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Buckling and Post Buckling Investigation of Thin Walled Shells Contain Elliptical and Circular Cutout, Subjected to Oblique Loading

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ABSTRACT

In the presented work, the buckling and post buckling behavior of circular thin walled shells with different thickness contain elliptical cutout or circular cutout with various locations, was investigated through experimental and numerical studies. Finite element analysis using Abaqus software was conducted to evaluate the Buckling load capacity of the shells.Also experiments are conducted on several Specimens made of stainless steel 316ti by using an Instron 8802 servo-hydraulic machine. A very good correlation was observed between numerical simulation and experimental results. The investigation examined the influence of the shell thickness and cutout position on the buckling and post-buckling responses of the thin walled shells with circular and elliptical cutout. Also, effect of cutout shape on thin walled shells under these kinds of loadings has been studied.
KEYWORDS: elliptical cutout, circular cutout, buckling, experimental method, finite element model, oblique loading

1. INTRODUCTION

Thin walled cylindrical members, due to their specific structural and geometrical characteristics, are commonly utilized as load carrying components in various fields of engineering. The prediction of buckling behavior of these shells is obviously necessary and, fortunately, is possible and feasible through various experimental and numerical methods. Recently, among the latter approaches, the FEM method is considered to be a powerful tool for investigation of the final buckling load of thin-walled shells. However, to assure the authenticity of the obtained results through this method, it seems necessary that these results are validated with experimental data. Buckling of thin-walled shells with circular sections was the subject of a massive study using both numerical and experimental approaches during the last decades [1-3]. Many studies were done that covered a wide range of thin-walled tube applications, among which were numerical and experimental investigations of the effects of circular, square, and rectangular cutouts on the buckling tests of cylindrical shells subjected to axial, bending, andtwisting loads; design curves were obtained for various loading conditions. Jullien [3] studied the influence of circular, square, and rectangular cutouts on the buckling of cylindrical thin-walled shells under axial load and presented a parametric relationship between the shape and dimensions of the cutouts. also, the effect of location and number of cutouts was studied. Shariati and rokhi [4] studied numerically simulation and analysis of steel cylindrical shells with various diameter and length having an elliptical cutout, subjected to axial compression. They investigated examined the influence of the cutout size, cutout angle and the shell aspect ratios L/D and D/t on the pre-buckling, buckling, and post-buckling responses of the cylindrical shells. Han et al. [5] studied the effect of dimension and position of square-shaped cutouts in thin and moderately thick-walled cylindrical shells of various lengths by nonlinear numerical methods using the ANSYS software. They also compared their results with experimental studies on moderately thick-walled shells. Finally, they developed several parametric relationships based on the analytical and experimental results using the least squares regression method. Ben Young [6,7] investigated hollow columns made of aluminum alloy using numerical and experimental methods. In this research,a nonlinear finite elements model was used to predict failure loads and modes. Moreover, it indicated that theprinciples of the design presented in this research has predicted the final tension of aluminum columns whose two ends have and have not been welded with a satisfactory precision.Dimopoulos [8] studied the buckling behavior of cantilevered shells with opening and stiffening experimentally and numerically. He focuses on shell slenderness as well as opening and stiffening reflecting the main geometric characteristics of wind turbine towers. Shariati and Mahdizadeh [9] performed numerical study using Abaqus software to investigate the response of steel cylindrical shells with different lengths and diameters, including elliptical cutout subjected to bending moment. They presented some relations for finding of buckling moment of these structures. Haipeng Han et al. [10] studied the effect of dimension and position of square-shaped cutouts in thin and moderately thickwalled cylindrical shells of various lengths by nonlinear numerical methods using the ANSYS software. They also compared their results with experimental studies on moderately thick-walled shells.

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Some investigations regarding oblique loading of tubular members have been carried out even if studies in this area are limited.Rahimi and Poursaeidi [11] carried out plastic analysis of cylindrical shells with a circular hole under the effect of end pure moment.Kim and Wierzbicki [12] explored numerically the crush behavior of columns subjected to combined bending and compression, by prescribing both displacements and rotations at the upper end of a cantilever column. Previous studies by Reyes et al.vaziri andEstekanchi [13], using the FE approach, examined the elastic buckling load of cracked cylinders under the combined actionof internal pressure and axial compression. They conducted aparametric study, using linear Eigenvalue analyses, on crackedcylindrical shells, in order to estimate the effect of crack type,size and orientation on the buckling load.Han and Park [14] investigated numerically columns of mild steel impacted at a declined rigid wall with no friction. Different angles were tested, and the response was divided into axial collapse, bending collapse and a transition zone. An empirical expression for the critical angle was found.Studies by Reyes et al. [15] of thin-walled aluminum extrusions subjected to oblique loading showed that the energy absorption drops drastically by introducing a load angle of 5° compared to the axial crushing. This is due to the different collapse modes, as the progressive buckling of axial crushing is a much more energy-absorbing process than bending.

In this paper, buckling of steel thin-walled shells with a circular cutout has been studied numerically and experimentally.For numerical methods, the finite element method program Abaqus has been applied in section 4. The influence of the thickness for shells contain elliptical cutout and also shells contain circular cutout on buckling and post buckling of these shells has been studied in section 5. Furthermore, the effect of cutout location and cutouts shape on the load displacement behavior of specimens and buckling behavior of shells has been studied thoroughly within this report.In section 6 experiments are conducted on several Specimens made of stainless steel 316ti by using an INSTRON 8802 servo-hydraulic machine. The results obtained from numerical and experimental methods are compared with each other in section7. In all of the abovementioned articles, buckling load has been analyzed for one cutout. Some of the goals of this paper are compare effect of cutout shape and thickness of shells on buckling and post buckling of thin walled shells under oblique loadings.

2. Profile of specimens

The chosen profile for this study is made ofstainless steel 316ti whose mechanical properties werespecified through application of tensile test inaccordance with ASTM E8. For the tensile test,thespecimens were taken from the face of thecolumn specimen.The stress-strain curve obtainedthrough tensile test has been shown in Fig. 1.Based on the linear portion of stress–strain curve, the value of elasticity module was computed as E=187 GPa and the value of yield stress was obtained as σ_y=334MPa. Furthermore, the value of Poisson’s ratio was assumed to be ϑ=0.33.For more information about true stress–strain curve and plastic property refer to [16].

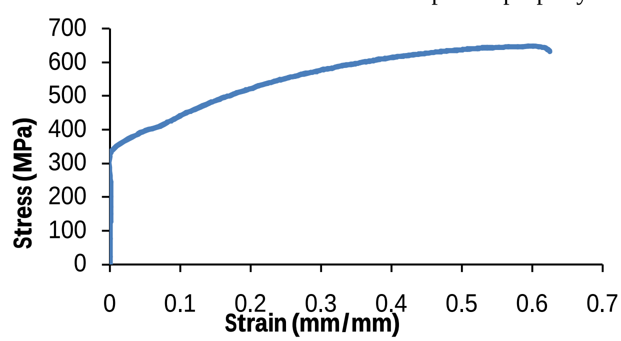

Fig.1: Stress–plastic strain curve

3. Geometry and labeling of samples

For this study, stainless steel 316ti thin-walled thin walled shells with various thicknesses t=1.00, 1.25 and 1.50 mm, and various cutouts were analyzed. An elliptical and circular geometry were selected for cutouts that were created in the specimens. Furthermore, the length of shells was L=250 mm and the diameter of shells was D=42 mm.

The geometry of specimens and the elliptical cutouts created on its, are illustrated in Fig. 2-a. As shown in Fig. 2-a, parameter a shows the size of cutout height, and parameter b shows the size of cut out width.Specimens with elliptical cutout were nominated as follows: D42-L250-CP125-a-b.Fig. 2-b, shows the geometry of the circular cutouts. According to this figure, parameter d shows the diameter of circular cutout. Specimens with circular cutout were nominated as follows: D42-L250-CP125-d.In both specimens name, the numbers following D and L show the diameter and length of the shell, respectively. And CP shows the distance between the center of the cutout and the lower edge of the shell.

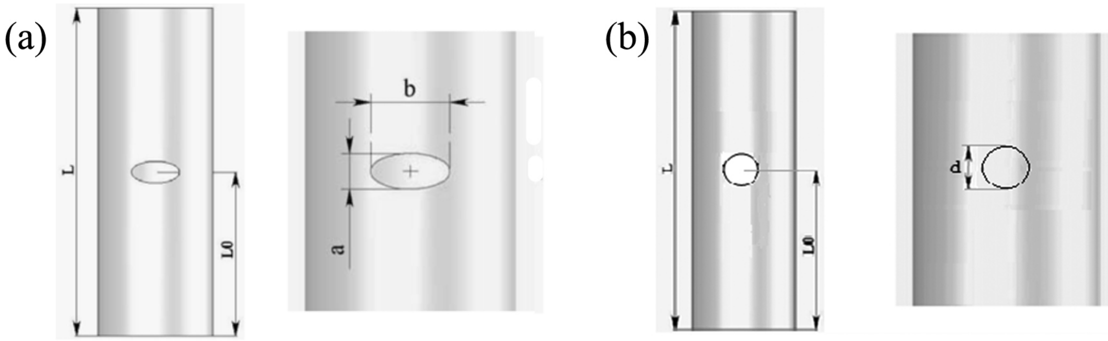

Fig.2: Geometry of (a) elliptical cutout and (b) circular cutout

4. Development of finite element model

For analyzing the buckling behavior of the steel shells program Abaqus has been applied. Elastic Modulus of the specimens which can be obtained from the linear part of Figure was 195MPa for all the specimens. The geometrical dimensions were chosen in accordance with the quantities measured in experimental tests. For this analysis, the nonlinear element S8R5, which is an eight-node element with six degrees of freedom per node, suitable for analysis of thin shells were used [17]. Part of a meshed specimen with elliptical cutout and specimen with elliptical cutout are shown in Fig. 3.

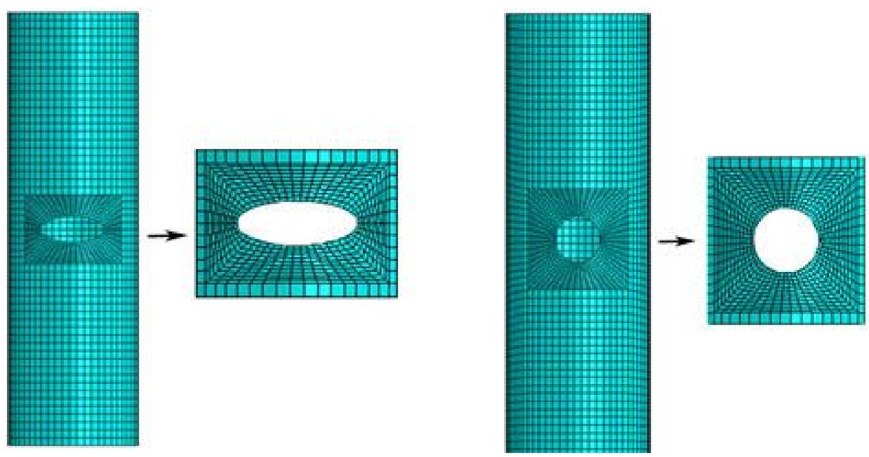

Fig. 3:Samples of FEM mesh for specimen with elliptical cutout and specimen with circular cutout.

In this study, the thin walled shells were considered as clamped. For applying boundary conditions on the edges of the thin walled shells, two rigid parts offixture were used that were attached to the ends of the shell.

In order to analyze the buckling subject to oblique loading similar to what was done in the experiments; a $20\ mm$ displacement was applied centrally to the center of the lower rigid base.

5. NUMERICAL ANALYSIS RESULTS

In this section, the results of the buckling analyses ofthin walled shells with elliptical and circular cutouts using the finite element method, arepresented. Three different shell thicknesseswere analyzed, (t=1.00, 1.25 and 1.50. Also Three different cutout positionwere analyzed(CP=L/2, L/3 and L/4).Fig. 4, shows how oblique loading was realized in the present study. The test specimen was clamped at the upper end, and the quasi-static force was applied through a rigid body at the lower end of the specimen.Load angle (γ) is fixed in this study.

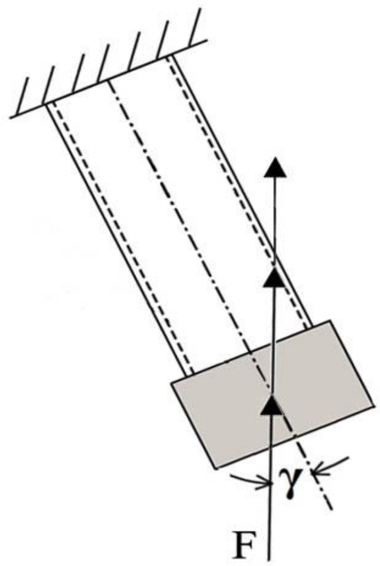

Fig. 4: Boundary and loading conditions.

5.1. The effects of shell thickness(t) on the buckling behavior of thin walled shells

To study the effect of a change in shell thickness on the buckling load of thin walled shells, chose shell with different thickness (t=1.00, 1.25 and 1.50 mm) and then create cutouts on specimen at the mid-height position of shells. Then, with changing the cutouts position in L/2,L/3 and L/4 of shell height, thechange in buckling load was studied.

5.1.1. Analysis of shells with elliptical cutout

In this section, created the elliptical cutout on specimens and then studied the effects of shell thickness (t) on the buckling behavior of thin walled shells. The results of thisanalysis are presented in table 1. Fig. 5 shows the load-displacement curvesresulting from the numerical analysis performed withAbaqus software for specimens withthickness t=1.00, 1.25 and 1.50 and contain elliptical cutout.

Table 1. Summary of numerical analysis for thin walled shells with different shell thickness contain elliptical cutout

Model designation	Shell thickness (mm)	Load angle, γ (degree)	Location of cutout (CP/L)	Buckling load (kN)
D42-L250-CP125-a18-b26	1	15	0.50	32.48
D42-L250-CP125-a18-b26	1.25	15	0.50	43.04
D42-L250-CP125-a18-b26	1.50	15	0.50	53.94

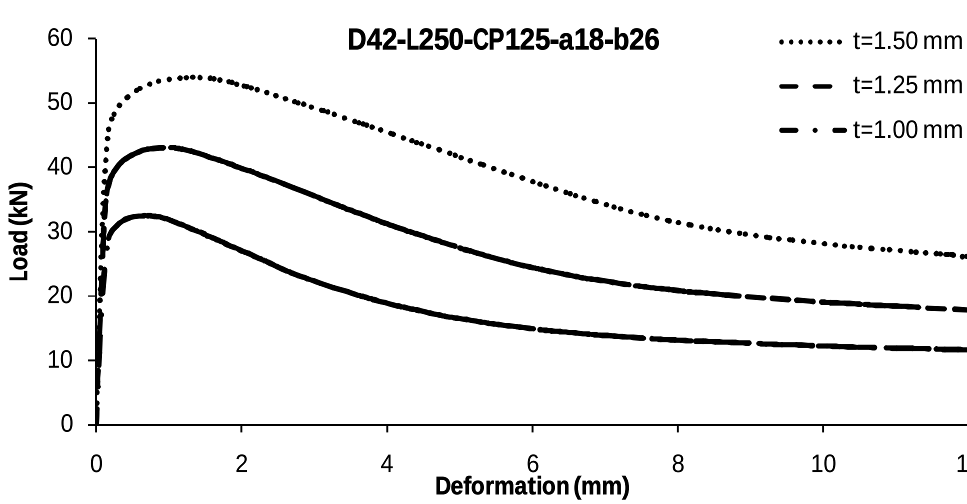

Fig.5: load-displacement curves resulting of thin walled shells with elliptical cutout

5.1.2.Analysis ofshells with circular cutout

In order to analyze the relationship between the buckling load and changes in the shell thickness, a circular cutout with fixed size (d=18mm) was created in the mid-height position of thin walled shells, with various thickness (t=1.00, 1.25 and 1.50 mm). The results of this analysis are shown in table 2. The buckling capacity of thin walled shells with circular cutout in CP=L/2 versus shell thickness was shown in Fig.6. The results show that increasing the thickness enhances the shell resistance against buckling and increases the amount of the critical load.

Table 2. Summary of numerical analysis for thin walled shells with different shell thickness contain circular cutout

Model designation	Shell thickness (mm)	Load angle, γ (degree)	Location of cutout (CP/L)	Buckling load (kN)
D42-L250-CP125-d18	1	15	0.50	34.66
D42-L250-CP125-d18	1.25	15	0.50	46.07
D42-L250-CP125-d18	1.50	15	0.50	57.58

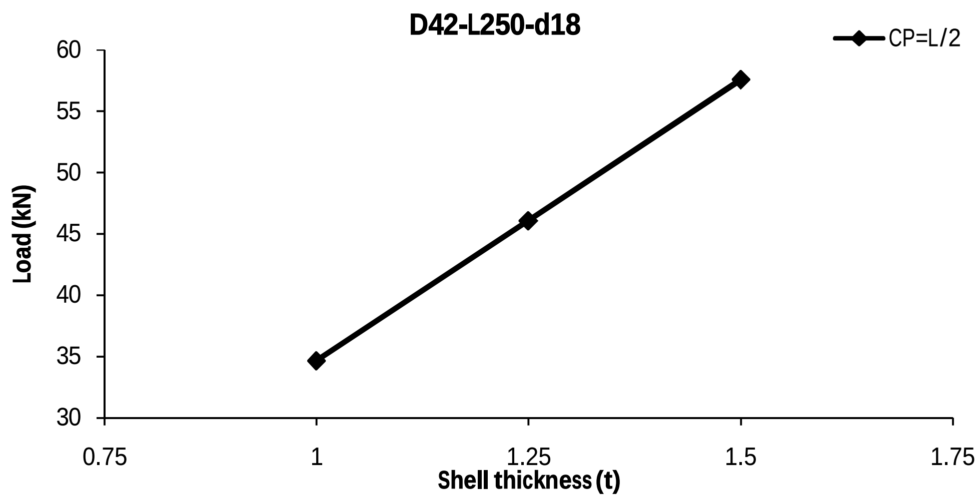

Fig. 6: summery of the buckling capacity of thin walled shells versus shell thickness, for shell with various thickness contain cutout in CP=L/2.

5.2. The effect of cutout position on the critical buckling load of thin walled shell contain elliptical cutout

FEM is used to assess the influence of cutouts location on the critical buckling load. To study the effect of a change in cutout position on thebuckling load of thin walledshells created the cutout with constantsize in the various locations ofshells with constant thickness. With changing the position of the cutouts fromCP=L/4 to L/2, the change in buckling load was studied. The results of thisanalysis for three thicknesses are presented in table 3. Buckling load versus CP/L ratio is shown in Fig. 7 shows. From this figure it can be seen that changing the position of cutout along the specimen length from CP=L/4 to CP=L/2, or from near the edge to the mid-height of specimen,decrease the critical buckling load.

Table 3. Summary of numerical analysis for thin walled shells with different shell thickness contain elliptical cutout situated at various locations.

Model designation	Shell thickness (mm)	Load angel, γ (degree)	Location of cutout CP/L	Buckling load (kN)
D42-L250-CP125-a18-b26	1	15	0.5000	32.48
D42-L250-CP83.3-a18-b26	1	15	0.3333	32.57
D42-L250-CP62.5-a18-b26	1	15	0.2500	32.71
D42-L250-CP125-a18-b26	1.25	15	0.5000	42.84
D42-L250-CP83.3-a18-b26	1.25	15	0.3333	43.24
D42-L250-CP62.5-a18-b26	1.25	15	0.2500	43.65
D42-L250-CP125-a18-b26	1.50	15	0.5000	53.94
D42-L250-CP83.3-a18-b26	1.50	15	0.3333	54.35
D42-L250-CP62.5-a18-b26	1.50	15	0.2500	54.75

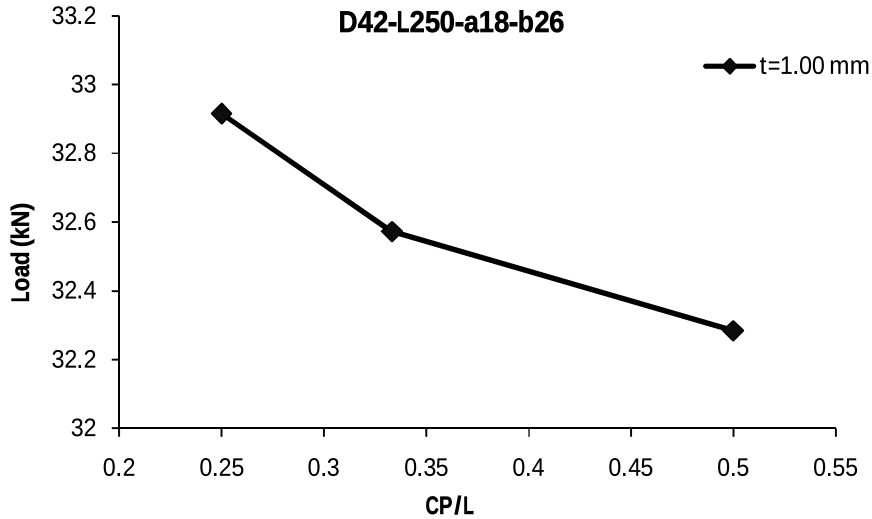

Fig.7: critical buckling load versus CP/L curve,for shell with thickness t=1.00 mm contain cutout in various locations.

5.3. Analysis of the effect of cutout shapeon buckling load of shells withconstant thickness

Tables 1 and 2 show that by changing the thickness of thin walled shell contain elliptical cutout with constant size, from the t=1 mm to t=1.5 mm, the critical buckling load increases 66.07% and changing the thickness of thin walled shell contain elliptical cutout with constant size, from the t=1 mm to t=1.5 mm, the critical buckling load increases 66.12%.Comparing the effect of the elliptical cutout and circular cutout on the critical buckling load of shells with various thickness shows that changing the cutout shape does not have a tangible effect on the critical buckling load.

In other case for analysis of the effect of cutout shape on buckling load of shells with constant thickness, specimens with various cutout shapesat various locations were analyzed. In this analysis, cutouts (elliptical and circular) have equal diameter perpendicular on shell axis. The designation andanalysis details of each model are summarized in Table 4. The results show that the critical buckling load is the same approximately for the cases that cutouts have same diameter perpendicular on shell axis, but having different shapes (elliptical and circular) and was not affected upon the changing the type of the cutout.In Fig. 8, buckling load curves are plotted against the cutout position for thin walled shells of various cutout shapes for elliptical and circular cutouts. This figure clearly shows that with changing the position of the cutout from mid-height of the shell toward the edges, the buckling load increases for elliptical cutout and circular cutout.

Table 4.Summary of numerical analysis for thin walled shells with constant thickness and contain various cutout shape situated at various locations.

Model designation	Shell thickness (mm)	Load angel, γ (degree)	Location of cutout CP/L	Buckling load (kN)
D42-L250-CP125-d18	1	15	0.5000	34.66
D42-L250-CP83.3-d18	1	15	0.3333	34.83
D42-L250-CP62.5-d18	1	15	0.2500	34.97
D42-L250-CP125-a26-b18	1	15	0.5000	33.93
D42-L250-CP83.3-a26-b18	1	15	0.3333	34.10
D42-L250-CP62.5-a26-b18	1	15	0.2500	34.41

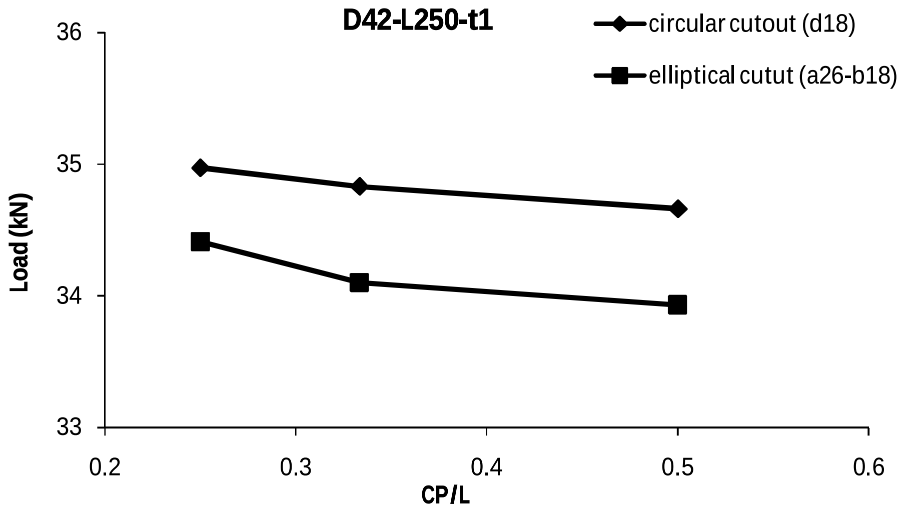

Fig.8:Comparison of the buckling capacity of thin walled shells with circular and elliptical cutout versus CP/L, for shell thickness t=1 mm.

6. Experimental tests

The experiment includes different tests performed on different specimens with different cutout position. The cutouts have been created on face of specimens. The specimens were tested by servo hydraulic machine (INSTRON 8802). The specimens were constrained by fixtures that design and inserted at both ends in the experimental tests, for the simulation of oblique loading, it will be shown in Fig. 9.

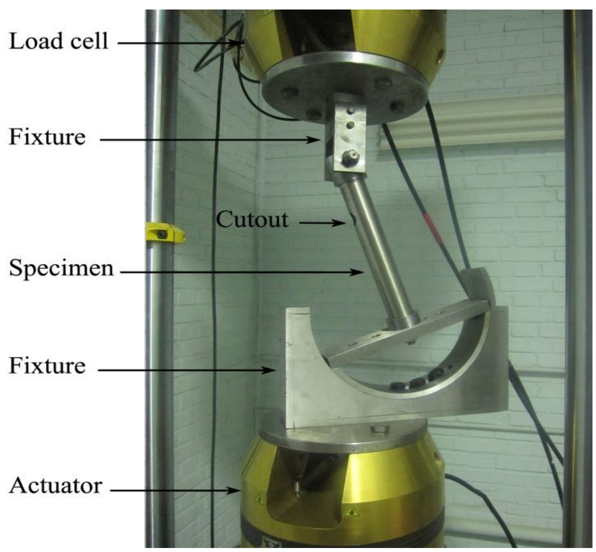

Fig. 9: Test setup (INSTRON 8802 machine and special used fixture)

7. Comparison of FEM and test results

Different experimental tests were conducted to confirm of the authenticity of the results obtained from the numerical method.For example,Fig. 10showsspecimen D42-L250-CP62.5-18after loading by test setup.

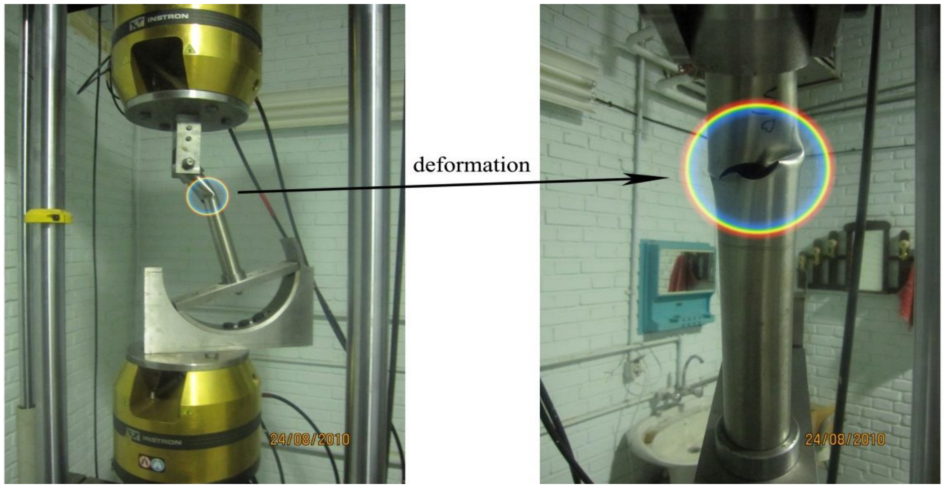

Fig.10:Specimen D42-L250-CP62.5-18 after loading by test setup

The results of experiments are compared with numerical findings in table 5. It is evident from table 5 that there is a little difference between experimental and numerical results. For example, the biggest discrepancy between the two sets of results is 3.6%.

Table 5: Comparisons of the experimental and numerical results

Model designation	Cutout shape	Buckling load (Experimental) (kN)	Buckling load (FEM Result) (kN)	Error (%)
D42-L250-CP62.5-d18	Circular	34.11	34.97	2.5
D42-L250-CP125-d18	Circular	33.44	34.66	3.6
D42-L250-CP125-d16	Circular	36.01	36.94	2.6
D42-L150-CP125-a18-b26	Elliptical	32.77	32.48	1.0

In addition for comparing the samples deformedshape and the behavior of them after occurrence ofbuckling, between the results obtained from theexperimental tests and the results from the finiteelements method, the deformed specimen's shape andthe load-displacement curve and deformed shapes for L250-D42-γ15-CP62.5-d18 have been illustrated in Fig. 11. Also the load-displacement curve and deformed shapes for L250-D42-γ15-CP125-d16 have been illustrated in Fig. 12. Studying thesepictures proves the fact that there is good agreement inthe specimens deformed shape, between the results ofthe FEM and the experimental method.

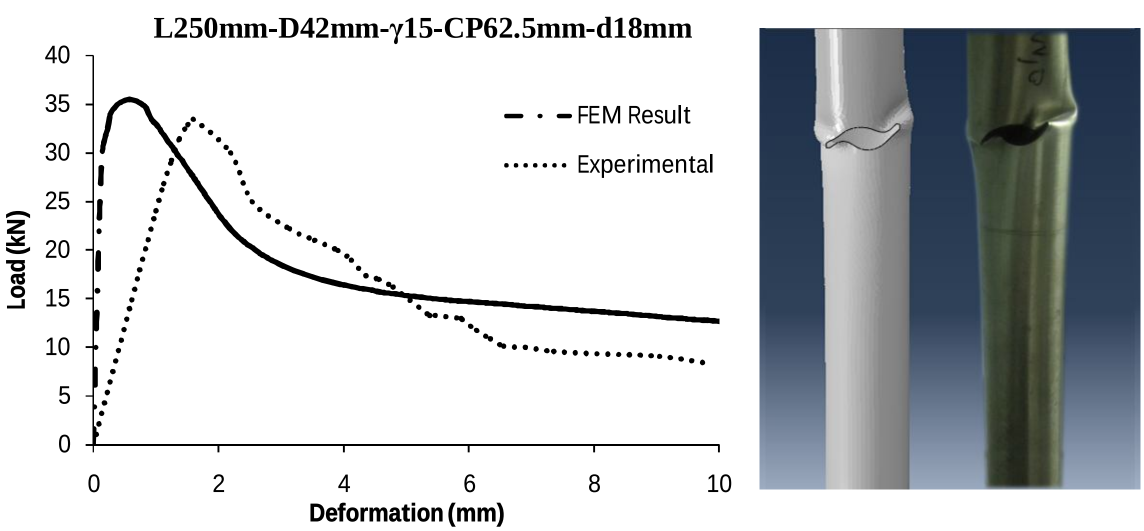

Fig.11:Comparison of the experimental and numerical results by means of obliqueloading-deformation curves and deformed shapes for the specimen D42-L250-CP62.5-d18.

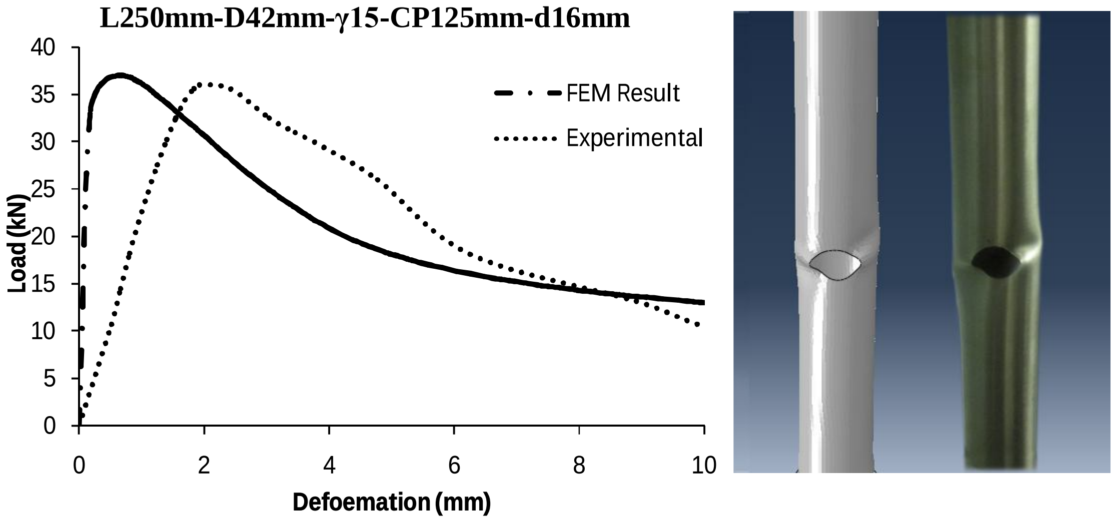

Fig. 12: Comparison of the experimental and numerical results by means of oblique loading-deformation curves and deformed shapes for the specimen D42-L250-CP125-d16

8. Conclusion

In this research, we studied the buckling load of steel thin walled shells of various thickness ratios with the cutout in different length using numerical and experimental methods. Also the buckling load of these shells is determined with different shape cutout. The following results were found in this study.

1. At the first glance it is fully evident that the presence of the cutout decreases the buckling load capacity of the specimens.
2. Changing the position of the cutout from the mid-height of the shell toward the edges decreases the buckling load.
3. Increasing the shell thickness with a fixed cutout size (elliptical and circular) increased the buckling load.
4. Forthin walled shells with a cutout, at first the buckling occurs locally, and then the shell experiences general bending.
5.Comparison of the curves shows that the numerical and experimental results are well matched.
6. Finally we can state that the critical buckling load is the same approximately for the cases that cutouts have same diameter perpendicular on shell axis, but having different shapes (elliptical and circular) and was not affected upon the changing the type of the cutout.

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