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

Mahmoud Shariati¹, Amin Akbarpour²

¹ Mechanical Department, Shahrood University of Technology, Shahrood, Iran
² Young Researchers Club, Semnan Branch, Islamic Azad University, Semnan, Iran

ABSTRACT

In this paper, simulation and analysis of stainless steel circular tubes with various orientation (a) 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) have been investigated in ultimate strength and buckling behavior of circular tubes. For several specimens, 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 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 buckling capacity. 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. Pouraiedi 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 in the tubes was circular or rectangular. The influence of the size, 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 dependent 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.

*Corresponding Author: Amin Akbarpour, Young Researchers Club, Semnan Branch, Islamic Azad University, Semnan, Iran. Tel: +989125942004, E-mail: Akbarpour.Amin@yahoo.com
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 holes orientation, tube orientation and location of holes on buckling capacity and ultimate strength of tube. Three different tube orientations were analyzed, representing 5, 15 and 25 tube orientation and four different hole orientations were analyzed, representing 00, 30, 60 and 90 hole orientations. Also holes situated at various location. 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 circular tubes with the length L=250 mm, and diameter D=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 between the 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 tube orientation and hole orientation, respectively.

The circular tubes 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 \( E = 187 \, \text{GPa} \) and the value of yield stress was obtained as \( \sigma_y = 334 \, \text{MPa} \). Furthermore, the value of Poisson’s ratio was assumed to be \( \nu = 0.33 \). For more information about true stress–strain curve and plastic property refer to [15].

Fig. 1: Geometry of hole.
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 all degrees of freedom in the upper rigid base, except in the direction of the longitudinal 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.

2.4. Analytical process

To analyze the ultimate strength and buckling behavior of circular tubes, 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 of circular tubes 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 0, 30, 60 and 90 hole orientations. Specimen under load is shown in Fig. 4.
3.1. The effects of tube orientation on ultimate strength and buckling behavior of circular tubes with hole

3.1.1. Analysis of the effect of change in tube orientation ($\alpha$) on ultimate strength and buckling behavior of circular tubes

In this section, the effect of tube orientation on the ultimate strength of circular tubes is studied. For this reason, holes with fixed size (18-26 mm) were created in the mid-height position of tubes. Then, with changing the tube orientation from 00 to 25 degree, the change in buckling load was studied. In other cases, holes were created in L/2 and L/3 of tube height and then with changing the tube orientation from 00 to 25 degree, the change in buckling load was studied. The results of this analysis are presented in Table 1.

Fig. 5 shows summary of the buckling capacity of circular tubes versus deformation, for elliptical hole without tube orientation and various locations. Fig. 6 shows summary of the buckling capacity of circular tubes versus deformation, for elliptical hole with tube orientation 25 and various locations.

The buckling load versus tube orientation is shown in Fig. 7. We can compare the changes in the buckling load with the change in tube orientation. The results show when the hole position is constant, an increase in tube orientation decreases the buckling load.

Table 1. Summary of numerical analysis for circular tubes with different tube orientation and with elliptical hole situated at various locations ($\theta=00$).

<table>
<thead>
<tr>
<th>Model designation</th>
<th>Tube thickness (mm)</th>
<th>Tube orientation $\alpha$ (degree)</th>
<th>Location of hole Lo/L</th>
<th>Buckling load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>00</td>
<td>0.5000</td>
<td>38331.5</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>00</td>
<td>0.3333</td>
<td>38401.49</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>00</td>
<td>0.2500</td>
<td>38455.95</td>
</tr>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>05</td>
<td>0.5000</td>
<td>36863.46</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>05</td>
<td>0.3333</td>
<td>36970.93</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>05</td>
<td>0.2500</td>
<td>37053.77</td>
</tr>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>15</td>
<td>0.5000</td>
<td>32483.85</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>15</td>
<td>0.3333</td>
<td>32573.27</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>15</td>
<td>0.2500</td>
<td>32715.24</td>
</tr>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>25</td>
<td>0.5000</td>
<td>26605.03</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>25</td>
<td>0.3333</td>
<td>26687.22</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>25</td>
<td>0.2500</td>
<td>26983.68</td>
</tr>
</tbody>
</table>

Fig. 5: Summary of the buckling capacity of circular tubes with elliptical hole versus deformation, for tube with orientation 00 and $\theta=00$. 
3.1.2. Analysis of the effect of change in position of hole with fixed tube orientation (α) on ultimate strength and buckling behavior of circular tubes

To study the effect of a change in hole position on the buckling load of circular tubes with constant orientation, create a hole with constant size (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. 8 shows buckling load versus Lo/L ratio, by use data from Table 1. It can be seen from this figure that when hole move from mid-height of circular tube to near the tube edge, buckling load increases.
3.2. The effects of hole orientation on ultimate strength and buckling behavior of circular tubes

3.2.1. Analysis of the effect of change in hole orientation on ultimate strength and buckling behavior of circular tubes

In order to analyze the relationship between the buckling load and changes in the orientation of elliptical holes, an elliptical hole with fixed size (18 x 26 mm) was created in the mid-height position of circular tubes, with various hole orientations between θ = 0 and 90°. In other cases, a hole was created in L/2 and L/3 of tube height and then with various hole orientations between θ = 0 and 90°, the change in buckling load was studied. The results of this analysis are shown in Table 2.

Fig. 9 shows summary of the buckling capacity of circular tubes versus deformation, for elliptical hole with constant dimensions and orientation 60°.

The results show that increasing the hole orientation enhances the tube resistance against buckling and increases the amount of the critical load. Additionally, for intermediate-length tubes with a diameter of 42 mm, with change orientations from 0 to 90° the buckling load increases 5.95%, respectively.

The buckling load versus hole orientation in various hole locations, are shown in Fig. 10. It can be seen that with an increase in the hole orientation, the buckling capacity of the tube increases.

Table 2: Summary of numerical analysis for circular tubes with various hole orientations, with elliptical hole situated at various locations (α = 15°).

<table>
<thead>
<tr>
<th>Model designation</th>
<th>Tube thickness (mm)</th>
<th>Holesterolation θ (degree)</th>
<th>Location of hole Lo/L</th>
<th>Buckling load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>00</td>
<td>0.5000</td>
<td>32483.85</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>30</td>
<td>0.3333</td>
<td>32573.27</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>60</td>
<td>0.5000</td>
<td>33589.68</td>
</tr>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>90</td>
<td>0.3333</td>
<td>33660.80</td>
</tr>
<tr>
<td>D42-L250-Lo83.3-18-26</td>
<td>1</td>
<td>00</td>
<td>0.2500</td>
<td>33931.17</td>
</tr>
<tr>
<td>D42-L250-Lo62.5-18-26</td>
<td>1</td>
<td>30</td>
<td>0.2500</td>
<td>34104.18</td>
</tr>
<tr>
<td>D42-L250-Lo125-18-26</td>
<td>1</td>
<td>60</td>
<td>0.2500</td>
<td>34416.78</td>
</tr>
</tbody>
</table>

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

Fig. 10: Comparison of the buckling capacity of tubes versus hole orientation (θ) for various hole locations and α = 15°.
3.2.2. Analysis of the effect of change position of hole with fixed hole orientation (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 hole with various orientations (α=15).](image)

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.

![Fig.12: test setup(INSTRON 8802 machine and special used fixture)](image)

<table>
<thead>
<tr>
<th>Model designation</th>
<th>Buckling load (Experimental test) (N)</th>
<th>Buckling load (FEM Result) (N)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D42-L250-a18-b26</td>
<td>34332.83</td>
<td>33641.52</td>
<td>2.1</td>
</tr>
<tr>
<td>D42-L250-a18-b26</td>
<td>32774.54</td>
<td>32483.85</td>
<td>1.0</td>
</tr>
<tr>
<td>D42-L150-Lo125-18-26</td>
<td>35127.90</td>
<td>33024.33</td>
<td>5.9</td>
</tr>
</tbody>
</table>

The load-end shortening curves and deformed shape of specimens in the buckling and post-buckling states in numerical and experimental tests are compared in Fig.13. It can be seen that the peak load of both curves are very near together, while the slope of linear part of load-end 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.
5. Concluding remarks

The paper examines the influence of elliptical holes with various orientations, various Lo/L ratios on ultimate strength and buckling behavior of stainless steel 316Ti circular tubes subjected to combined loading. Also we determined the ultimate strength and buckling behavior of tubes with various orientations. The following results were found:
1- Increasing the tube orientation while the hole size and orientation are constant, decreases the ultimate strength.
2- When the hole size and tube orientation are constant, by increasing hole orientation, the ultimate strength increases. Therefore, it is preferable to design the tubes in such a way that the greater dimension of the hole is aligned with 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.

REFERENCES


14. ASTM A370-05, Standard test methods and definitions for mechanical testing of steel products.