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Instability of Conical Shells with Multiple Dimples under Axial Compression

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Abstract: Thin-walled conical shells are primary structures in offshore application. Presence of imperfection can considerably reduce the load carrying capacity of such structures when in use. This study examines the buckling behavior of axially compressed imperfect steel cones using the multiple perturbation load analysis (MPLA). This is both a numerical and experimental study. Eight conical shell test models were manufactured in pairs and collapsed under axial compression: two perfect, and the remaining six with MPLA imperfection amplitude, A, of 0.56, 1.12 and 1.68 having two equally-spaced dimples on each cones. Experimental test results for all the conical shell models and the accompanying numerical predictions are given in this paper. Repeatability of experimental data was good. The errors within each pair were 3%, 13%, 1% and 0%. In addition, there was a good comparison between experimental and numerical data. The ratio of experimental to numerical buckling loads varies from 0.91 to 1.13.

***Keywords**: Buckling, conical shells, axial compression, imperfection sensitivity, multiple dimples.*

I. INTRODUCTION

Presence of imperfection is believed to have significant influence on the buckling behavior of thin-walled structures such as conical shells. This can be mainly attributed to the detrimental consequence of stress concentration in the neighborhood of the imperfection, resulting in the localized buckling or plastic collapse of such structures. Thereby, reducing the load carrying capability of the structural components. Hence, a need to better understand the effect of imperfection on thin-walled structures. This is not a new problem; several work has been carried out over the years of different types of imperfection. Review of past researches on imperfection sensitivity of conical shells can be found in [1, 2]. This paper will focus on the influence of multiple dimple imperfection on the buckling behavior of cones subjected to axial compression.

Since, the advent of the single perturbation load approach (SPLA) by [3] in 2008 for composite cylindrical shells under axial compression, there have been growing interest in the use of this imperfection approach to estimate the imperfection sensitivity of thin-walled structures (i.e., cylindrical and conical shells) under axial compression. This is because, the simple perturbation load analysis (SPLA) imperfection is seen as one of the most realistic types of imperfection commonly observed in shell structures. In the SPLA imperfection approach, an initial geometric imperfection via single lateral load is introduced to typical model's surface prior to axial compression loading. Dimple will be produced (mostly at the middle section) as an effect from the lateral load application. Buckling process will initiate at this localized dimple [4, 5].

Several research work have been carried out on imperfection sensitivity of cylindrical shell structures using the SPLA imperfection approach [6] – [10]. In 2013, three independent research work by [6], [7], and [9], presented numerical investigations into the behavior of imperfection sensitive unstiffened composite cylindrical shells subjected to axial compressive loads using ABAQUS finite element software. The SPLA imperfection method was used to characterize the buckling behavior of the composite cylindrical shells. The SPLA imperfection approach was extended for axially loaded composite cylindrical shells by [10]. In [10], the single boundary perturbation approach (SBPA) was used to perform a comprehensive numerical study on the influence of length on the buckling load of composite cylindrical shells subjected to axial compression. Unlike the SPLA approach, the SBPA on the other hand induced a single dimple at the top of the shell by means of a boundary perturbation under axial compression which causes an additional small bending moment. Comparison between experimental and numerical predictions on the buckling of axially compressed, unstiffened composite cylinders with the additional of lateral load was presented in [8]. Results from all investigations except [9], were compared with knockdown factor prediction (KDF) by NASA SP-8007 guideline [11]. It is found that the KDF prediction by NASA SP-8007 is more conservative as compared to the SPLA and SBPA imperfection approach. Furthermore, [6] benchmarked its results with the statistical knock-down factors calculated by [12]. Again, it is found that SPLA gives less conservative results than [12] 99% probability KDF. However, is the single perturbation load enough to represent the worst geometrical imperfection case or can the SPLA provide a conservative enough results to use as a design guideline?

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To answer this question, there is a need to consider influence of multiple perturbation load approach (MPLA) on the buckling behavior of such structures. Numerical investigations into

the buckling behaviour of cylindrical shells with multiple perturbation load approach (MPLA) can be found in [13, 14]. Whilst, [13] is devoted to axially compressed composite cylinder with multiple perturbation imperfection, [14] was devoted to the aluminium alloy cylindrical shells with multiple perturbation imperfection subjected to axial compression. Results indicates that the cylindrical shells with MPLA imperfection are more sensitive as compared to cylinders with SPLA imperfection when subjected to axial compression.

Early study on the effect of dimple imperfection on the elastic buckling of axially compressed unstiffened aluminum conical shells was presented by [15]. References on the use of the SPLA imperfection method for conical shells structures can be found in [5], and [16] – [18]. Ref. [16] present a semi-analytical study using Ritz method on the non-linear behavior of unstiffened composite cylinders and cones considering initial geometric imperfections and various loads and boundary conditions. A constant perturbation load is applied to the middle of the cone. The kinematic equations for the model were derived using the Classical Laminated Plate Theory (CLPT) and the Donnell-type of non-linear equations. The latter was used to solve the full displacement field for axial compression using a modified Newton-Raphson algorithm. Ref. [5] present numerical studies on the effect of different geometry, lamina and layup of axially compressed unstiffened composite conical shells using a Single Perturbation Load Analysis. From the implemented study it could be concluded that the KDF values obtained using SPLA is less conservative than the NASA KDF. Ref. [18] analyzed numerically the effect of the SPLA imperfection on the load carrying capacity of steel conical shells under axial loading having various shell thickness and semi-vertex angles. It is found that with increasing semi-vertex angle, the sensitivity of the structures to imperfection also reduces. In [19], the Single Boundary Perturbation Approach (SBPA) was used to investigate the buckling behavior of composite conical shells under axial compression. The boundary perturbation is applied at the axially compressed edge of the cone. The parameter which determines the amplitude of the single dimple within the framework of the SBPA is the boundary perturbation height. Reference into the buckling of imperfect cones with multiple perturbation load imperfection can be found in [17]. Ref. [17] presented numerical investigation on the influence of dimple-shape imperfections on the load-carrying capacity of axially compressed stiffened composite conical shells. Several perturbation load approaches are used which are SPLA and MPLA. Since the stiffness of stiffened conical shells varies along axial direction, SPLA was used to examine the effect of axial location of dimple on axially compressed stiffened conical shells. In general, the knockdown effect of the position near the lower end of cone is found to be greater than that near the upper end of cone. It is also noticed that with the increase of perturbation load, the discrepancy of imperfection amplitudes for different positions becomes remarkable. Furthermore, [17] employed the Worst Multiple Perturbation Load Approach (WMPLA) which is an improvement of the MPLA using an optimization algorithm to find the worst dimple location. The WMPLA is used to find the lower bound of the collapse load of axially compressed stiffened conical shells, and also provides the knowledge to determine the number of dimples in the MPLA. The MPLA imperfection is applied by assuming equally spaced perturbation loads along circumferential direction, and located at the mid-length along axial direction. From the numerical investigations, models with 6 perturbation loads were seen to produce the worst result thereby producing the WMPLA. Although, this is slightly different for the WMPLA of 4 perturbation load presented for cylinder in [13].

It appears that there has been only limited research into the buckling of cones with multiple dimple imperfections. In fact, to the authors' amazement, there is no experimental data on buckling behavior of conical shells with multiple perturbation load subjected to axial compression. Hence, there is still a large gap of knowledge that must be explored which brought about the production of this paper. The current paper seeks to examine the effect of MPLA imperfection dimple amplitude on the buckling behavior of axially compressed mild steel conical shells. This is both numerical and experimental study. First, details of experimental test results on eight conical models (two perfect and six imperfects with two dimples imperfection amplitude of 0.56, 1.12 and 1.68) manufactured in pairs and its accompanying numerical results were presented. Then, experimental results were benchmarked with numerical prediction using ABAQUS FE code [20].

II. METHODOLOGY

A. Method and Material

Eight conical models were manufactured by using the conventional rolling and welding process. Two models were assumed perfect shells, while the remaining six models were imperfect shells with multiple (2) dimple imperfections. To ensure repeatability of experimental data, all the conical specimens were manufactured in pairs. Fig. 1 depicts the geometry of conical shell with two opposite dimple imperfections having cone small radius, r_1, cone big radius, r_2, cone axial length, L, cone slant length, L_{slant}, cone angle, β, constant wall thickness, t, and dimple amplitude, A. The model is subjected to axial force, F and perturbation load, PL. The nominal geometric parameters of the shells were set to: $r_1/t = 50$, $r_2/r_1 = 2.0$, $L/r_2 = 2.24$, $\beta = 12.6°$. Cones were assumed to have a constant wall thickness, t, of 0.5 mm. Specimen were labelled as CM1 - CM8. CM1 and CM2 were perfect cones, CM3 and CM4 were imperfect cones with 0.56 mm dimple imperfections, CM5 and CM6 were imperfect cones with 1.12 mm dimple imperfections, while CM7 and CM8 were imperfect cones with 1.68 mm dimple imperfections.

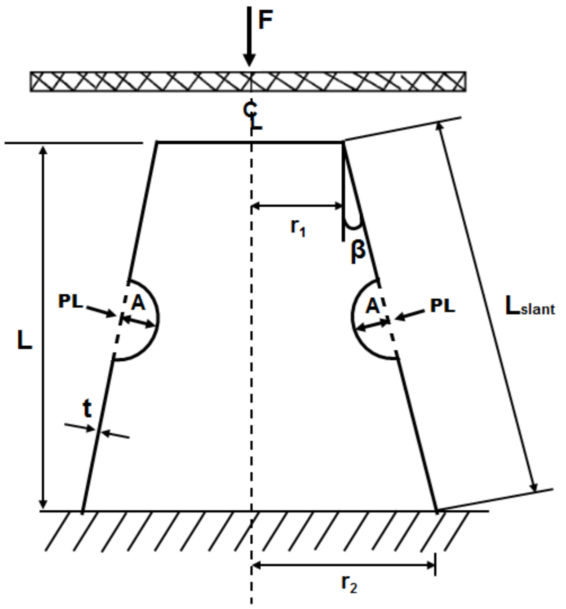

Fig. 1.Geometry of the analyzed cone with multiple perturbation load imperfection.

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. More detailed discussion of the manufacturing processes can be found in [21]. During the manufacturing process, dimple imperfections of different amplitude were introduced on the cones through a manual pressure from a conventional milling machine. The dimples are located at the mid-length of cone's meridional surface and uniformly spaced. Fig. 2 shows typical samples for perfect and imperfect cones with imperfection amplitude, A, 0.56 mm, 1.12 mm and 1.68 mm after manufacturing. To better illustrate multiple number of dimples on the conical shells, Fig. 3 depicts the (a) front view and (b) side view of a typical cone with imperfection amplitude, A = 1.68.

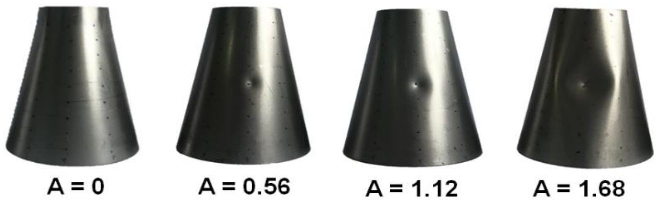

Fig. 2.Typical photograph of conical specimens with different dimple amplitude.

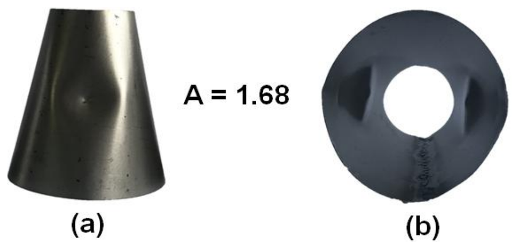

Fig. 3.Typical photograph of conical specimens having two dimples (a) front view, and (b) side view.

The material used to manufacture all model is JIS G 3141 mild steel. To obtain the specific properties of the material used for manufacturing the conical shells, 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 [22]. 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. This data will be used for numerical analysis latter in this paper.

B. Specimen Measurement

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. First, micrometer screw gauge, with accuracy of 0.01 mm, was used to measure the thickness of eight samples to verify the accuracy of the geometries of the fabricated conical shells. The specific measurement method was as follows: eleven points along the circumferential direction of the cones were measured, along with eleven points along the slant length direction; each conical shell had a total of 121 measuring points. The minimum thickness, t_{min}, average thickness, t_{avg}, maximum thickness, t_{max}, and standard deviation, t_{std}, are provided in Table 1. It is evident from Table 1, that model CM4 has the largest thickness deviation, while model CM1 has the lowest deviation from the nominal thickness value. Next, Vernier caliper was used to measure the inner and outer diameter of both top and bottom ends of each of the manufactured conical shells. Five diameter spaced at equal interval were used as measuring points. The average measured mid-surface diameter for all of the conical models are listed in Table 2. Then, the axial height of the manufactured cones was measured using a digital height gauge while Vernier caliper was used to measure the cones slant length. The average measured axial height and slant height for all of the conical models can be found in column 6 and 7 in Table 2. Lastly, Vernier caliper was used to measure the dimple magnitude for all the tested cones as given in Table 3. It must be mentioned here, that because of the method of introducing the dimple, it was relatively difficult to obtain the same dimple amplitude required on both sides of the cones. Hence, a need for better way of introducing the dimple in the future.

Table- I: Measured wall thickness of tested cones

Model	N	A	t_{min}	t_{max}	t_{ave}	t_{std}
			(mm)			
M1	0	0	0.480	0.490	0.482	0.00400
M2	0	0	0.480	0.500	0.484	0.00568
M3	2	0.56	0.480	0.500	0.490	0.00485
M4	2	0.56	0.470	0.500	0.483	0.00575
M5	2	1.12	0.470	0.500	0.487	0.00541
M6	2	1.12	0.470	0.500	0.481	0.00514
M7	2	1.68	0.480	0.500	0.489	0.00539
M8	2	1.68	0.480	0.500	0.488	0.00549

Table- II: Measured mid-surface diameters at small and big ends and average lengths of tested cones

Model	N	A	$2r_1$	$2r_2$	L	L_{slant}
			(mm)			
M1	0	0	50.430	99.399	111.992	114.630
M2	0	0	52.655	98.918	112.507	114.911
M3	2	0.56	50.379	99.068	112.079	114.677
M4	2	0.56	50.166	99.101	112.127	114.626
M5	2	1.12	51.168	98.921	112.113	114.718
M6	2	1.12	50.599	98.189	112.075	114.566
M7	2	1.68	50.650	99.178	112.389	114.672
M8	2	1.68	50.034	99.901	112.100	114.697

C. Axial Collapse Test

After the pre-test measurement, compression test was conducted on the eight samples to obtain their maximum load carrying capacity and investigate their buckling behavior. INSTRON universal testing machine was used to apply axial compression on all of the specimens. The axial testing is carried out at a rate of 1mm/min, which is the same as the rate of loading used for the material testing. A top and bottom plate were used to cover the small and big radius ends of the cone respectively as exemplified in Fig. 4 for (a) perfect cone and (b) cone with two dimples having imperfection amplitude, A of 1.68. The covering plates is to help provide the necessary boundary conditions at both ends. The axial compressive load and the corresponding axial shortening of the conical models are recorded by machine controller during the experiment.

Fig. 4.Experimental setup for conical shells with different imperfection amplitude, A = 1.68.

III. RESULT AND DISCUSSION

Experimental results from the testing and its accompanying numerical predictions for all the conical models is discussed in this section. Fig. 5 presents the plot of average load against imperfection amplitude for all the tested conical specimens. The corresponding magnitude of buckling load for each specimen is given in column 5 of Table 3. From Fig. 5, it can be seen that there is a good repeatability of experimental data. The percentage errors within each pairs are 3%, 13%, 1% and 0% for A = 0, 0.56, 1.12 and 1.68, respectively. The small error recorded for models CM7 and CM8, can be attributed to the small deviation of the wall thickness between the samples as provided in Table 1. Although, there is large discrepancies observed for cones with imperfection amplitude, A = 0.56, the reason for this is not entirely clear. The combination of thickness and dimple amplitude deviation from the nominal value could be responsible. Fig. 6 presents a typical plot of experimental load versus axial shortening for perfect cones (model CM1) and imperfect cones with two dimples having amplitude of A = 1.68 (model CM8). It can be seen from Fig. 6, that both curve follow the same pattern. The curve is linear up to collapse and then a sudden drop in the load deflection curve at the post-collapse region.

However, for the imperfect cone (CM8) with two dimples having imperfection amplitude, A, of 1.68, local instability (at about 11 kN) was observed prior to the global buckling (at about 13 kN) in the load deflection curve. This phenomenon was also observed by [5], where it was stated that this will occur within a certain range of perturbation load.

Table- III: Comparison of experimental and numerical collapse load of perfect and imperfect cones. N = number of dimple (Exptl ≡ experimental).

Model	N	Dimple amplitude (mm)		Collapse load (kN)		Exptl /ABAQUS
		Nominal	Measured	Exptl	ABAQUS	
CM1	0	0	0	14.67	15.25	0.96
CM2	0	0	0	15.15	15.35	0.99
CM3	2	0.56	0.86	14.39	15.32	0.94
			0.62			
CM4	2	0.56	0.81	16.52	15.12	1.09
			0.61			
CM5	2	1.12	1.29	15.45	14.95	1.03
			1.37			
CM6	2	1.12	1.30	15.58	14.75	1.06
			1.40			
CM7	2	1.68	1.72	13.07	14.74	0.89
			1.65			
CM8	2	1.68	1.70	13.05	14.97	0.87
			1.65			

To validate the experimental results, numerical calculations have been carried out for both the perfect and imperfect cones with dimples imperfection. The models were generated using ABAQUS finite element code with 3D deformable body. Four noded shell elements with six degree of freedom (S4R) were employed in the numerical calculations. To mimic the experiment set-up, a rigid plate is assembled together with the conical models to represents the top platen of the INSTRON machine used in experimental testing. Two equally-spaced nodes located along the mid-circumference of the cone were selected to be the dimple application points where the perturbation load were applied. Surface-to-surface contact interaction between the top nodes of the small radius of the cone and the internal surface of the plate was created and is assumed to have a frictionless tangential behavior.

Static general method was used for dimple applications while nonlinear static Riks analysis was used to apply axial loading onto the reference point located in the middle of the horizontal plate. The bottom of the cone is assumed to be fixed and at the top of the cone, the same condition was applied except allowing movement in the axial direction. The buckling behavior, i.e., collapse load and deformed shape between experimental testing and numerical analysis is explored.

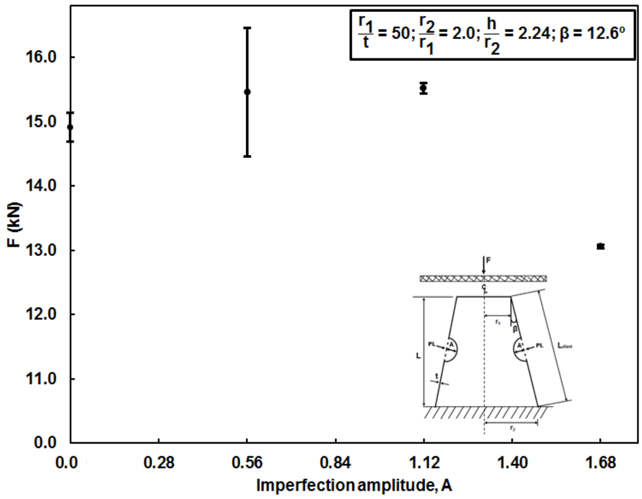

Fig. 5.Plot of average axial compression load against imperfection amplitude, A, for conical models with radius-to-thickness ratio, $r_1/t = 50$.

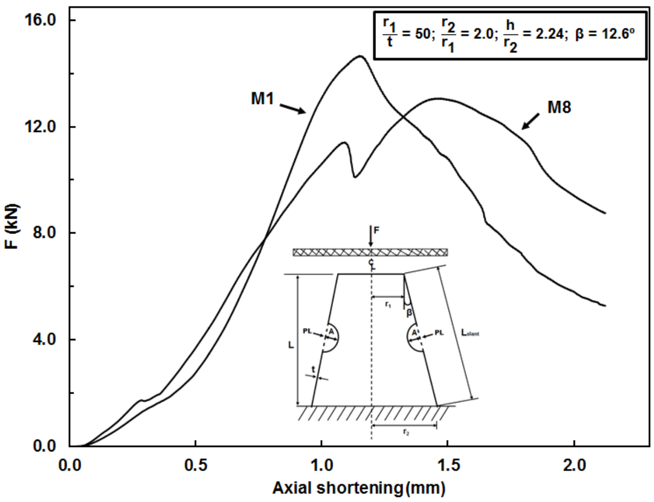

Fig. 6.Typical plot of experimental load versus axial shortening curve for perfect and imperfect cones.

Comparison between experimental results and numerical predictions are given in Table 3. The numerical predictions are satisfactory to their experimental collapse load. The ratio between experimental data and numerical results varied between 1% to 13%. Results demonstrate that, for the conical models, an introduction of two perturbation loads having dimple amplitude of 0.56 mm, will slightly increase the load carrying capacity of an axially compressed conical shell. However, it is obvious that as the magnitude of the dimple increases, the load carrying capacity decreases.

Further computations were carried out to explore the worst multiple perturbation load for conical models with imperfection amplitude, A, ranging from 0.28 to 1.68. The number of dimple on the cones was varied between 1 and 8. Table 4 gives the perturbation load required to produce the different dimple imperfection. It is clear that the perturbation load increases as the dimple magnitude is increased from 0.28 to 1.68. The collapse load for perfect and imperfect conical shells with different dimple magnitude having different number of dimples is summarized in Table 5. The number in bracket is the ratio of collapse load of imperfect cone to perfect cone, F/F_{coll}. From Table 5, results indicate that steel conical shells with multiple perturbation load (MPLA) imperfection are more sensitive as compared to cones with single perturbation load (SPLA) imperfection when subjected to axial compression. This is consistent with the result of [17] for composite cones, [13] for composite cylinders and [14] for aluminium alloy cylinders. Furthermore, in contrary to the suggestion by [17], where models with 6 perturbation loads were said to produce the worst result thereby producing the WMPLA for axially compressed stiffened composite conical shells, it can be seen that conical models with 2 multiple perturbation load (two dimples) gives the worst result thereby producing the worst multiple perturbation load (WMPLA) for all the dimple amplitude considered, except for A = 0.28, where 4 multiple perturbation load (four dimples) gives the worst result.

Table- IV: Perturbation loads applied on cones with corresponding dimple amplitude

Imperfection amplitude, A (mm)	0.28	0.56	1.12	1.68
Perturbation load, PL (kN)	0.519	0.541	0.75	0.835

Table- V: Collapse load (kN) of cones with t = 0.5 mm using MPLA approach

No of Dimple(s), N	Collapse load (kN) for different magnitude of dimple (mm)			
	0.28	0.56	1.12	1.68
0	15.8289 (1.0)	15.8289 (1.0)	15.8289 (1.0)	15.8289 (1.0)
1	15.786 (0.997)	15.7153 (0.993)	15.5423 (0.982)	15.4103 (0.974)
2	15.7765 (0.997)	15.7143 (0.993)	15.5358 (0.981)	15.338 (0.969)
4	15.7461 (0.995)	15.7227 (0.993)	15.5717 (0.984)	15.406 (0.973)
8	15.7555 (0.995)	15.7456 (0.995)	15.5125 (0.980)	15.6446 (0.988)

IV. CONCLUSION

Experimental and numerical axial compressive test results for eight conical samples with multiple perturbation load imperfection were presented in this paper. Repeatability of experimental results was good. It is proven that presence of imperfection (such as dimple) has significant influence on the load carrying capacity of the conical shells. From the foregoing results, the following conclusions can be drawn: (i) steel conical shells with multiple perturbation load (MPLA) imperfection subjected to axial compression is seen to produce a more conservation lower bound curve as compared to cones with single perturbation load (SPLA) imperfection when subjected to axial compression, and (ii) axially compressed conical models with 2 multiple perturbation load (two dimples) produce the worst result thereby producing the worst multiple perturbation load (WMPLA) for all the dimple amplitude considered, except for small dimple amplitude, A = 0.28, where four multiple dimples gives the worst result.

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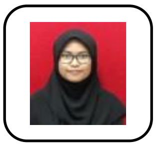

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