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Numerical and experimental investigation of the steel square shells with circular cutout subjected to compression

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Abstract

Within this contribution, buckling of square-sectioned thin-walled steel shells will be analyzed. The experimental results will be assessed by FEM simulation results within various circular cutouts of the specimen. The experimental buckling tests have been conducted using a Servo hydraulic machine (Instron 8820). Considering the broad application range of square-sectioned thin-walled shells, prediction of the behavior of these elements in axial loading cases, and especially for buckling behavior, has gained a great level of importance. In this study, the influence of size and location of cutouts on the predicted buckling values for the square-sectioned thin-walled has been explored. Numerical simulations of square sections subjected to axial load were conducted and the analytical solutions show excellent agreement with the numerical results predicted by FEM.

Keywords: Square sectioned shell, Circular cutout, Axial buckling, Finite element method

Introduction

Shells with square sections are widely used in various structures, including aerospace structures and other engineering applications. These shells, depending on the conditions, may have cutouts with various geometries. In most cases, the shells are subjected to axial compressive loads. 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, and twisting 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. Moreover, the effect of location and number of cutouts was also studied. The results indicated that buckling load is affected by the opening angle or the circumferential size of the hole and that the function of the critical load-opening angle is linear for large openings, while initial geometrical imperfections in the sample can be ignored. Ben Young [4,5] investigated hollow columns with square and rectangular sections 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 the principles 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.

Buckling of steel thin-walled shells with square sections with a circular cutout has been studied, and the results obtained from these two methods are compared with each other. Furthermore, the influence of the size effect, cutout number, and cutout location on the load-displacement behavior of specimens has been studied thoroughly within this report. For numerical methods, the finite element method program ABAQUS [6] has been applied. In all of the abovementioned articles, buckling load has been analyzed for one cutout. One of the goals of this paper is to simulate the mechanical behavior of the mentioned profile by using two cutouts on opposite faces of the specimen.

Experimental tests

The steel thin-walled square-section shells have been cut in three different lengths 120, 200 and 280 mm. The experiment includes 22 different loading tests performed on different specimens with different cutout position and numbers. The geometry of specimens and the cutouts created on its, are illustrated in Fig. 1. As shown in Fig. 1, B represents the length of cross section side, T the thickness of the specimen’s wall and D shows the diameter of cutout. The openings have been created either on one face or two opposite faces. The results obtained from some samples having cutouts have been compared with those who don’t have any cutout. All specimens have cross section dimension of 25 x 25 x 0.85 mm.

The specimens were tested between two fixed ends. All tests were conducted by a 250-kN Servo hydraulic machine (Instron 8802). The chosen profile is made of carbon steel whose mechanical properties were specified through application of tensile coupon test in accordance with ASTM E8. For the tensile coupon test, the coupon specimen were taken from the face of the column specimen .The stress-strain curve obtained through tensile test has been shown in Fig. 2.

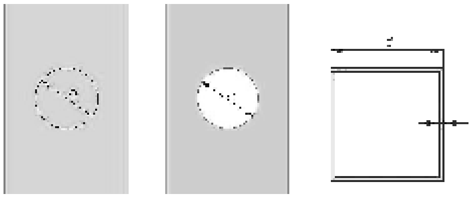
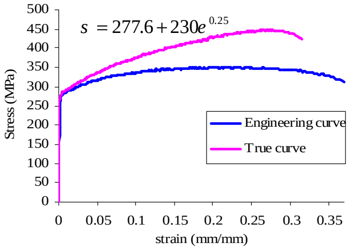


Fig. 1: Geometry of cross section and cutouts



Strain (mm/mm)	Stress (MPa)
0	0
0.00017	37.757
0.00033	70.563
0.00044	92.574
0.0006	124.52
0.00068	144.33
0.00086	173.3
0.000995	193.62

Fig. 2: Stress – Strain curves

Labeling of samples

Labeling of specimens has been in accordance with the geometry of the it including length, width, and thickness of the section surface and also the type, size and location of opening in form of L1-Bb-Ti-Cca-Dd. “L” is the symbol of the length of specimen, and “1” is its quantity, “B” is the symbol of the width of cross section and “b” is its quantity, “T” is the symbol of the thickness of the sample and “t” is its quantity, “Cc” is the symbol of the circle cutout and “a” is the distance from center of the cutout to the end bottom of the specimen, “D” the symbol of cutout dimensions and “d” the symbol of circle cutout indicate the diameter of circle (14mm).

Development of finite element model

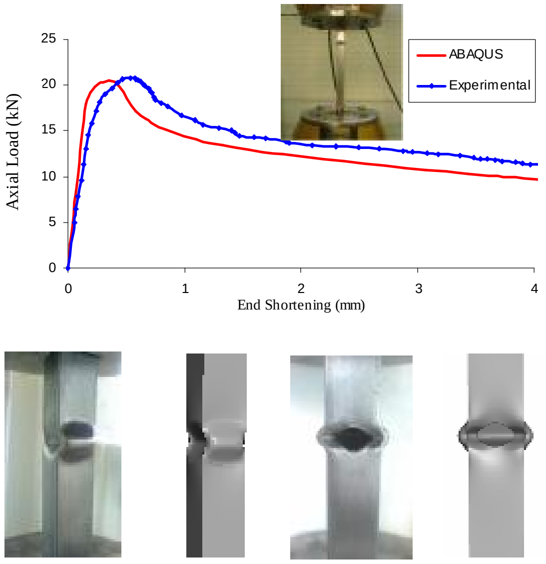
For analyzing the buckling behavior of the steel shells program ABAQUS has been applied. Elastic Modulus of the specimens which can be obtained from the linear part of Figure was 195MPa for all the specimens. Ultimate strength and the Poisson’s ratio of specimens assumed to be 448MPa and 0.33 respectively. Moreover the geometrical dimensions were chosen in accordance with the quantities measured in experimental tests. The type of the element applied for the analysis is to S4R which is 4-node element witch has 6 degrees freedom per node. The size of the elements used in the finite elements model is around 2 x 2 mm. finer mesh size was used around the cutout as indicated in Figure 3 in order to enhance the precision of analysis in determination of final buckling load.

The specimen has been placed between two fixed ends. All the degrees of freedom have been restrained on one of these ends. On the other end all nodes are capable to move only along the axial (load) direction and the other degrees of freedom are restrained. The compressive load was applied to the column by specifying an axial displacement to the nodes at one end of the column. Moreover the specimen has been inserted into the supports at each end by 10 mm in a way that all degrees of freedom, except translation along the axial direction, have been restrained on these surfaces.

Comparison of FEM and test results

Many experimental tests were conducted to confirm of the authenticity of the results obtained from the numerical method. Later on for better comparison the load-displacement curves obtained through experimental and numerical methods with changing the location of cutout in some cases have been studied .(Fig. 3)

In addition for comparing the samples deformed shape and the behavior of them after occurrence of buckling, between the results obtained from the experimental tests and the results of from the finite elements method the deformed specimen’s shape and the load-displacement curve for L140-B25-T.85-Cc49-D14 have been illustrated in Fig. 3. Studying these pictures proves the fact that there is good agreement in the specimens deformed shape, between the results of the FEM and the experimental method.



Experimental ABAQUS Experimental ABAQUS

Fig. 3: Comparison of the experimental and numerical results by means of Axial Load-End shortening curves and deformed shapes for the specimen L140-B25-T.85-Cc49-D14

We find out that the slope of the load-end shortening curves, for numerical results are more than experimental results before occurrence of buckling. This is due to the presence of initial imperfections in the material which decreases the stiffness in specimens and involved tests, while in the numerical method the material is considered to be ideal.

But in post-buckling region, this behavior become inverted, that is to say, the slope of the curve is less in the numerical analysis than in the experimental state. This behavior has also been observed for other load-displacement curves in various shells with different cross sections and various cutouts and the reason could be attributing to the effect of beginning of plastic deformation leading to mechanical locking in the structure and creation of work-hardship. In the experimental method as a result of mechanical and metallurgical defect in material this phenomenon is considerable and therefore buckling load is higher within the plastic scope for experimental method than for the numerical method.

In a view of Fig. 4(a) we observe that the linear part of the diagram in specimens with two cutout and those having one cutout are exactly the same. Upon the increase of load and reaching to buckling, the difference of these two diagrams becomes more perceptible. As mentioned earlier, we can observe that this difference is less, when the cutout is smaller .

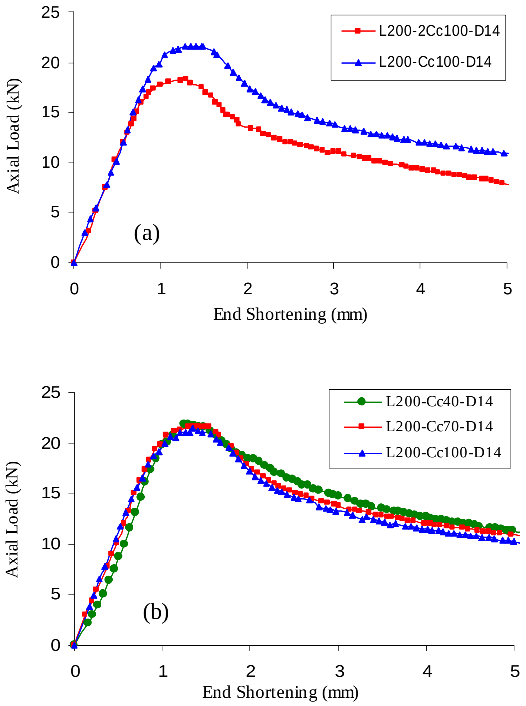


Fig. 4: Comparison of the experimental results by means of Axial Load-End Shortening curves after occurrence of buckling (a) for the two specimens with various numbers of cutouts (b) for the three specimens with various locations of cutouts

Upon the decrease of the load the two diagrams are placed on each other and become closer to the numerical results. In Fig. 4(b) the behavior of the critical buckling load in proportion to the location of the cutout has been shown. We can observe that before occurrence of the buckling, with increasing the distance from the center of cutout to the end bottom of specimen, the slope of curve will decrease. But after the buckling this behavior becomes inverted. That is to say the diagrams, cross from each other in one point which as showed in the fig. 4(b).

Furthermore FEM is used to assess the influence of cutouts size and also its location on the critical buckling load. Comparing the effect of the opening's location on the critical buckling load of columns (see Fig. 5) show that changing the position of cutout along the specimen length in L_0=0.5L, 0.6L, 0.8L, 0.9L (L_0 is the distance of the cutout center to the top of the specimen) does not have a tangible effect on the critical buckling load (Definitely the shells with the bigger length are more sensitive on this change). In addition we find out that changing the size of cutout has important effect on the final buckling of the specimens.

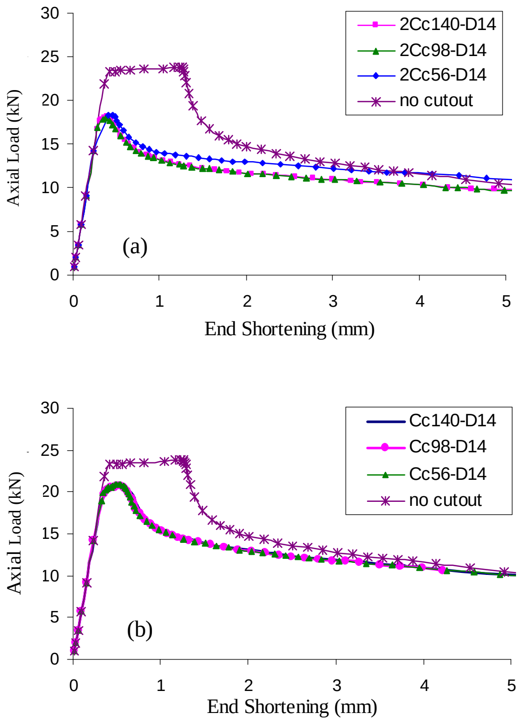


Fig. 5: Comparison of the influence of cutout location on final buckling load for specimens with L=280mm(a)with two circular cutouts on two opposite faces(b) with one circular cutout on one face

Conclusion

A series of experimental tests and numerical analyses was carried out to investigate the influence of the circle cutout on the critical buckling load of thin-walled shells with square sections, which are subjected to an axial compressive load. In this process, we have used a series of steel thin-walled shells with the same square cross-section but with three different lengths (120 mm, 200 mm, and 280 mm). The effects of size, type, and the location of cutout has been verified and we can state that the numerical analyses carried out in finite element simulation were in good correlation with the result of experimental tests. The following points can be extracted from these comparisons:

1-At the first glance it is fully evident that the presence of the cutout decreases the load bearing capacity of the specimens and upon the increase of the number of the cutout, this change becomes more considerable.

2-The final buckling load for the cases have two cutouts in opposite faces is less than the one-cutout state and this decrease is less for smaller cutouts.

3-We observe that the critical buckling load in most of experimental tests is averagely %2.5 higher than the results obtained from the finite elements analysis .

4-Upon the increasing of the columns length, the buckling load is decreased for the cutouts located in same position. In fact upon the increase of L/b ratio the buckling load is decreased. In accordance with the tests and the finite elements method analysis, we observe that changing the location of cutout of same shape doesn't have a tangible effect on the critical buckling load, but upon the increasing the length of the samples, this change will influence the buckling capacity.

5-Finally we can state that the critical buckling load is the same for the cases that cutouts have same section area, but having different shapes (square and circle) and was not affected upon the changing the type of the cutout.

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