BUCKLING OF AXIALLY COMPRESSED IMPERFECT STEEL CONES WITH LOCAL DENTS

O. IFAYEFUNMI[1*], F. M. MAHIDAN[2] & N. ABU BAKAR[3]

[1,3]*Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia*

[2]*Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia*

ABSTRACT

This paper presents the comparison of the influence of single and multiple local dents on the load carrying capacity of steel conical shell subjected to axial compression. Cones were assumed to be made from 0.5 mm mild steel with geometric parameters characterized by: $r_1/t = 50$, $r_2/r_1 = 2.0$, $L/r_2 = 2.24$, $\beta = 12.6°$. Result of fourteen test specimens having local dents ranging from 0 to 2 and indent depth of 0.56, 1.12 and 1.68 is presented in the paper with the accompanying numerical results. The results confirm the strong influence of local dents on the buckling load of axial compressed cones. It is clear that increasing the indent depth results in reduction of the cone strength i.e., the larger the imperfection amplitude, the larger the reduction the buckling load of the cone. Furthermore, it can be seen that cone with multiple dents are more sensitive to imperfection as compared to cone with single dents. Lastly, it can be seen that in most cases, for cone having thinness ratio of 50, two local dents on the mid-surface is enough to produce the largest reduction in the load carrying capacity of the shell as evident for imperfection amplitude A = 0.56 and 1.68. However, as the thinness ratio increase (i.e., $r_1/t = 250$), the greatest reduction in the buckling load of the cone is produced by the highest number of local dents.

KEYWORDS: Axial compression, Buckling, Imperfection sensitivity, Single/multiple load indentation & Steel cone

Original Article

1. INTRODUCTION

Thin-walled conical shells are primary structures used in many engineering applications. When in use, they are often subjected to various types of loading such as axial compression, external pressure, internal pressure or combination of loads. It is a general belief that presence of imperfection can considerably reduce the load carrying capacity of such structures when in use. Imperfections created by indentation such as Single Load Indentation (SLI) or Multiple Load Indentation (MLI) – often referred to as Single Perturbation Load Analysis (SPLA) or Multiple Perturbation Load Analysis (MPLA) is one of the most commonly encountered imperfection type in practice. Comprehensive review of the past researches on sensitivity of conical shells to various types of imperfections can be found in [1 - 2].

The single load indentation imperfection method was originally proposed by Hühne et al. [3] for composite cylindrical shells under axial compression. In the single load indentation imperfection approach, an initial geometric imperfection in the form of dent is produced on the model's surface at the meridional mid-length via single lateral concentrated load prior to axial compression loading thereby resulting in a dent which initiate the buckling process of the shell structures during axial compression [4 – 5]. Ever since the introduction of this approach, several numerical investigations on imperfect cylindrical shell using the single load indentation imperfection approach has

been conducted [6 – 9]. Furthermore, Refs [10, 11] presents the numerical investigations into the buckling behavior of axially compressed cylindrical shells using the multiple load indentation approach. Whilst, [10] is devoted to composite cylinder, Ref. [11] on the other hand, covers aluminium alloy cylindrical shells. In Ref. [12], study on the effect of local dent imperfection on the elastic buckling of axially compressed unstiffened aluminum conical shells was presented. References on the use of the single load indentation imperfection method for conical shells structures can be found in [5], and [13 – 15]. While Ref. [13] is devoted to theoretical studies, Ref. [5, 14, 15] on the other hand, concentrate on numerical studies.

Although the local dent imperfection (i.e., SLI and MLI) approach is gaining more popularity, it is surprising to note that there is no available experimental data on buckling behavior of relatively thick steel conical shells with dimple imperfection subjected to axial compression prior to this time. The current paper presents the buckling behavior of axially compressed imperfect steel cones having local dent imperfection using both experimental and numerical approach. A total of fourteen (14) laboratory scaled mild steel conical models collapsed under axial compression. This work complements the results presented in refs [16, 17].

2. MATERIAL AND METHOD

Fourteen conical models were manufactured by using the conventional rolling and welding process. Two models were assumed perfect shells, while the next six models were imperfect shells with a single local dent imperfection and the remaining six models were imperfect shells with multiple local dents. To ensure repeatability of experimental data, all the conical specimens were manufactured in pairs. The nominal geometric parameters of the shells were set to: $r_1/t = 50$, $r_2/r_1 = 2.0$, $L/r_2 = 2.24$, $\beta = 12.6°$ as shown in Figure 1.
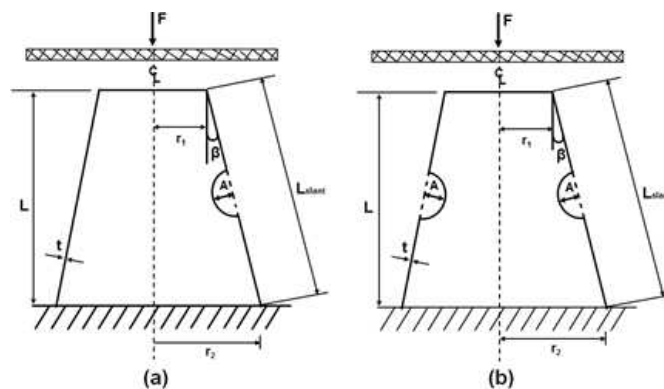
Figure 1: Geometry of the analyzed conical shell with (a) single local indentation and (b) multiple local indentations.

Cones were assumed to have a constant wall thickness, t, of 0.5 mm. Specimen were labelled sample 1 - 14. The material used to manufacture all model is JIS G 3141 mild steel. To manufacture the conical models, several manufacturing processes were employed. First, the steel plate was cut into desired dimension using a laser cutting machine. Next, the specimens were rolled into conical shape using a conventional slip-roll machine by manipulating the angle of one end of the machine to create the small radius of the cone. After that, Metal Inert Gas (MIG) welding was used to weld the seam of each rolled specimens. During the manufacturing process, local indents of different depth were introduced on the cones through a manual pressure from a conventional milling machine. For multiple local dents, the dimples are located at the mid-length of cone's meridional surface and uniformly spaced as shown in Figure 2b for typical imperfect cone with imperfection amplitude, A = 1.68.
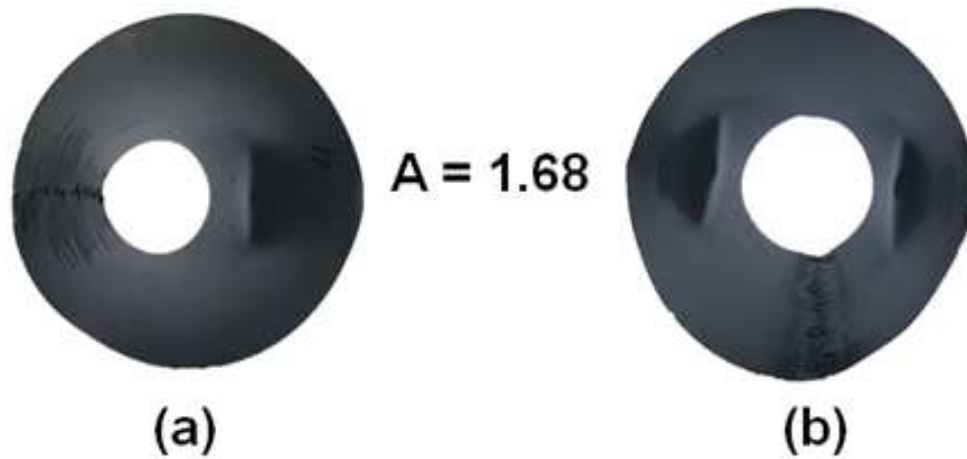
Figure 2: Typical photograph of imperfect cones with: (a) Single Local Indentation and (b) Multiple Local Indentations.

In addition, six tensile coupons (three in horizontal direction –H1, H2, H3 and three in vertical direction –V1, V2 and V3) were made according to the British standard (BS EN 10002-1, 2001) to obtain the specific properties of the material used for manufacturing the conical shells. The materials of these tensile coupons and the conical shell models were the same as they were cut from the same plate. The coupons were tested at the rate of 1mm/min until failure using INSTRON testing machine. The average material properties obtained were as follows: Young's modulus E = 166.228 GPa, Poisson's ratio ν = 0.3, and the yield stress based on 0.2% offset, σ_{yp} = 194.6 MPa. All the conical models were subjected to axial collapse test via INSTRON universal testing machine at the rate of 1mm/min. During compression test, top and bottom plate were used to cover the small and big radius ends of the cone respectively (see refs [16, 17] for more details about the manufacturing techniques and the material testing via uni-axial tensile test). The specimens and the tensile coupon were not stress relieved at any stage of their manufacture.

3. RESULTS AND DISCUSSIONS

Prior to testing, several measurements such as wall thickness, diameter, axial length and slant length of all the specimens were taken to investigate the manufacturing-caused imperfection. The minimum thickness, t_{min}, average thickness, t_{avg}, maximum thickness, t_{max}, and standard deviation, t_{std}, are provided in Table 1.

Table 1:Experimental collapse load for all tested cones with the corresponding measured dimple amplitude and wall thicknesses. Note: Exptl ≡ experimental, and Num ≡ Numerical

Sample number	N	Dimple amplitude (mm)		t (mm)			t_{std}	Collapse load (kN) Exptl (Num)
		Nominal	Measured	t_{min}	t_{max}	t_{ave}		
1	0	0	0	0.48	0.49	0.482	0.00398	14.67 (15.25)
2	0	0	0	0.48	0.50	0.484	0.00568	15.15 (15.35)
3	1	0.56	0.74	0.47	0.50	0.483	0.00632	15.62 (15.08)
4	1	0.56	0.63	0.48	0.50	0.483	0.00493	16.73 (15.15)
5	1	1.12	1.22	0.48	0.50	0.484	0.00516	15.91 (15.00)
6	1	1.12	1.16	0.47	0.50	0.484	0.00657	14.14 (15.02)
7	1	1.68	1.62	0.47	0.50	0.481	0.00526	14.75 (14.80)
8	1	1.68	1.64	0.47	0.49	0.482	0.00462	14.87 (14.73)

9	2	0.56	0.86	0.48	0.50	0.490	0.00482	14.39 (15.32)
			0.62					
10	2	0.56	0.81	0.47	0.50	0.483	0.00572	16.52 (15.12)
			0.61					
11	2	1.12	1.29	0.47	0.50	0.487	0.00538	15.45 (14.95)
			1.37					
12	2	1.12	1.30	0.47	0.50	0.481	0.00511	15.58 (14.75)
			1.40					
13	2	1.68	1.72	0.48	0.50	0.489	0.00536	13.07 (14.74)
			1.65					
14	2	1.68	1.70	0.48	0.50	0.488	0.00546	13.05 (14.97)
			1.65					

In addition, the magnitude of collapse load for all the tested conical specimens is given in column 9 of Table 1. From Table 1, it can be seen that there is a good repeatability of experimental data. The percentage errors within each pairs are 3%, (7%, 11%, 1%), and (13%, 1%, 0%) for perfect cone, imperfect cone with single dimple (A = 0.56, 1.12, 1.68), and imperfect cone with multiple dimple (A = 0.56, 1.12, 1.68) respectively. The smallest error recorded for samples (13 and 14), can be attributed to the small deviation of the wall thickness between the samples as provided in column 8 of Table 1. Again, it is apparent from Table 1, that samples (13 and 14) with very close measured dimple data produce almost the same result of collapse load. Hence, more attention should be devoted to the manufacturing process.

Figure 3 presents the plot of comparison of average collapse load against imperfection amplitude for cones with single and multiple dimple. From Figure 3, it can be seen that for axially compressed conical shells with local indentation, as the magnitude of the indent increases, it results in a decrease in the load carrying capacity of the shell. Again, it is apparent that cones with multiple dents are more sensitive to imperfection as compared to cones with single dent. As an example, for cone with indent depth of 0.56, average buckling load as a result of single and multiple dents are 16.18 kN and 15.46 kN, respectively. Resulting in reduction percentage difference of about 4.5% between the single and multiple dents. Whereas, for cone with indent depth of 1.68, a larger reduction in average buckling load was experienced for both single and multiple dents (i.e., 14.81 kN for single dent and 13.06 kN for multiple dents). However, it is not clear if this multiple dent (2 dents) will produce the worst multiple dimple imperfection. Further experiments with higher multiple dimples will be advisable in the future. It is worth mentioning that for the case of A = 1.12, multiple dents produce a higher value as compared to single dents, this can be said to be as a result of deviation of the imperfection amplitude. From column 4 of Table 1, the percentage difference between the measured imperfection amplitude for single and multiple dents is higher for A = 1.12, as compared to other imperfection amplitude. Hence a need for further numerical analysis.
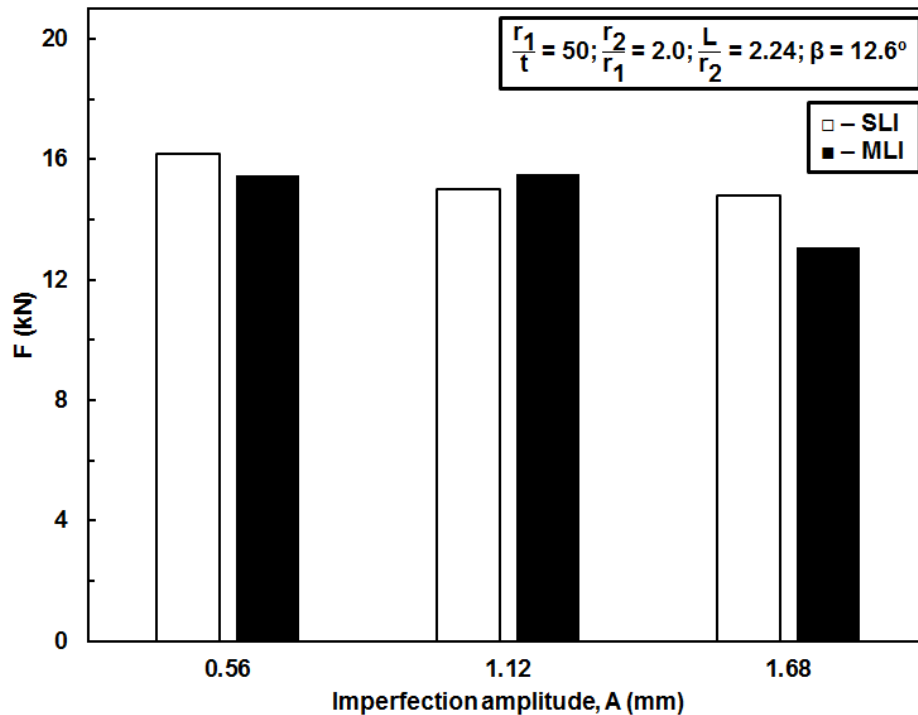
Figure 3: Comparison of average collapse load against imperfection amplitude for cones with single multiple local indentations.

Subsequently, numerical analysis was carried out using ABAQUS finite element code to validate the assumption that multiple dents are more sensitive than single dent. In the numerical modelling, four noded shell element were used and average material data obtained from experiment (see section 2 - material and method) were adapted. The dents were located at the mid-section of the cone meridional length, and for multiple dent, they are equally spaced across the circumference of the cone. Elastic-perfectly plastic material modelling behaviour was used in the numerical modelling. First, numerical calculations were carried out to benchmark the experimental data. Here, the average measured data given in columns 4 and 7 of Table 1 were used. The corresponding numerical results are presented in parenthesis in column 9 of Table 1. It can be observed that there is a good comparison with percentage difference between experimental and numerical predictions within ±10%, except for sample 13 and 14 with multiple dent amplitude of 1.68, where the percentage difference was 11% and 13% respectively. Generally, it can be said that cone with single dent produce a better comparison between experimental data and numerical prediction (ranging from -6% to 10%) as compared to cone with multiple dents (ranging from -13% to 9%).

Next, it was decided to implement the nominal geometry parameter of the cone in the numerical analysis. The imperfection amplitude considered here ranges from 0.56 to 1.68 and the radius-to-thickness ratio, r_1/t are 50 and 250. Figures 4 and 5 depict the comparison of buckling load for cone with single dent and multiple dents using nominal thickness and imperfection amplitudehaving radius-to-thickness ratio, r_1/t = 50 and 250, respectively. Again, it can be seen that as the indentation amplitude increases, there is a reduction in the buckling load of the cones and also, it is apparent that cone with multiple dents (2 dents) is more sensitive as compared to cone with single dent (1 dent) for all the imperfection amplitude considered i.e., $0.56 \leq A \leq 1.68$. This result validates the experimental data previously discussed and also clarify the disparity experiences in experimental results for A = 1.12 as seen in Figure 3. It is worthy of note that the influence of number of local dents is more pronounced as the cone thinness ratio (r_1/t) increases (see Figures 4 and 5).
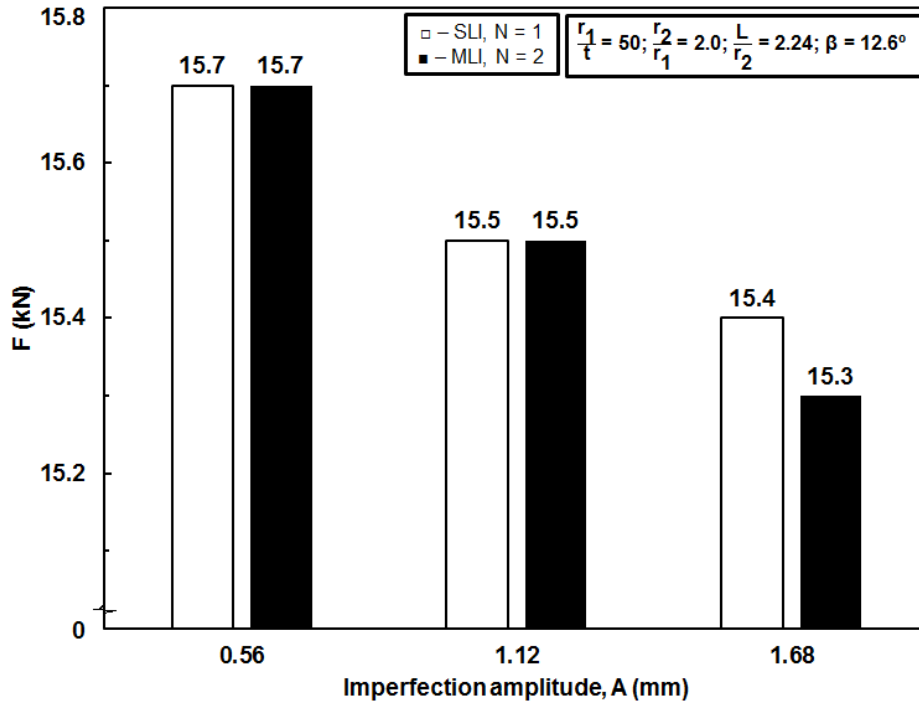
Figure 4: Comparison of buckling load for cone with single dent and multiple dents using nominal thickness and imperfection amplitude having radius-to-thickness ratio, r_1/t = 50.
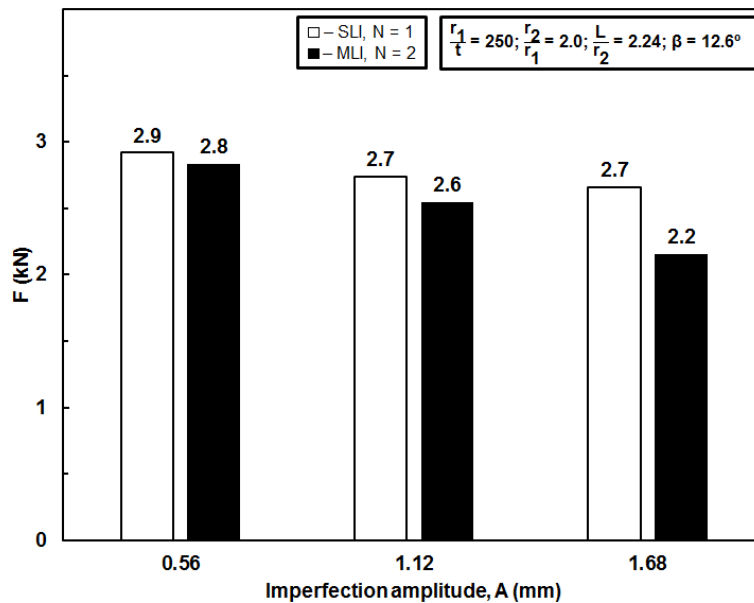

Figure 5: Comparison of Buckling Load for cone with single dent and multiple dents using Nominal Thickness and imperfection Amplitude having radius-to-thickness ratio, r_1/t = 250.

Lastly, to verify the worst multiple load indentation for the conical shells, further numerical calculations were carried out on cones having dent of 1, 2, 4, and 8. Again, indent depth was within the range $0.56 \leq A \leq 1.68$ and the thinness ratio (r_1/t) covers are 50 and 250. Figure 6 presents the plot of buckling load for cone with different number of dents having imperfection amplitude of 0.56 to 1.68 and thinness ratio of 50. The same trends of behaviour as previously discussed were observed. That is, increasing indent depth produces a larger reduction in buckling load of the structures, and also cones with multiple indents are more sensitive to imperfection as compared to its counterpart with single indent.

This is consistent with the result of [10] for composite cylinders, [11] for aluminium alloy cylinders and [14] for composite cones. Surprisingly, more frequently, from Figure 6, cone with two dents is enough to cause the greatest reduction in buckling load as evident in A = 0.56 and 1.68. This appear to be true only for relatively thick cone with small thinness ratio. Moreover, as the thinness ratio increases from 50 to 250, cone with eight indent are more sensitive to imperfection as evident in Figure 7. It can be said that for thinner cones, the highest number of dents will cause the maximum reduction in the load carrying capacity of the conical structures. This submission is somewhat in agreement with the suggestion by [14], where models with six indent (i.e., maximum number of indent) were said to produce the worst result thereby producing the worst multiple load indentation for axially compressed stiffened composite conical shells.
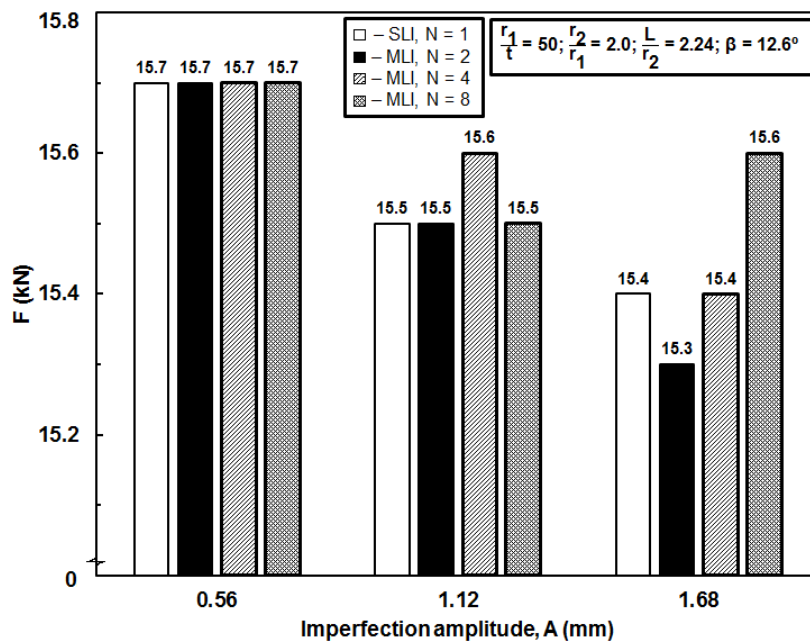

Figure 6: Plot of Buckling Load for different number of dents having imperfection amplitude of 0.28 to 1.68 having radius-to-thickness ratio, $r_1/t = 50$.
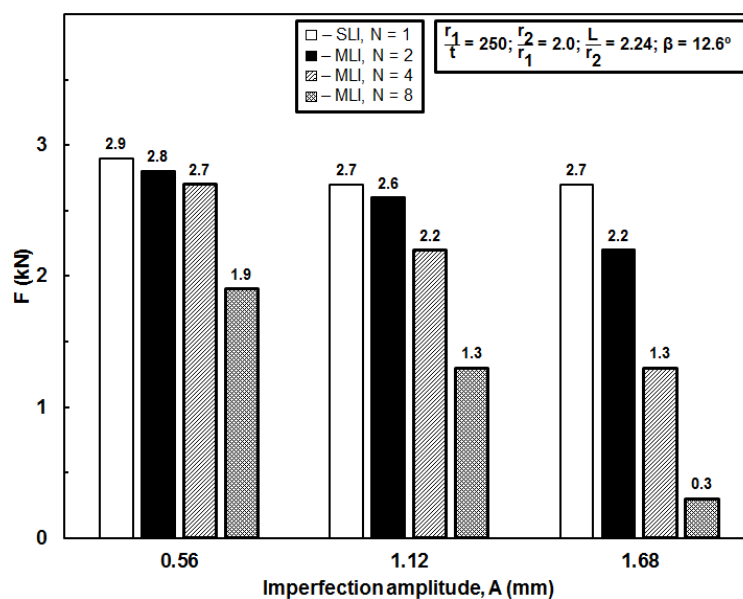

Figure 7: Plot of buckling load for different number of dents having imperfection amplitude of 0.28 to 1.68 having radius-to-thickness ratio, $r_1/t = 250$.

4. CONCLUSIONS

First experimental data of axial collapse test on fourteen steel conical samples with dimple imperfection is presented in this paper. From the foregoing results, the following conclusions can be drawn:

- repeatability of experimental collapse load for seven nominally identical conical pairs was good. The errors within each pair were: 3% (1 and 2), 7% (3 and 4), 11% (5 and 6), 1% (7 and 8), 13% (9 and 10), 1% (11 and 12), and 0% (13 and 14). However, the goodness of the repeatability of the result was seen to be strongly dependent on the accuracy of cone geometry (such as wall thickness) and the precision of the dimple amplitude.

- the presence of dimple imperfection results in the reduction of the load carrying capacity of the axially compressed steel conical shells.

- axially compressed steel conical shells with multiple perturbation load (MPLA) imperfection is seen to produce a more conservation lower bound curve as compared to the same cones with single perturbation load (SPLA) imperfection.

5. ACKNOWLEDGEMENT

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AUTHOR'S PROFILE

Olawale Ifayefunmi received his MSc (Eng) in Advanced Manufacturing Systems and Technology in 2006 and PhD in Mechanical Engineering in 2011 from The University of Liverpool, United Kingdom. He worked as Research Associate for six months in 2012 and as Honorary Research Fellow for two months in 2013 at The University of Liverpool. He was appointed Senior Lecturer at Faculty of Mechanical and Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka in 2013. Whilst in the UK, he has developed unique expertise in experimental and computational mechanics. Initially he has worked on combined stability of conical shells – the theme directly relevant to offshore/underwater, petrochemical and energy industries. He then briefly moved to bioengineering field, and more recently he has expanded his expertise to burst failures of pressure vessels components. He has published more than 30 papers in reviewed scientific journal and proceedings. His research interest includes buckling of shells, structural integrity

of pressure vessels components, imperfection sensitivity of shell components.

Fairuz Mardhiah Mahidan received her Bachelor in Engineering Technology degree in Automotive Technology from Universiti Teknikal Malaysia Melaka (UTeM) in 2019. She currently is a first year post graduate student of Masters in Engineering (Mechanical) at Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM). Her research interest includes buckling of shells and imperfection sensitivity of shell components. He has published more than 5 papers in reviewed scientific journal and proceedings.

Norinni Abu Bakar is studying for her Bachelor in Engineering Technology degree in Maintenance Technology from Universiti Teknikal Malaysia Melaka (UTeM). She is currently on industrial attachment. Her research interest includes buckling of shells and imperfection sensitivity of shell components.