA6063 under quasi-static and dynamic compressive loads on as-received and annealed tubes. Abramowicz and Jones, and Alexander's analytical models considered the flow stress as the average of ultimate stress and stress at 0.2% strain,also flow stress isthe same as ultimate stress. Experimental results are found to be in good agreement with some of the analytical models based on mean crush loads.

KEYWORDS: *Impact Energy Absorption, Mean Crushload, Flow Stress, Axial Compression*

Nomenclature

- t = thickness of the circular tube (mm)
- R = radius of the tube (mm)
- L = length of the tube (mm)
- Pm= mean crush load (kN)
- M_0 = plastic bending moment (N-m)
- σ_O = flow stress (N/mm^2)
- σ_u = ultimate stress (N/mm^2)
- $\sigma_{0.2}$ / σ_y= stress at 0.2% strain or yield stress (N/mm^2)
- Tm = melting temperature (^{0}C)

1. INTRODUCTION

Aluminium alloys are widely in use for automotive parts, machinery, load-bearing structures, and aircraft parts owing to their low weight, greater strength, and efficient energy absorption capacity during impact. Lightweight components with thin-walled cross-sections are the priorities in automobiles as impact energy absorbers or collision-proof structures. The structural behaviour of these components implies the change in shape or dimension of the structure once subjected to the impact loading. Buckling is the predominant deformation or instability, that occurs when an external load distorts a structure until itreaches a certain threshold where a new deformation mode whichis different from the previousmode formed.

The measure of crashworthiness is to test the structural safety of protective structures or any loaded assemblies[1,2]. Any material under compression experiences strain-hardening, the effects of strain hardening can be nullified by the process of annealing [3].

To understand the deformation behaviour of these components under compression, it is necessary to demonstrate the deformation behaviour of thin-walled tubes under axial compression that reflects buckling effects under quasi-static and dynamic loads [4]. In a thin-walled circular tube, the deformation mode depends on the parameters such as the thickness to radius ratio (t/R) and length to radius ratio (L/R) of the tubes. The buckling behavior is further classified as axisymmetric and non-axisymmetric deformation modes [5,6].

The deformation mechanisms are governed by crystallographic defects, grain orientation, and homogeneity of the material. The mean crush load is termed the average of all the peak loads [7].Experiments have been carried out under quasi-static loading on aluminium 6063 alloy circular and square tubes and validated the mean crush load with analytical models Yob et al. [8]. Table 1 reveals the considered analytical models and flow stress used in this study [9-17].

Table 1: Analytical Model Equations

Sl. No.	Analytical Model	Remarks
1	$P_{mean} = \left(20.75\sqrt{\frac{2R}{t}} + 6 \cdot 283\right) Mo$	Alexander Modelhas presented the rigid plastic analysis for the concertina mode of deformation.
2	$M_0 = \frac{1}{4}\sigma_O t^2$	Thisequation is used to determine the fully plastic bending moment in all the 6 established analytical models.
3	$P_m = \left(22.366\sqrt{\frac{2R}{t}} + 11.766\right) M_0$	Abramowicz and Jones presented the mean crushing load for an axisymmetric and non-axisymmetric mode of deformation.
4	$\sigma_O = \frac{\sigma_{0.2} + \sigma_u}{2}$	Alexander‘s model presented that the flow stress is an average ofstress at 0.2% strain and ultimate stress.
5	$\sigma_o = \sigma_u$	Abramowicz and Jones‘s model presented that the flow stress is equal to ultimate stress
6	$P_m = \left(25.23\sqrt{\frac{2R}{t}} + 15.09\right) M_0$	Abramowicz and Jones also presented the mean crushing mode for Non-axisymmetric crush mode of deformation

Table 1 Contd

7	$P_m = \left(35.22\sqrt{\frac{2R}{t}}\right)M_0$	Wierzbicki and Bhat‘s modelhas compared the solution featuring a stiffening phase of the tube resistance.
8	$P_m = \left(22.27\sqrt{\frac{2R}{t}} + 5.632\right)M_0$	Singace et al. Model, axisymmetric mode of deformation and develop the equation for mean crushing load.
9	$P_m = \left(31.74\sqrt{\frac{2R}{t}}\right)M_0$	Wierzbicki et al.mode proposed the proposed model that includes finite values of peak loads, alternating heights and unequal distance between peaks and active zone of plastic deformation.

This research reveals the experimentation of uni-axial compression of aluminium tubes under quasi-static and dynamic loadingwhich contribute a change in deformation modes of axisymmetric (circular) or non-axisymmetric (lobed) Also, the effects of strain-hardening on deformation modes and hence the impact energy absorption have been investigated. The mean crush loads were experimentally determined under quasi-static and dynamic loading conditions and verified with the 6 established analytical modelsunder consideration.The flow stress has been defined as two entities based on Alexander and Abramowicz and Jones model[20]. The main objective of the study is to quantify the mean crush load, peak load, and impact energy absorption subjected to a quasi-static and dynamic uniaxial compression.

II. MATERIAL AND METHODS

2.1 Specimens

As received circular aluminium tube were turned on lathe to the specimen for a length of 140mm and are finished to perfect flat ends. The external diameter of 50 mm and thickness of 1.6 mm were used.

2.2 Material Properties

The detailed material properties of AA6063 aluminium tube for as-received and annealed in Table 2.

Table 2: Properties of AA6063

Property	Value (MPa) (Static)	Value (MPa) (Dynamic)
Yield stress (as received)	276	400
Ultimate stress (as received)	310	465
Yield stress (annealed)	100	210
Ultimate stress (annealed)	170	290
Young’s Modulus	69 GPa	
Density	2700 kg/mm^3	

2.2 Annealing Procedure

The annealing temperature is decided on the basis of stability, stress-relieving conditions, melting point, recrystallisation and hardness of the material. Annealing requires heating the aluminium alloy between 0.4Tm to 0.6Tm, the recrystallization temperatureis 340^{0}C to 400^{0}C[21, 22]. Annealing reduces the residual stresses in the material and thus makes it more ductile. The as-received tubes were annealed by soaking them at 360^o C for half an hour and then allowed for coolingin the furnace. The Vickers hardness test was conducted and found that, the annealed tubes had an average Vickers hardness value of 35 VHN.

III. Experiments

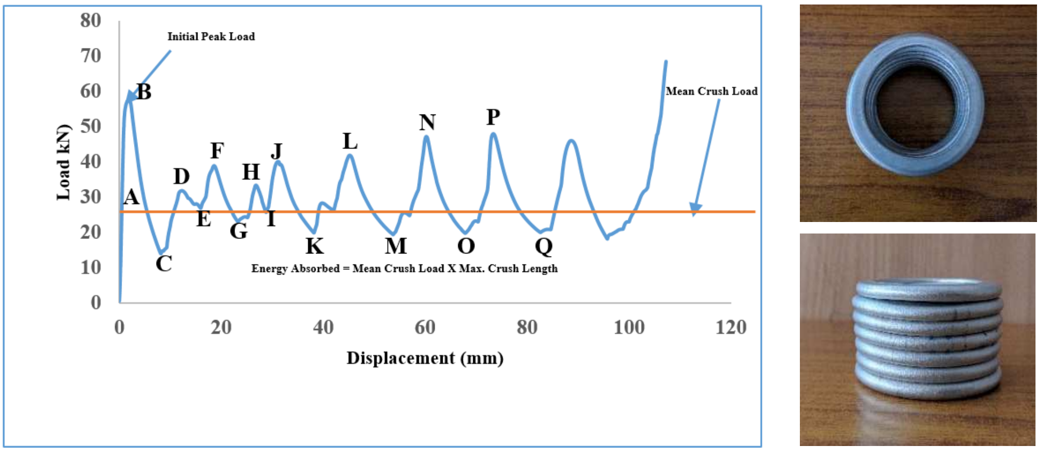
3.1 Quasi-static uni-axial compression tests

3.1.1 As Received Tubes

Uni-axial, quasi-static compression tests were carried out on an electronic universal testing machine of 400 kN capacity (UTES-40) at a constant deformation rate of 8 mm/min [23]. The machine consists of two parallel rigid steel platens. The upper crosshead is fixed, while a computer-controlled hydraulic drive controls and drives the lower crosshead up or down. The specified experimental parameters such as dimensions, the crosshead speed, maximum load, or displacement rate are fed into the computer before the start of each test. All experimental data acquired are stored in the computer, allowing for easy retrieval and processing[24].

The quasi-static compression tests were conducted as per equivalentstandard, which is the standard test method for compression test of tubes[25].

Figure 1(a) shows the typical load-displacement response. The area under the curvegives the impact energy absorption, It was observed that the mean crushload is approximately 26.5 kN. Table 3represents the initial crush load, mean crush load, impact energy absorption, specific energy absorption for different specimens.



(a) (b)

Figure 1: (a) Typical Load-Displacement Response for as Received Tube Under Quasi-Static Loading (b) Deformed Specimen

Table 3 Quasi-Static Test Results for as Received Tubes

Specimen	Mass(gm)	Initial Crush Load (kN)	Mean Crush Load (kN)	Energy Absorbed (kJ)	Specific Energy Absorbed (kJ/kg)
Al_as_1	95.5	57.64	26	2.37	25
Al_as_2	96.2	55.58	27	2.41	25
Al_as_3	95.8	55.35	27	2.18	22
Al_as_4	95.5	52.16	26	2.28	24
Al_as_5	95.1	54.58	26	2.31	25
Average	95.62	55.06	26.4	2.31	24.2

3.1.2 Analytical Mean Crushusing Analytical Models for as-received tubes

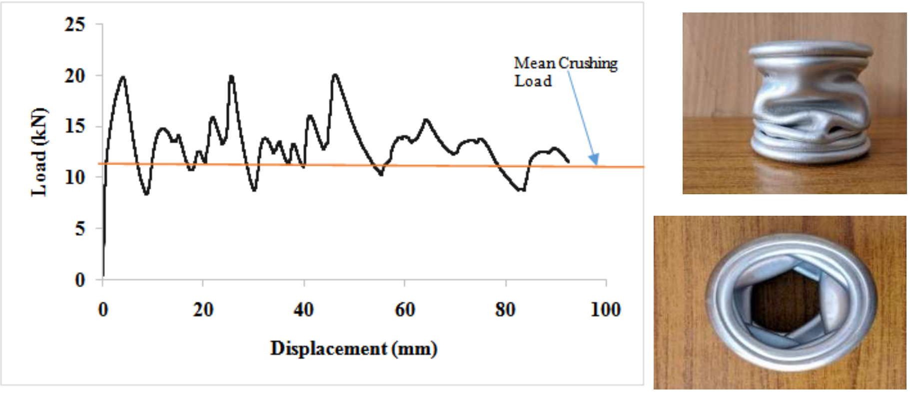
The experiments results were compared with 6 established analytical models as shown in Table 4.

Table 4: Analytical Mean Crush Load For As-Received Tube Under Quasi-Static Load

Analytical Model (Circular Tubes)	Mean Crush Load, *Pm* (kN) $\sigma_0 = \frac{\sigma_u + \sigma_{0\cdot2}}{2}$	Mean Crush Load, *Pm* (kN) $\sigma_0 = \sigma_u$
Alexander Model (1960)	22.92	24.26
Abramowicz and Jones (1984)	25.65	27.14
Abramowicz and Jones (1986)	29.27	30.97
Wierzbicki and Bhat (1986)	36.91	39.06
Singace et al. (1995)	24.41	25.87
Wierzbicki et al. (1992)	33.27	35.20

3.1.3 Annealed Tubes

Figure 3(a) shows the typical load-displacement response of annealed tubes under quasi-static loading conditions. It was observed that the mean crush load is 11.81 kN. Table 5 gives the initial crush load, mean crush load, impact energy absorption, and specific energy absorption for different specimens.



(a) (b

Figure 2: (a) Typical Load-Displacement Response for as Received Tube Under Quasi-Static Loading (b) Deformed Specimen.

Table 5: Quasi-Static Test Results for Annealed Tubes

Specimen	Mass (gm)	Initial Crush Load (kN)	Mean CrushLoad (kN)	Energy Absorbed (kJ)	Specific Energy Absorbed (kJ/kg)
Al_an_1	94.3	20	11	1.08	11
Al_an_2	95.2	21.76	12.5	1.03	11
Al_an_3	95.3	21.61	12	0.99	10
Al_an_4	94.8	22.04	11.82	1.04	11
Al_an_5	95.4	21.92	12.23	1.21	13
Average	95	21.46	11.91	1.07	11.2

3.1.3 Analytical Mean Crush Using for as Annealed Tubes

The experiments results were compared with 6 established analytical models as shown in Table 6.

Table 6. Comparison between Pm Analytical Model for an Annealed Tube Under Quasi-Static Load

Analytical Model (Circular Tubes)	Mean Crush Load, *Pm* (kN) $\sigma_0 = \frac{\sigma_u + \sigma_{0\cdot 2}}{2}$	Mean Crush Load, *Pm*(kN) $\sigma_0 = \sigma_u$
Alexander Model (1960)	10.69	13.31
Abramowicz and Jones (1984)	11.82	14.88
Abramowicz and Jones (1986)	13.48	16.98
Wierzbicki and Bhat (1986)	17.01	21.42
Singace et al.(1995)	11.24	14.16
Wierzbicki et al.(1992)	15.33	19.30

3.1 Dynamictests

Testing Procedure

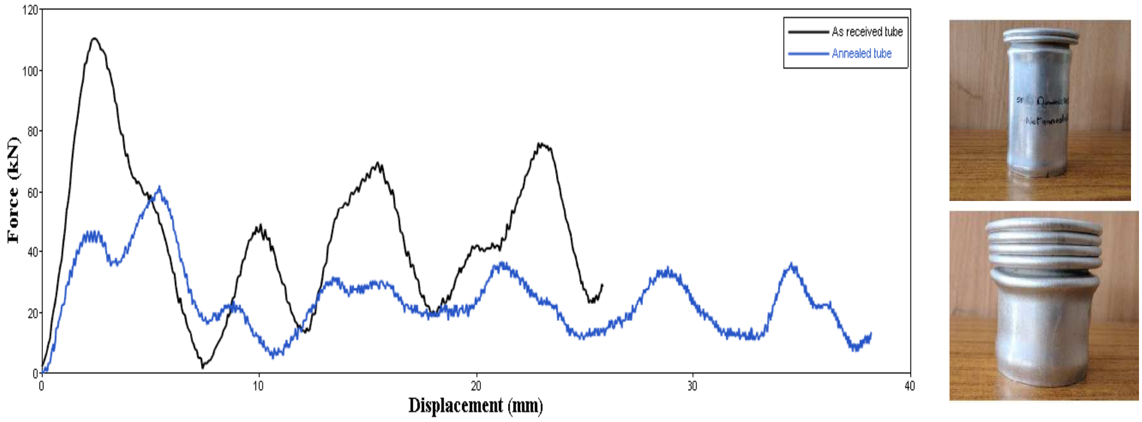
Figure 3: Drop Hammer.

The dynamic tests were conducted using an indigenously developed drop weight impact test machine is shown in Figure 3.A specimen was placed on the top plate of the load cell, the drop mass was then lifted up manually to the required height based on the defined velocity. The data acquiring and storing instruments were checked. The drop mass was released using the automated load-releasing mechanism, this impacts the specimen and compresses it. In some cases, there was a rebound and the mass falls back onto the specimen again. The metal frame carrying the drop mass was brought down to the loading platform. The drop mass was then lifted and supported on the safety rods provided in the machine.

The crushed specimen was then removed fora detailed examination. The voltage-time data acquired by the data acquisition system was saved in a personal computer for further processing[26].

A series of low-velocity impact tests were carried out on as received and annealed specimens of aluminium tubes.Thedrop height for a given specimen during the impact test was determined from the knowledge of quasi-static test behavior. A comparison of mean crush load with 6 established analytical modelswas made. A drop hammer of mass 63.5 kg with two different velocities was used in dynamic experiments[27].

Similarly, experiments were carried on as-received and annealed tubes and validated with 6 analytical models. Figure 4 shows comparative load-displacement curves for as received and annealed aluminium tubes under dynamic loading. It is observed that the mean crushload for as-received tubes is about 1.6 times that of annealed aluminium tubes. Table 7 and 8 represents the series of test results for as received and annealed tubes under dynamic loading conditions.



(a) (b)

Figure 4: (a) A Typical Comparative load-Displacement Curve for as Received and Annealed Aluminium tube (b) Deformed Specimen.

Table 7: Dynamic Test Results for as Received Aluminium Tubes (Height = 3.5 Velocity 8.3m/s)

Specimen	Mass of the Specimen (gm)	Energy absorbed(kJ)	Mean Crush Load (kN)	Specific Energy Absorbed (kJ/kg)
Al_as_1	94.8	1.33	33.2	14
Al_as_2	94.6	1.23	33.5	13
Al_as_3	95.1	1.15	30.1	12
Al_as_4	95.8	1.19	33.2	12
Average	95.07	1.22	32.5	12.75

Table 8: Dynamic Test Results for Annealed Aluminium Tubes (Height = 2 Velocity 6.2m/s)

Specimen	Mass (gm)	Energy absorbed(kJ)	Mean Crush Load (kN)	Specific Energy Absorbed (kJ/kg)
Al_dyn_1	96.1	0.61	19.5	6
Al_dyn_2	95.8	0.57	20.2	6
Al_dyn_3	95.4	0.56	19.5	6
Al_dyn_4	96.4	0.62	19.6	6
Al_dyn_5	96.2	0.58	21.5	6
Average	95.98	0.58	20.06	6

3.2.2 Analytical Mean Crush load for as Received Tubes

The experiments results were compared with 6 established analytical models as shown in Table 9.

Table 9: Mean Crush Load Analytical Model for as-Received Tube Under Dynamic Load

Analytical Model (Circular Tubes)	Mean Crush Load, *Pm* (kN) $\sigma_0 = \frac{\sigma_u + \sigma_{0\cdot 2}}{2}$	Mean Crush Load, *Pm* (kN)$\sigma_0 = \sigma_u$
Alexander Model (1960)	33.42	35.97
Abramowicz and Jones (1984)	37.820	40.71
Abramowicz and Jones (1986)	43.16	46.48
Wierzbicki and Bhat (1986)	54.43	58.59
Singace et al. (1995)	35.97	38.72
Wierzbicki et al. (1992)	49.05	52.81

3.2.3 Analytical Mean Crush load for as Annealed Tubes

The experiments results were compared with 6 established analytical models as shown in Table 10.

Table 10: Comparison Between Pm Analytical Model for an Annealed Tube Under Dynamic Load

Analytical Model (Circular Tubes)	Mean Crush Load, *Pm* (kN) $\sigma_0 = \frac{\sigma_u + \sigma_{0\cdot 2}}{2}$	Mean Crush Load, *Pm* (kN) $\sigma_0 = \sigma_u$
Alexander Model (1960)	19.34	22.43
Abramowicz and Jones (1984)	21.886	25.388
Abramowicz and Jones (1986)	24.98	28.97
Wierzbicki and Bhat (1986)	31.5	36.54
Singace et al. (1995)	20.82	24.15
Wierzbicki et al. (1992)	28.38	32.93

4. RESULTS AND DISCUSSIONS

4.1 Quasi-Static Tests

Figure 1 and 2 shows the typical load-displacement responses for as received and annealed tubes under quasi-static loading. These curves represent the distinct phases of deformation namely elastic, elastic-plastic, and densification.

In Figure 1 , the elastic deformation region OA is followed by elastic-plastic non-linear region AB in which the tube was seen to bulge out slightly at both ends. The tube collapse at point B at the bottom end. At point C the fold appeared to be completed and the beginning of a new fold was seen. The second fold was clearly seen to be initiated at F. The load required for the first collapse (at B) was higher than the required for the second one at F. Also the subsequent folds formed were higher than the immediately previous one. There are secondary fluctuations (DE, HI etc) in between the peak(like CFG, GJK etc), which become smaller and disappear after a few folds.

Similarly in annealed tubes, the material behaves more ductile and initially it starts with concertina modes, slowly it transforms to lobed mode deformation. In Figure 2, the elastic deformation region is followed by the elastic-plastic region nonlinear region. after the first peak, there are more fluctuations followed by a second fold. In the further stage of the deformation, the formation of fold initiates at the bottom end of the tube and continues to deform until the first fold is completely formed [28].The experimental results are summarized in Table 3 and Table 5.

The test results of mean crush load values are consistent for as received and annealed tubes are shown in Table 4 and Table 6obtained from the load-displacement response under quasi-static loading. The experimental mean crush load is in good agreement with the analytical model of Alexander, Abramowicz et al. and Singace et al. when the flow stress is equal to ultimate stress. Also, Alexander, Abramowicz et al, and Singace et al when flow stress is equal to ultimate stress with stress at 0.2% of strain.

Similarly, the annealed tube hasa lesser experimental mean crush load compared to as-received tubes. The experimental mean crush load of an analytical model of Alexander, Abramowicz et al, and Singace are comparable in 6 established models.

4.2 Dynamic Tests

Figure 4 reveals the load-displacement curves for the as-received and annealed tube. The specimens first buckle elastically to a point where it reaches maximum yield point. Once the material reaches its maximum yield stress, the specimen starts to buckle plastically and the one lobe mode is formed. The fluctuation and fold formation continue till the velocity reaches zero. Specimens of as-received are crushed at the velocity of 8.28 m/s. Tables 7 and 8 reveal the experimental results under dynamic loading conditions. Similarly, the specimen of annealed crushed at the same height of 2 m with a velocity of 6.26 m/s. Annealed specimens show a lower load-carrying capacity when compared to as-received tubes. Tables 9 and 10 reveal the analytical results for 6 established analytical models. The experimental mean crush load of an analytical model of Alexander and Singace et al. for as received and agreeable than the other 6 established models. While for annealed tube Alexander, Abramowicz and Jones, and Singace et al., are agreeable in 6 established models.

5. CONCLUSIONS

A series of quasi-static and dynamic tests are conducted on as-received and annealed tubes to understand the deformation response and to quantify the mean crush load and impact energy absorption capacity. Experimental results are compared with 6 established analytical models on mean crush load. Following conclusions are drawn from the study.

- The mean crush load for 3 analytical models viz. Alexander, Abramowicz et al, and Singace et. al for as received tubes and 3 analytical modelsviz. Alexander, Singace et al., and Abramowicz et al. for annealed tubes are in good agreement with experimental results. Experimental mean crush load for as-received are approximately 47% more compared to annealed tubesunder quasi-static loading. Similarly, the analytical mean crush load for as-received tubes is 50% more compared to annealedtubes.

- The experimental mean crush load under dynamic loading conditions for received tubes is about 60% more thanthe annealed tubes. The analytical mean crush load for as-received tubes is about 58% more compared to annealed tubes.

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