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EFFECTS OF STRAIN-HARDENING DURING PLASTIC BUCKLING FOR AXIALLY COMPRESSED ALUMINIUM TUBES

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ABSTRACT

The purpose of this work is to explore the effects of strain hardening on circular tubes made of aluminium (6063) that have undergone plastic buckling as a result of axial compression under quasi-static and dynamic loads. As part of the experimentation, a comparison will be made between the modes of deformation and buckling behaviour shown by sets of annealed and as received tubes. In order to assess the effects of strain-hardening and strain rate, a series of systematic investigations were carried out. In order to describe the load-deformation behaviour and the deformation pattern, quasi-static tests were performed on as received (VHN- 75) and annealed (VHN-35) tubes. In order to investigate the effects of strain hardening, interrupted loading experiments were carried out on specimens that had been intermittently annealed and annealed on a set of annealed tubes. All of the quasi-static test cases were run again under dynamic loading circumstances at different velocity ranges, and the results were compared to the amount of energy that the cases could absorb when subjected to quasi-static loading.

KEYWORDS

Aluminium tubes, strain-hardening, dynamic tests, quasi-static test, buckling, energy absorption capacity.

INTRODUCTION

Aluminium alloys relating to its strength and durability and impact energy absorption capacity have established applications in the design, development and production of lightweight parts which are used in testing crashworthiness depending on the structural integrity. Aluminium alloys are vastly available and provide more stability to their impact energy absorption, it is necessary to understand their deformation behaviour concerning loading rate and a change in a crystalline behaviour. The measure of crashworthiness is to test the structural safety of protective structures, aircraft, vehicles or any loaded bodies. The energy absorption capacity of materials is used in various transportation systems has led to increased interest in thin-walled high strength sections. The energy absorption capabilities of such components are important in improving crashworthiness without increasing the weight.

Strain-hardening is the ability of the material to plastically deform. This means that as a material of is compressed, due to plastic deformation strain hardening increases. The hardening in a material can be nullified by the annealing process. Also, the strain-hardening in a material can be varied by the thee methods of interrupting loading and intermittently annealing processes. The microstructure of a substance determines the strength of the material. The engineering procedures that are applied to a material have the potential to change its underlying microstructure. The mode of deformation is determined by many properties of the tubes, such as -their thickness-to-radius ratio (t/R) and length-to-radius ratio (L/R), respectively.

THEORETICAL BACKGROUND

The subject of buckling, both elastic and plastic, of thin-walled cylindrical tubes subjected to axial compression has been studied extensively [1]. This applies to a wide variety of materials and models. Buckling of an axisymmetric circular tube can be investigated either as elastic buckling or plastic buckling, depending on whether the buckling stress is greater than the material's yield stress. The effects of strain-hardening [2] are also affected by the microstructure of materials. The analytical models related to crushing behaviour for various models is also a well-versed [3]. Strain-hardening helps in understanding the deformation behaviour and impact stability of the material depending on the folding behaviour of the specimens

The effects of strain-hardening and change in the mode of deformation were investigated by Reddy and Zhang [4]. Strain-hardening enhances mean flow stress and also affects the geometry of deformation. The use of ultimate stress σu as mean flow stress σo as produced agreeable results [5]. A mathematical model was proposed that theorized the mean crushing load and the plastic bending moment.

$$P_m = \left(22.366\sqrt{\frac{2R}{t}} + 11.766)\right)M_0 \qquad \mathbf{1}$$

where R and t are the radius and thickness of the tube respectively. Mo is full plastic bending moment which is given as,

$$M_0 = \frac{1}{4}\sigma_O t^2 \qquad \mathbf{2}$$

where σ_O and t refer to the flow stress and thickness of tubes respectively. For mean stress σ_O, it was considered as ultimate stress is equal to mean flow stress.

At the initial stage of loading, the tube starts to deform at either of the two ends. The compressive forces are exerted axially on the surface of the tube. This makes the tube deform radially outward and enter into axisymmetric mode of buckling [6]. Increasing the length of the tube can lead to global buckling, also called Euler buckling. Depending on the deformation modes and buckling behaviour, experiments have been conducted to determine the mechanical behaviour and material properties [3] [7].

To analyze the deformation in axial loads, several material models were proposed to calculate mean crushing load Pm. One such model was proposed by Singace et. al. [8] for axisymmetric folds, where Pm is given as,

$$P_m = \left(22.27\sqrt{\frac{2R}{t}} + 5.632\right)M_0 \qquad \mathbf{1}$$

To start with, it is necessary to obtain the mechanical properties of the material used for experimentation such as the Young's Modulus, Poisson's Ratio, Yield Stress, Ultimate Stress and so on. One such method, namely the ring compression test will be useful in determining the Yield Stress of the material. [9] [10]. A method namely the ring compression test wherein a circular tube

undergoing lateral compression under a maximum elastic load Po is used to determine the yield stress σ_o is given as,

$$Po = \frac{\sigma_o t^2 b}{R} \qquad \mathbf{2}$$

Where t is the cross-sectional thickness, b is the lateral length and R is the radius of the tube.

EXPERIMENTS

In this research, aluminium 6063 circular tubes were chosen as test specimens. Tubes of 50mm outer diameter, 1.6mm thickness and 140mm length were used for all the experiments. A set of tubes were annealed at 360oC for about 30 minutes and soaked in the same environment for about two days until the temperature in the furnace temperature reduces to the ambient or surrounding temperature.

A series of tests were carried out under quasi-static and dynamic loading condition. The load-deformation response was recorded and change in response for each of these conditions were noted relating to deformation behaviourand impact energy absorption. The tubes when received had an average hardness of 75VHN and when annealed had an average hardness of 35VHN. The next set of experiments were conducted based on interrupting the loading after each fold. After the completion of one-fold, the specimen is unloaded and reloaded from the same point. The results of these tests help in giving a comparative study for the changes between interrupted and continuously loaded specimens. All the quasi-static tests were carried out on a universal testing machine (UTM) (Figure 1) capacity of 400kN and the dynamic tests were carried out in a drop weight test facility indigenously designed and developed in the institution (Figure 2). The drop weight facility is an electromechanical system which includes a load cell of 400kN capacity which in turn is connected to a strain gauge/load cell amplifier. The data was recorded using a digital oscilloscope. A digital signal oscilloscope was used to acquire the amplified signal that produces a voltage versus time signal plot as its output. Calibrating the load cell, a constant was determined that was used to convert the voltage values to force which was then converted to force versus displacement plots to calculate energy absorbed by the tubes during impact.

Figure 1 Universal testing machine

Figure 2 Drop weight testing machine

Every one of the static tests was carried out at a constant rate of deformation of 6 mm/min. During the compression test that was performed on the tubes, the corresponding load-deformation curves were charted and recorded. The total amount of energy that the specimen absorbed due to compression can be determined by plotting the area that is under the load-deformation curve. The same result can be used to calculate the required drop height for the dynamic test to be carried out. The required height of the drop for the dynamic impact test can be calculated as follows:

$$E = mgh \qquad 5$$

RESULTS AND DISCUSSIONS

1. Ring compression test

A tube of length 50mm was laterally compressed under quasi-static load. The corresponding load-deflection curve was plotted. The tangent drawn to the curve corresponds to the maximum elastic load of the material in the Y-axis. Eq. 4 gives the elastic yield modulus of the material and it was found to be 195MPa

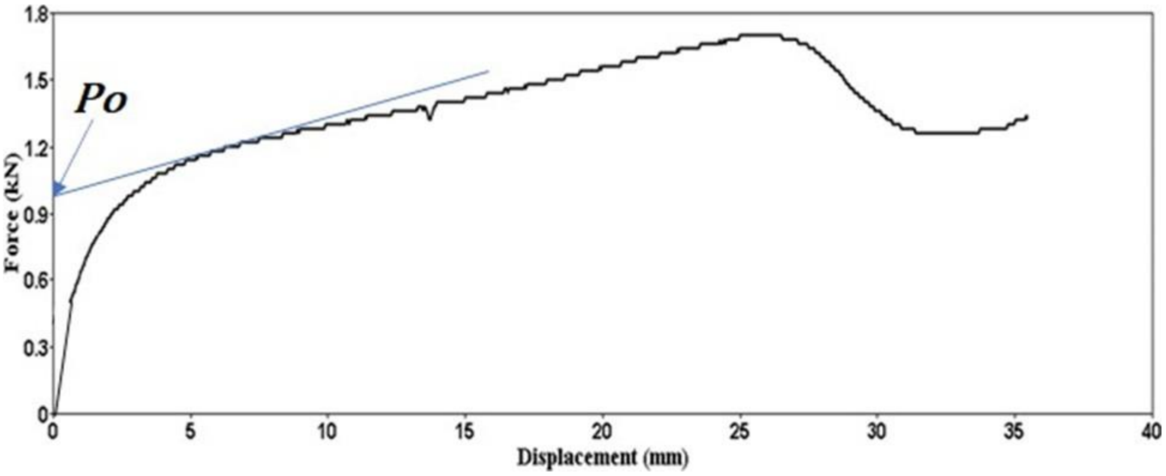

Figure 3 Load-displacement response for the ring compression test

Figure 3a Stages of compression for ring compression test

2. Quasi-static tests

Tests on aluminium tubes, both in their as-received and their annealed states, were carried out while subjected to a quasi-static stress. The load-deformation curves that corresponded to each figure were plotted (Figure 4), andthe total energy that was absorbed by the tubes was calculated. In order to get a comparison analysis (Table 1) between the two sets of findings, it was necessary to plot each set of findings up to a displacement of 95mm.

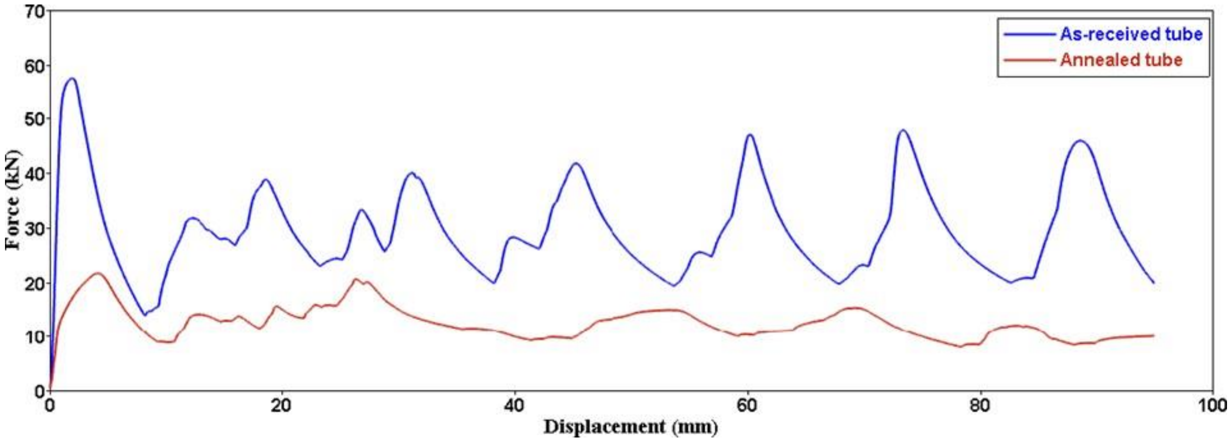

Figure 4 Comparison of load-displacement response for an as-received tube under quasi-static load

Figure 3a Quasi-static test specimen for an as-received tube

Figure 3b Quasi-static test specimen for an annealed tube

Table 1 Results of Quasi-Static for two state of tests

Specimen State	Energy Absorbed (Joules)	Max load (kN)
As received	2841.16	70.7
Annealed	1185.63	21.6

The energy absorption capacity for the as-received specimen is 2.4 times more than annealed specimen under quasi-static load. Annealing has contributed to substantial reducing in strain- hardening effects.

3. Dynamic tests

Similarly, tests were conducted under dynamic loads for an as received and annealed tube (Figure 5Error! Reference source not found.). The drop heights were based on the energy absorption capacity of quasi-static tests. The calculated heights were set accordingly in the drop weight test apparatus. For the tests conducted on an as-received and annealed tube, the drop heights were set to 4.5m and 2m respectively.

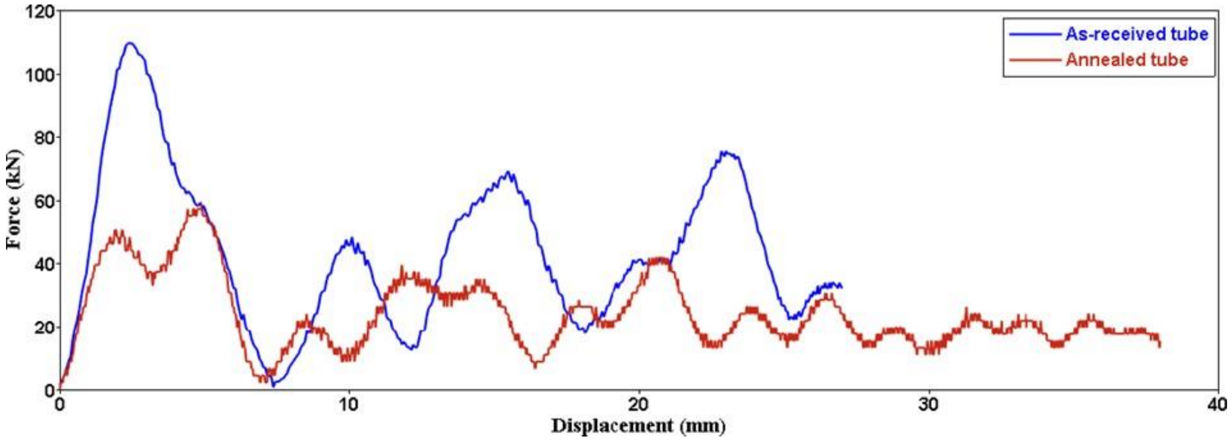

Figure 5 Comparison of load-displacement response for an as-received tube under dynamic load

Figure 5a Dynamic test specimen for an as-received tube

Figure 5b Dynamic test specimen for an annealed tube

Table 2 Results of Dynamic for two state of tests

Specimen	Energy (J)	Max load (kN)	Displacement (mm)	Drop height (m)	Velocity (m/s)
As-received	1183.5	110.15	27	4.5	9.39
Annealed	914.56	59.1	38	2	6.26

The energy absorption capacity for the as-received specimen is 1.7 times more than annealed specimen under dynamic load. For both the tests at a displacement of 27mm, the energy absorption capacity for the as-received specimen is 1.7 times more than annealed specimen under dynamic load.

4. Interrupted loading tests

Under quasi-static and dynamic load, tests were conducted by interrupting the load at every intermediate stage of folds. After the completion of one fold, the tubes were unloaded and reloaded from the same state of deformation (Figure 6). This study was conducted to understand the strain- hardening effects at every fold lengths.

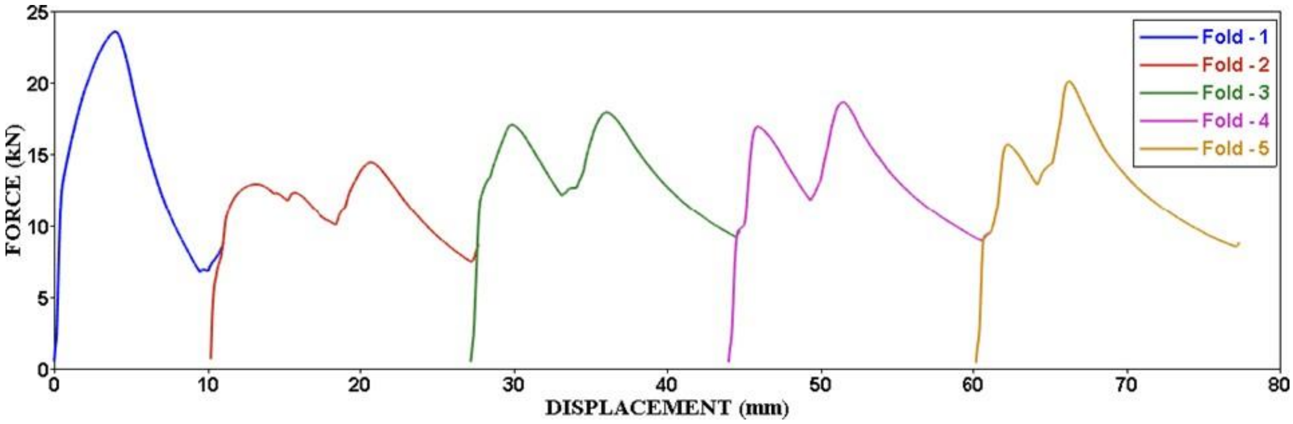

Figure 6 Load-displacement response for an annealed tube under quasi-static interrupted load

Figure 6a Quasi-static test specimen for an annealed tube under interrupted load

Table 3 Quasi-static test results under interrupted loading of the aluminium specimen

Fold	Energy (J)	Displacement (mm)
1	160.4	11.2
2	192.4	16.8
3	235.7	17.2
4	219.6	16.4
5	213.6	15.6
Total	**1021.7**	**77.2**

The displacement and energy absorbed were calculated for every fold. The test was conducted until the completion of five folds. The energy absorbed from every fold was used to determine the drop heights for the dynamic tests. The deformation behaviour was similar to a continually crushed tube. Similarly, all the load-deformation curves for every fold were plotted together(Figure 7). The totality of all the folds gives the total energy absorbed under dynamic loading conditions.

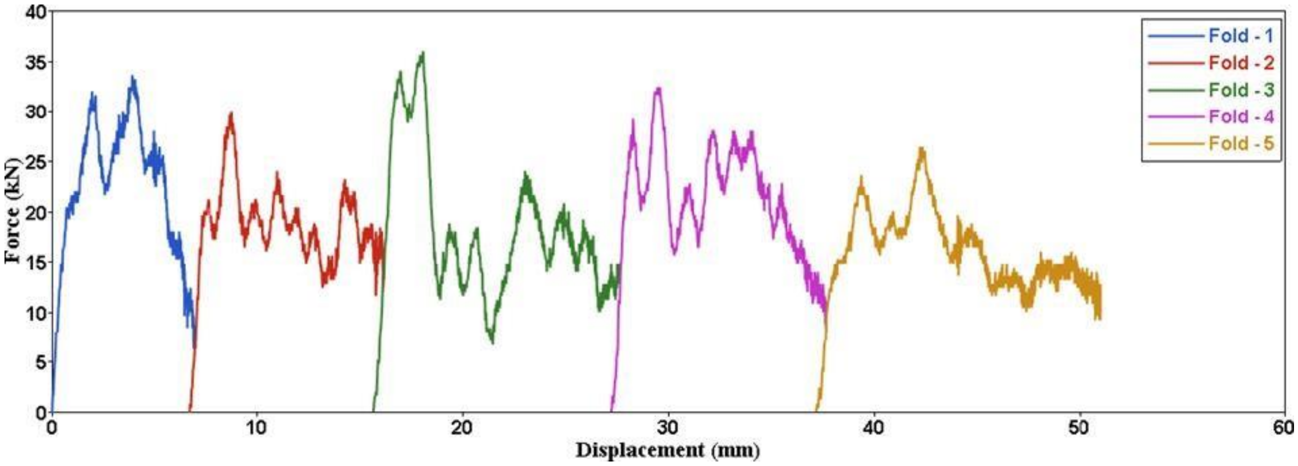

Figure 7 Load-displacement response for an annealed tube under dynamic interrupted load

Figure 7a Dynamic test specimen for an annealed tube under interrupted load

Table 4 Dynamic test results under interrupted loading of the aluminium specimen

Fold	Energy (J)	Displacement (mm)	Drop height (m)	Velocity (m/s)
1	178.8	6.9	0.26	2.25
2	186.8	9.1	0.31	2.46
3	231.9	11.5	0.37	2.69
4	219.7	10.2	0.35	2.62
5	219.2	13.2	0.34	2.6
Total	**1036.4**	**50.9**		

5. Intermittently annealing tests

As the tubes were annealed at intermediate stages, the material becomes more ductile which renders its properties to its deformation behaviour. After the completion of every fold, the tube was unloaded, annealed and loaded again. The fold was initiated at a very lower load. The test was conducted under static and dynamic loading condition. The results were recorded up to the completion of five folds. The load-displacement curves were plotted separately and then combined based on deformation of every fold.

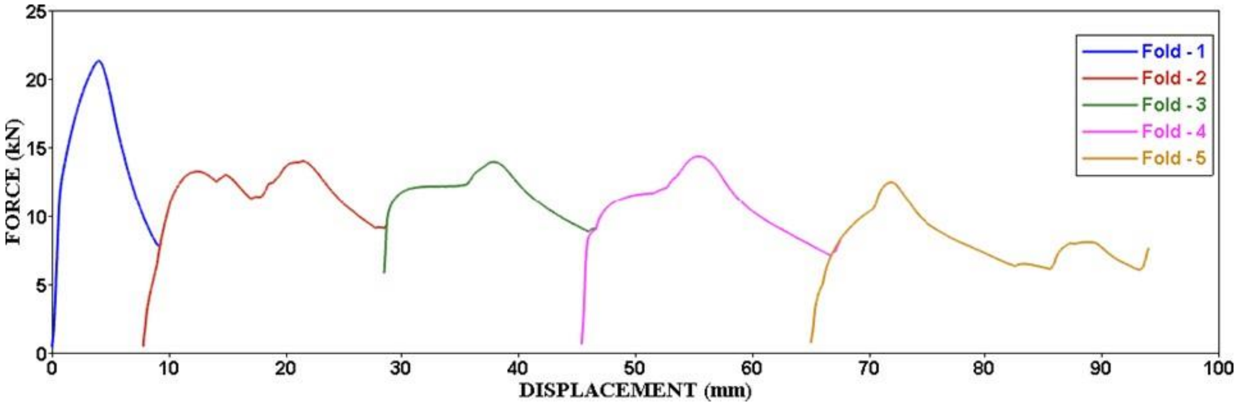

Figure 8 Load-displacement response under quasi-static load for an annealed tube for intermittently annealed conditions

Figure 8a Intermittently annealed tube under quasi-static interrupted load

Table 5 Quasi-static test results for intermittently annealed specimen

Fold	Energy (J)	Displacement (mm)
1	134.9	9.3
2	234.5	19.6
3	211.2	18.3
4	227.8	21.1
5	224.6	27.4
Total	**1033.7**	**95.7**

The same procedure (interrupted loading) was followed to conduct the dynamic test, but tubes were annealed after every fold. The required drop heights were set according to the energy absorbed under quasi-static load.

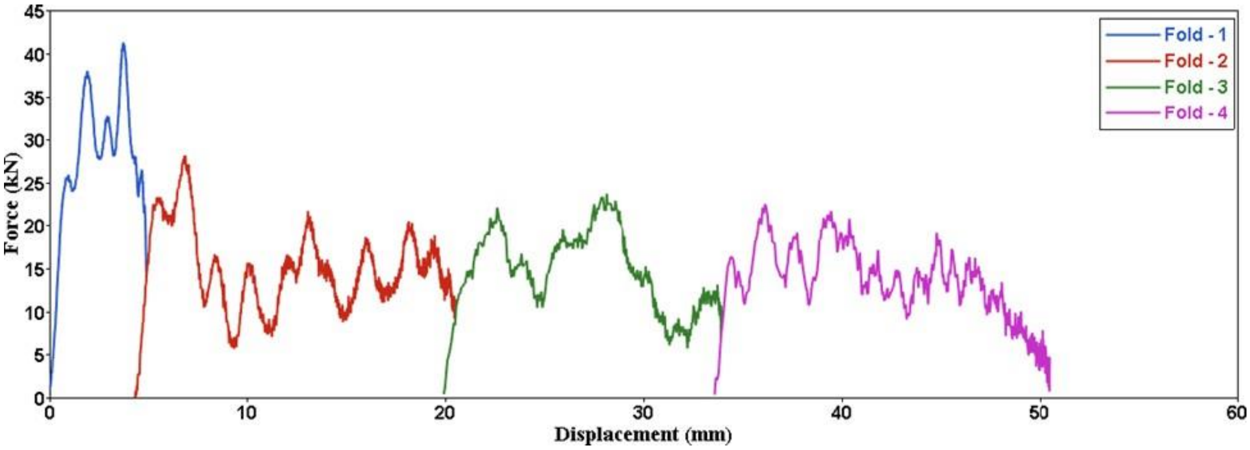

Figure 9 Load-displacement response under dynamic load for an annealed tube for intermittently annealed conditions

Figure 9a Intermittently annealed tube under dynamic interrupted load

Table 6 Dynamic test results for intermittently annealed specimen

Fold	Energy (J)	Displacement (mm)	Drop height (m)	Velocity (m/s)
1	133.575	5.24	0.216	2.06
2	239.618	15.61	0.376	2.716
3	205.472	13.57	0.339	2.57
4	229.907	16.54	0.365	2.67
Total	**808.57**	**50.96**		

CONCLUSIONS

Buckling is geometry dependent phenomena. It was noticed that the mode changed from concertina to lobed when subjected to force that was both quasi-static and dynamic. There is a lack of comprehension regarding theprocess that leads to the transition from axisymmetric mode to lobed mode. Nevertheless, annealed tubes are where the transition has been seen most frequently noticed.

The load-displacement properties and deformation behavior of the tubes do not appear to be affected by repeated loading and unloading of the tubes.

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