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Ultimate Strength Analysis of Combined Loaded Stainless Steel Circular Tubes with Hole

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ABSTRACT

In this paper, simulation and analysis of stainless steel circular tubes with various orientation (α) contain elliptical holes under combined loading have been studied by using experimental and finite element method. Also the effect of hole orientation (θ) and hole position (Lo/L ratio) have been investigated on ultimate strength and buckling behavior of circular tubes. For several specimens, buckling test was performed using an In stron 8802 servo-hydraulic machine and the results of experimental tests were compared to numerical results. A very good correlation was observed between numerical simulation and experimental results.
KEYWORDS : ultimate strength, experimental test, numerical analysis, combined loading, hole

1. INTRODUCTION

The effect of holes on ultimate strength and buckling behavior of circular tubes is an essential consideration in their design. Circular tubes are frequently used in the manufacturing of aircrafts, missiles, boilers, pipelines, automobiles, and some submarine structures. These structures may experience combined loaded in their longevity and yield to buckling. Furthermore, these structures usually have disruptions, such as holes, which may have adverse effects on their stability.

Tafreshi [1] numerically studied the buckling and post-buckling response of composite cylindrical tubes subjected to internal pressure and axial compression loads using Abaqus. She studied the influences of size and orientation of holes on bucklingcapacity. Also, Tafreshi and Colin [2] performed a numerical study using non-linear finite element analysis to investigate the response of composite cylindrical tubes subjected to combined load, in which the post buckling analysis of cylinders with geometric imperfections is carried out to study the effect of imperfection amplitude on critical buckling load. Poursaeidi et al. [3] considered an elastoplastic material and used Abaqus Software to analyze the plastic behavior of cylindrical tubes with holes under pure bending. The tube had a circular cross section and both ends had been clamped. The shape of the holes inthe tubes was circular or rectangular. The influence of thesize, location and number of the holes on the limiting bending moment of a cylindrical tube was presented. Vartdal et al. [4] studied on simply supported steel tubes with rectangular holes of different sizes positioned at their mid-length subjected to axial compression to assess the effect of the holes on the deformation behavior.Han et al. [5] studied the effect of dimension and position of square-shaped holes in thin and moderately thick-walled cylindrical tubes of various lengths by nonlinear numerical methods using the ANSYS software. They also compared their results with experimental studies on moderately thick-walled tubes.Finally, they developed several parametric relationships based on the analytical and experimental results using the least squares regression method. Shariati and Mahdizadeh [6] studied the effect of position of elliptical holes with identical dimensions on the buckling and post buckling behavior of cylindrical tubes with different diameters and lengths and developed several parametric relationships based on the numerical and experimental results using the Lagrangian polynomial method. Holst et al. [7] investigated the method of considering the strains resulted from fabrication misfit of perfect and imperfect shells to attain equivalent residual stresses. Shen and Chen [8] studied buckling and post buckling behavior of perfect and imperfect shells with finite length which were subjected to combined axial and external pressure. They showed that this behavior is dependant on geometry, loading and initial imperfections. Shariati and Mahdizadeh [9] performed a similar numerical study using Abaqus software to investigate the response of steel cylindrical tubes with different lengths and diameters, including elliptical hole subjected to bending moment. They presented some relations for finding of buckling moment of these structures. Almroth and Holmes [10] presented results from a numerical and experimental study on the response of compression-loaded cylindrical shells with reinforced and unreinforced rectangular cutouts. Their results show that the arrangement of the cutout reinforcement, that is, whether the reinforcement is positioned along the axially aligned free-edges of the cutout or around all of the edges of the cutout, can have a significant effect on the buckling response of the shell. Komur [11] carried out the buckling analysis on laminated tubes with elliptical hole numerically.

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Some investigations regarding combined loading of tubular members have been carried out even if studies in this area are limited. Han and Park [12] 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. Kim and Wierzbicki [13] 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. [14] of thin-walled aluminum extrusions subjected to combined 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. The studies also showed that the energy absorption increased by increasing the wall thickness, and this changed the characteristics of the force–displacement curves. A different approach to increase the energy absorption could be to fill the hollow columns with aluminum foam.

In this paper, ultimate strength and buckling behavior of stainless steel circular tubes under combined loading is studied numerically and experimentally. In section 3, numerical analyses using the Abaqus finite element software were carried out in order to study the effect of holesorientation, tubeorientation and location of holes on buckling capacity and ultimate strength of tube.Three different tube orientationswere analyzed,representing 5, 15 and 25 tube orientation andfour different hole orientationswere analyzed, representing 00, 30, 60 and 90 hole orientations. Also holes situated at variouslocation. Additionally, in section 4, for several specimens, experimental buckling test was performed using an Instron 8802 servo-hydraulic machine and the results of experimental tests were compared to numerical results. A very good correlation between experiments and numerical simulations was observed.

2. Numerical analysis using the finite element method

The numerical simulations were carried out using the general finite element program Abaqus 6.10-1.

2.1. Geometry and mechanical properties of the tubes

For this study, stainless steel 316ti circulartubes with thelength L=250 mm, and diameterD=42 mm were analyzed. An elliptical geometry was selected for holes that were created in the specimens.

Furthermore, the thickness of tubes was t=1 mm. Fig. 1 shows the geometry of the elliptical hole. According to this figure, parameter (a) shows the size of hole height, and parameter (b) shows the size of hole width. The distance betweenthe center of the hole and the lower edge of the tube is designated by Lo, as shown in Fig. 1. Specimens were nominated as follows: D42-L250-Lo125-a-b.The numbers following D and L show the diameter and length of the specimen, respectively. Also parameters α and θ depict tubeorientation and holeorientation, respectively.

The circulartubes used for this study were made of stainless steel 316ti. The mechanical properties of this steel alloy were determined according to ASTM E8 standard [12], using the INSTRON 8802 servo hydraulic machine.

The stress–strain curve is shown in Fig. 2. 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$\sigma_y = 334\ MPa$. Furthermore, the value of Poisson's ratiowas assumed to be$\vartheta = 0.33$.For more information about true stress–strain curve and plastic property refer to [15].

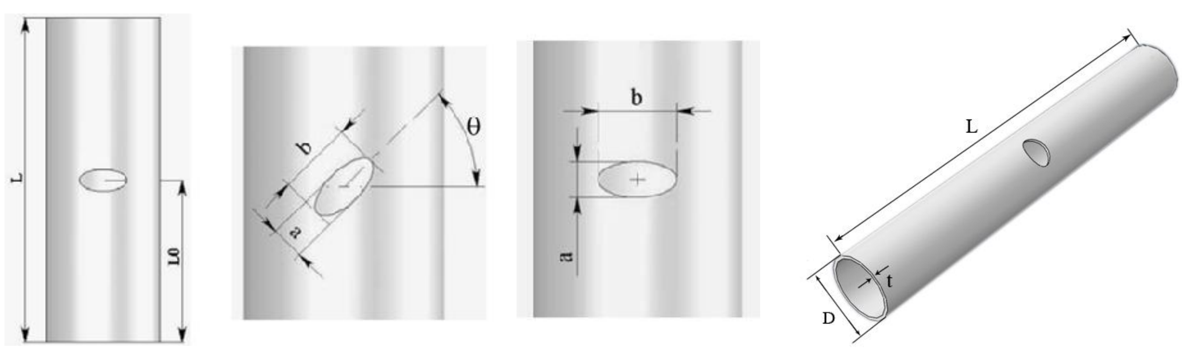

Fig.1: Geometry of hole.

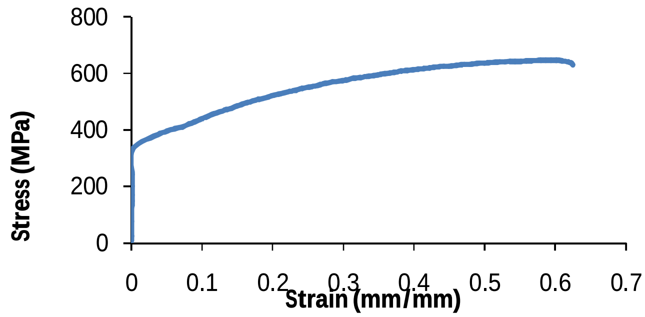

Fig.2:Stress–plastic strain curve

2.2. Boundary conditions

For applying boundary conditions,in the combined loading simulation, two ends of the stainless steel tube are supported by rigid bases.

In order to analyze the buckling subject to combined load similar to what was done in the experiments; a $20\ mm$ displacement was applied centrally to the center of the upper rigid base, which resulted in a distributed, compressive load on both edges of the tube.Additionally, all degrees of freedom in the lower rigid base were constrained. Also alldegrees of freedom in the upper rigid base, except in the direction oflongitudinal axis, were constrained.

2.3. Element formulation of the specimens

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 tubes was used. Part of a meshed specimen is shown in Fig. 3.

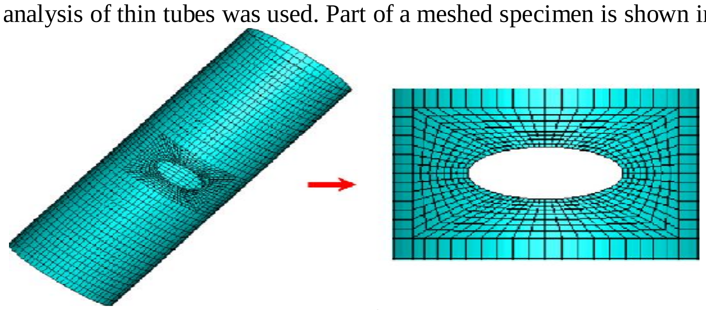
Fig.3:A sample of FEM mesh.

2.4. Analytical process

To analyze the ultimate strength and buckling behavior of circulartubes, two analysis methods, linear eigenvalue analysis and geometric nonlinear, were employed using the “Buckle” and “Static-Riks” solvers respectively. For more information about these FE analyses you can refer to Shariati and Mahdizadeh [6 and 9] and Abaqus user manual.

3. Results of Numerical Analysis

In this section, the results of the buckling analyses ofcirculartubes with different orientations and contain elliptical holes with different orientations, by using the finite element method, are presented. Three different tube orientations were analyzed, representing 5, 15 and 25 tube orientation. Also four different hole orientations were analyzed, representing 00, 30, 60 and 90holeorientations. specimen under load is shown in Fig. 4.

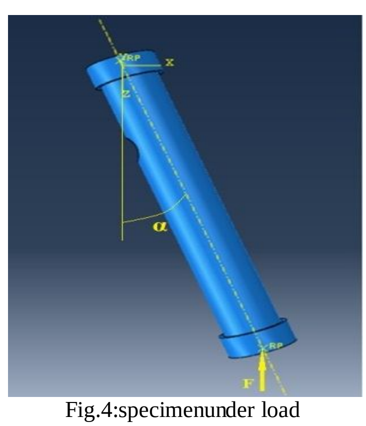

Fig.4:specimenunder load

3.1. The effects of tubeorientationon ultimate strength and buckling behavior of circulartubes with hole

3.1.1. Analysis of the effect of change in tubeorientation(α) on ultimate strength and buckling behavior of circular tubes

In this section, the effect of tubeorientationon the ultimate strength of circular tubes is studied. Forthis reason, holes with fixed size (18-26 mm)werecreated in the mid-height position of tubes. Then, withchanging the tubeorientation from 00 to 25degree, thechange in buckling load was studied. In other cases hole created in L/2 and L/3 of tube height and then withchanging the tubeorientation from 00 to 25 degree, thechange in buckling load was studied. The results of thisanalysis are presented in table 1.

Fig. 5 shows summary of the buckling capacity of circulartubes versus deformation, for elliptical hole without tubeorientation and various locations.Fig. 6 shows summary of the buckling capacity of circulartubes versus deformation, for elliptical hole with tubeorientation25 and various locations.

The buckling load versustubeorientationisshown in Fig.7.Wecan compare the changes in the buckling load with thechange in tubeorientation. The results show when theholeposition is constant, an increase in tubeorientation,decreases the buckling load.

Table 1. Summary of numerical analysis for circulartubes with different tubeorientation and with elliptical hole situated at various locations (θ=00).

Model designation	Tube thickness (mm)	Tubeorientation α(degree)	Location of hole Lo/L	Buckling load (N)
D42-L250-Lo125-18-26	1	00	0.5000	38331.50
D42-L250-Lo83.3-18-26	1	00	0.3333	38401.49
D42-L250-Lo62.5-18-26	1	00	0.2500	38455.95
D42-L250-Lo125-18-26	1	05	0.5000	36863.46
D42-L250-Lo83.3-18-26	1	05	0.3333	36970.93
D42-L250-Lo62.5-18-26	1	05	0.2500	37053.77
D42-L250-Lo125-18-26	1	15	0.5000	32483.85
D42-L250-Lo83.3-18-26	1	15	0.3333	32573.27
D42-L250-Lo62.5-18-26	1	15	0.2500	32715.24
D42-L250-Lo125-18-26	1	25	0.5000	26605.03
D42-L250-Lo83.3-18-26	1	25	0.3333	26687.22
D42-L250-Lo62.5-18-26	1	25	0.2500	26985.68

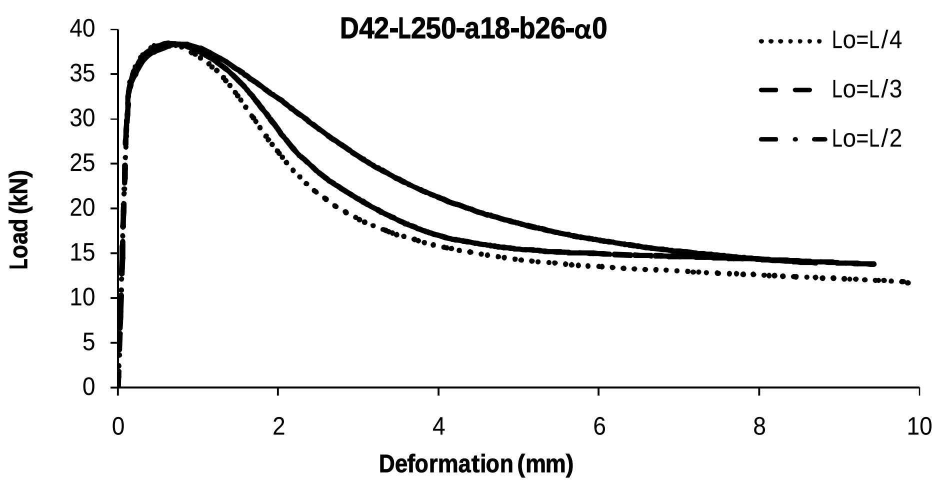

Fig.5: Summary of the buckling capacity of circulartubes with elliptical hole versus deformation, for tube with orientation 00 and θ=00.

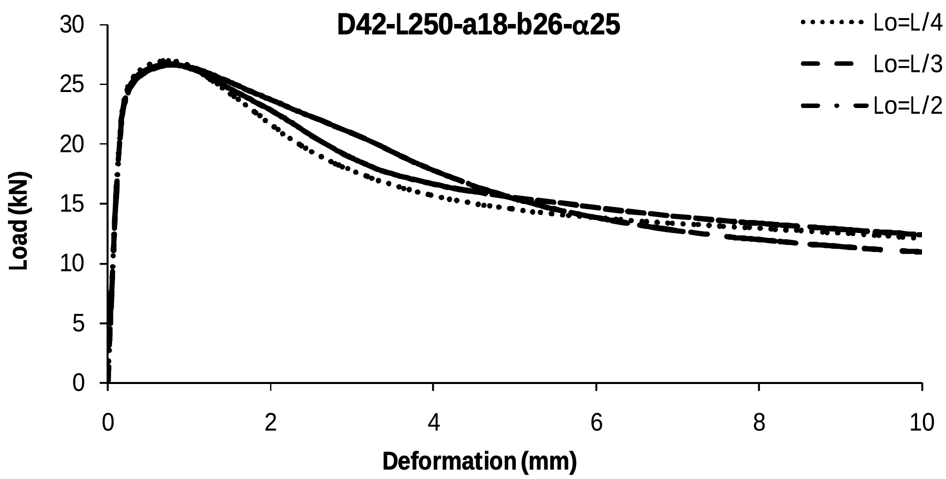

Fig.6: Summary of the buckling capacity of circulartubes with elliptical hole versus deformation, for tube with orientation25and θ=00.

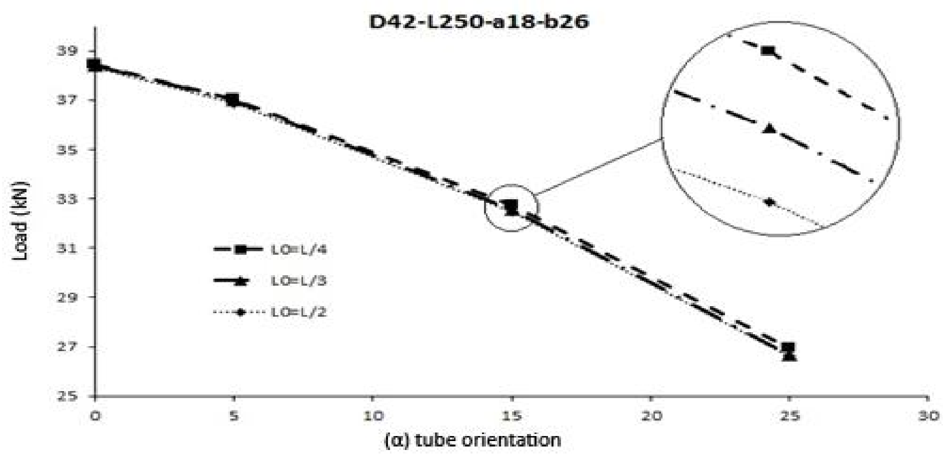

Fig.7:Comparison of the buckling capacity of circulartubes versustubeorientation(α) for various holelocations and θ=00.

3.1.2. Analysis of the effect of change in position of hole with fixed tubeorientation (α) on ultimate strength and buckling behaviorof circular tubes

To study the effect of a change in holeposition on thebuckling load of circulartubes with constant orientation,createhole with constantsize (18×26 mm) in tubes. Then, with changing the position of the holes from Lo=L/4 to L/2 mm, the change in buckling load was studied. Fig.8showsbuckling load versus L0/L ratio,by use data from table.1. It can be seen from this figure that when hole move from mid-height of circulartube to near the tube edge, buckling Load increases.

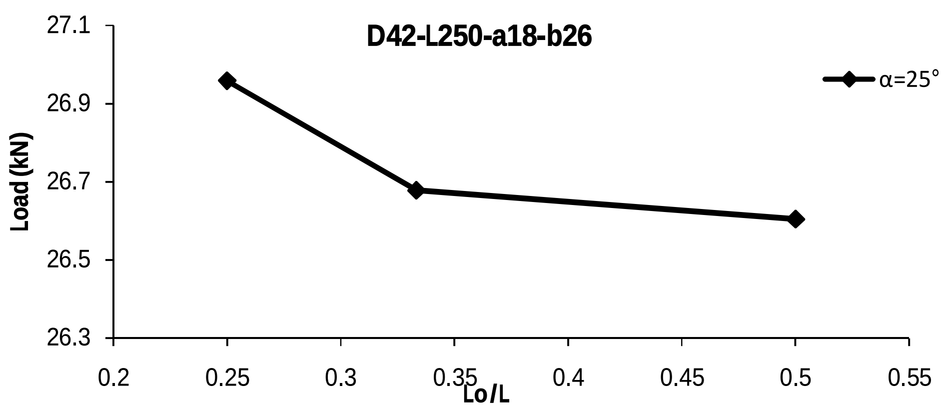

Fig.8: comparison of the buckling capacity of tubes with orientation 25 versus ratio Lo/L, including elliptical hole.

3.2. The effects of holeorientation(θ) on ultimate strength and buckling behaviorof circulartubes

3.2.1. Analysis of the effect of change in holeorientation (θ) onultimate strength and buckling behavior of circulartubes

In order to analyze the relationship between the bucklingload and changes in the orientation of elliptical holes, anelliptical holewith fixed size (18×26mm) was created inthe mid-height position of circulartubes, with varioussholeorientations between θ=0 and 90.In other cases hole created in L/2 and L/3 of tube height and then with various holeorientations between θ=0 and 90, thechange in buckling load was studied. The results of this analysis areshown in table 2.

Fig.9. showssummary of the buckling capacity of circulartubes versus deformation, for elliptical hole with constant dimensions and orientation 60.

The results show that increasing the holeorientationenhances the tube resistance against buckling andincreases the amount of the critical load. Additionally, forintermediate-lengthtubes with a diameterof 42mm, with change orientations from 0 to 90 the buckling load increases 5.95%,respectively.

The buckling load versusholeorientation in varioushole location, are shown inFig.10. It can be seen that with an increase in the holeorientation, the buckling capacity of the tube increases.

Table 2. Summary of numerical analysis for circulartubes with various holeorientations, with elliptical hole situated at various locations (α=15).

Model designation	Tube thickness (mm)	Holeorientation θ(degree)	Location of hole Lo/L	Buckling load (N)
D42-L250-Lo125-18-26	1	00	0.5000	32483.85
D42-L250-Lo83.3-18-26	1	00	0.3333	32573.27
D42-L250-Lo62.5-18-26	1	00	0.2500	32715.24
D42-L250-Lo125-18-26	1	30	0.5000	32827.42
D42-L250-Lo83.3-18-26	1	30	0.3333	32979.92
D42-L250-Lo62.5-18-26	1	30	0.2500	33264.74
D42-L250-Lo125-18-26	1	60	0.5000	33589.68
D42-L250-Lo83.3-18-26	1	60	0.3333	33660.80
D42-L250- Lo62.5-18-26	1	60	0.2500	33931.17
D42-L250-Lo125-18-26	1	90	0.5000	33933.46
D42-L250-Lo83.3-18-26	1	90	0.3333	34104.18
D42-L250- Lo62.5-18-26	1	90	0.2500	34416.78

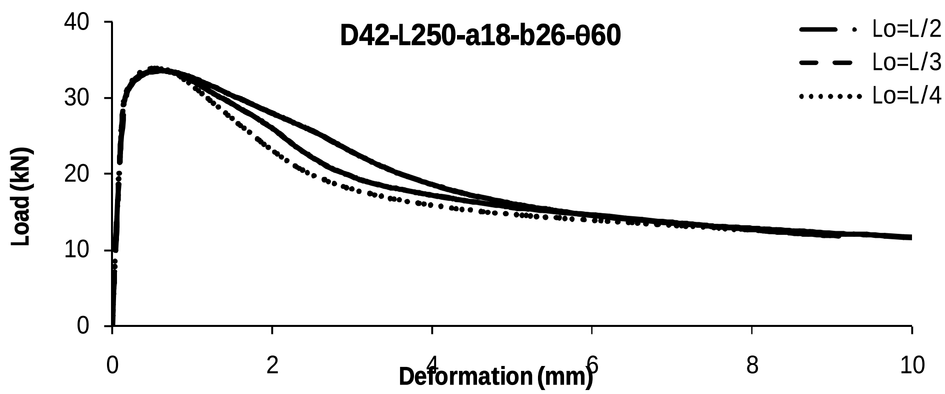

Fig.9: Summary of the buckling capacity of tubes versus deformation, for elliptical hole withorientation 60and α=15.

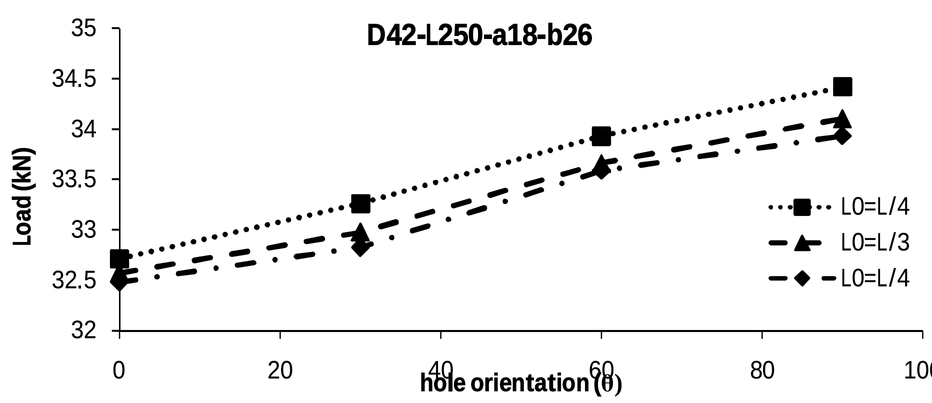

Fig.10: Comparison of the buckling capacity of tubes versus holeorientation (θ) for varioushole locationsand α=15.

3.2.2. Analysis of the effect of change position of hole with fixed holeorientation (θ) on ultimate strength and buckling behavior of circular tubes

The buckling Load versus L0/L ratio is shown in Fig.11. It can be seen that for a hole with fixed orientation, the buckling Load decreases when change hole position from near the tube edge to the mid-height of tube.

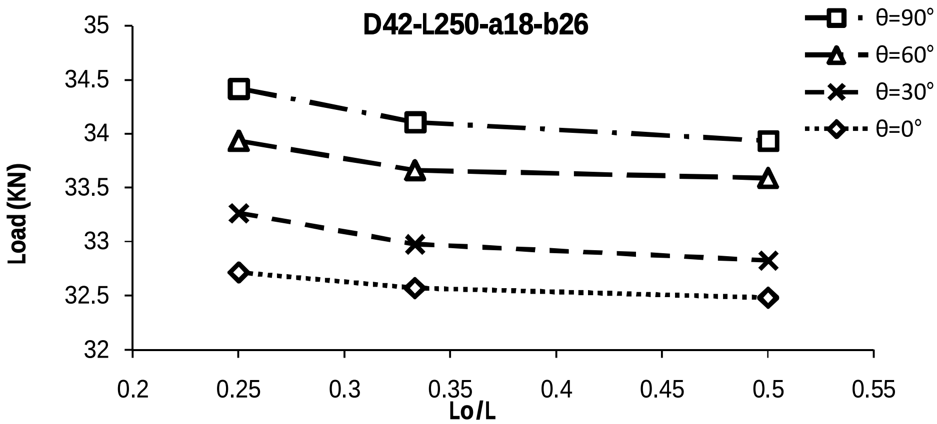

Fig.11: Plots of buckling load versus ratio Lo/L for tubes including an elliptical holewith various orientations (α=15).

4. Experimental verification

Experimental tests using a servo-hydraulic, Instron 8802 machine were conducted to verify some of the cases investigated in the numerical simulations.

The specimens were constrained by fixtures that design for this result and inserted at both ends, which mimics the fixed boundary condition used in the finite element simulations (see Fig. 12). Three specimens were tested for each case and almost identical results were obtained compared to those obtained from the numerical simulations. The experimental results are compared to numerical findings in table 3. The comparison shows that there is little difference between the two sets of data.The mean difference between the numerical calculations and the experimental results is about 3% of experimental buckling load.

Table 3: Comparisons of the experimental and numerical results

Model designation	Buckling load (Experimental test) (N)	Buckling load (FEM Result) (N)	Error (%)
D42-L250-Lo125-18-26	34332.83	33641.52	2.1
D42-L250-Lo125-18-26	32774.54	32483.85	1.0
D42-L150- Lo125-18-26	35127.90	33024.33	5.9

The load-end shortening curves and deformed shape of specimens in the buckling and post-buckling states in numerical and experimental tests are compared inFig.13. It can be seen that the peak load of both curves are very near together, while the slope of linear part of loadend shortening curves is higher in numerical analysis than in experimental results. This is maybe due to the presence of internal defects in the material which reduce the stiffness of the specimens in the experimental method, while the materials are assumed to be ideal in the numerical analyses.

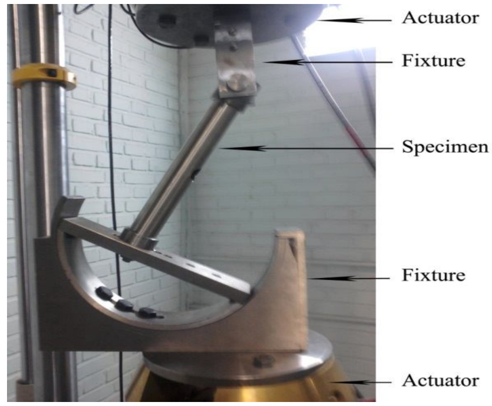

Fig.12: test setup(INSTRON 8802 machine and special used fixture)

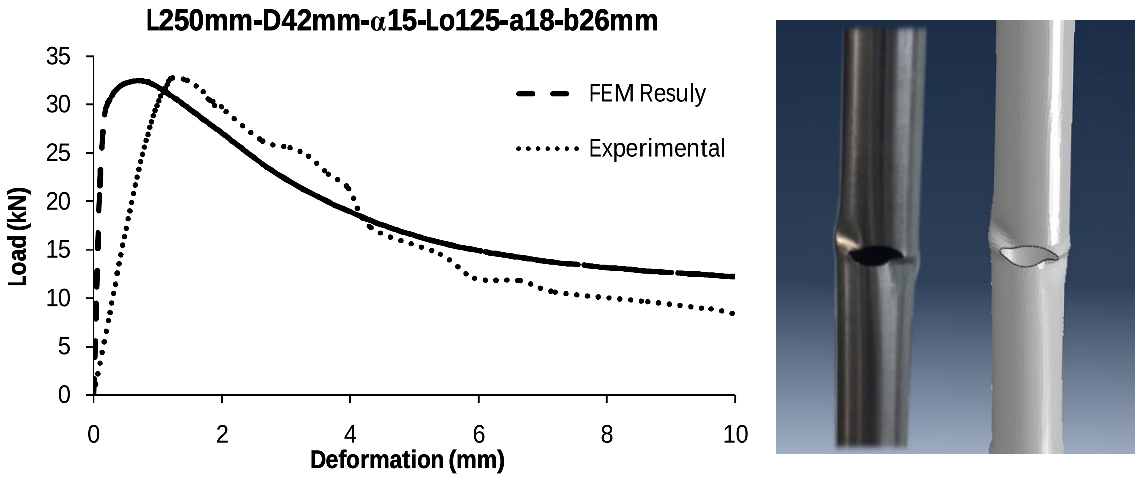

Fig.13: Comparison of the experimental and numerical results for the specimen D42-L250-Lo125-18-26 under combined loading (α=15).

5. Concluding remarks

The paper examines the influence of elliptical holes with various orientations, various Lo/L ratioson ultimate strength and buckling behavior of stainless steel316ticirculartubes subjected to combinedLoading. Also we determined the ultimate strength and buckling behavior of tubes with various orientations. The following results were found:

1- Increasing the tubeorientation while the hole size and orientation are constant, decreases the ultimate strength.

2-When the hole size and tubeorientation are constant, by increasing holeorientation, the ultimate strength increases.Therefore, it is preferable to design the tubes in such a way that the greater dimension of the hole is alignedwith the longitudinal axis of the tube.

3- Increasing the hole orientation enhances the tube resistance against buckling and increases the amount of the critical load.

4- Changing the position of the hole from the mid-height of the tube toward the edges, increases the buckling load.

5- Presence of a hole may significantly alter the buckling behavior of cylindrical shells by provoking local buckling as the dominant buckling mode of the circular tubes.

6- Very good correlation was observed between the results of the experimental and numerical simulations.

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