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Numerical and Experimental Investigation of Loading Band on Buckling of Perforated Rectangular Steel Plates

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Abstract

The aim of this paper is to investigate the buckling behavior of the steel rectangular plates with circular and square cut outs under uniaxial in-plane compressive loading in elasto-plastic range with various loading bands using the numerical and the experimental methods. Some effective parameters on the buckling of plates have been studied separately and the required data for analysis have been gained through the experimental tests. The finite element Abaqus software has been used for the numerical analysis and a set of servo hydraulic INSTRON8802 was applied in the experimental tests. Numerical and experimental results show good agreement with each other.

Keywords: Buckling, steel plates, cut out, finite element, loading band.

Introduction

Thin-walled members are the elements of many engineering structures. They become unstable and start to buckle if they subjected under a compressive loads greater than their ultimate buckling load. Moreover, some of these members usually have cut outs due to their applications and these discontinuities can affect on their stability.

The stability analysis of thin-walled structures under axial compression has been investigated by some researchers[1-3]. Obviously, the stability of these structures is dependent on the type of support and loading. The buckling and the geometrically nonlinear elasto-plastic collapse of perforated plates were investigated using finite element solutions[4]. Elasto-plastic postbuckling of damaged orthotropic plates based on the elasto-plastic mechanics and continuum damage theory have been studied[5]. El-Sawy et al[6] employed the FEM to determine the elasto-plastic buckling stress of uniaxially loaded square and rectangular plates with circular cutouts. Plates with simply supported edges in the out-of-plane direction and subjected to uniaxial end compression in their longitudinal direction were considered.

The nonlinear mathematical theory for initial and post local buckling analysis of plates of abruptly varying stiffness have been established by Azhari et al[7] using the principle of virtual work. In another numerical investigation, the foundations of the design of perforated trapezoidal sheeting on effective stiffness values for perforated sheeting with different arrays of holes are provided by Kathage et al.[8] Liu and Povlovic[9] revisited the stability of simply supported rectangular plates under patch compression using Ritz's energy method. Both single and double Fourier series are adopted as deflection series to compute the values for buckling coefficients. An experimental and numerical study on buckling of thin-walled cylindrical shells under oblique Loading were done by Shariati et al.[10] they Investigations on buckling and postbuckling behavior of stainless steel 316ti cylindrical shells with cutout. Also in another study Shariati et al[11] investigate the buckling of tubular steel shells with circular cutout subjected to combined loading. In their study the influence of shell length, shell diameter, shell angle and diameter of circular cutouts on the predicted buckling values has been explored.

The elastic buckling behaviors of rectangular perforated plates were studied using the finite element method by Komur and Sonmez[12]. To evaluate the effect of cutout location on the buckling behavior of plates, they chose circular cutout at different locations along the principal x-axis of plates subjected to linearly varying loadings. Their results shown that the center of a circular hole should not be placed at the end half of the outer panel for all loading patterns. A new approximate procedure for buckling analysis of simply supported rectangular stepped or perforated plates subjected to uniform edge stresses was formulated by Rahai et al[13]. The procedure uses energy method based on modified buckling mode shapes. Eccher et al[14] have been presented the application of the isoparametric spline finite strip method to the geometric nonlinear analysis of perforated folded-plate structures. Paik et al[15] has been studied the ultimate strength of perforated steel plates under axial compressive loading along short edges using FEM. The plates are considered to be simply supported along all (four) edges, keeping them straight. The cutout was circular and located at the center of the plate.

In this paper, the numerical and the experimental investigation on the buckling behavior of the rectangular plates with circular and square cut outs under uniaxial in-plane compressive loading in elasto-plastic range with various loading bands are performed. Moreover, the relation between stability of the rectangular plates having square and circular cut out with the same cross section has been studied. Several buckling tests were performed using an INSTRON 8802 servo hydraulic machine, and the results were compared with the results of the finite element method. A very good correlation between experiments and numerical simulations was observed. Finally, based on the experimental and numerical results, formulas are presented for the computation of the buckling load in such plates.

Material and Methods

The geometry and type of loading are shown in figure 1 in this figure, l is the loading band which varies in the range of ($0 \leq l \leq a$). The position $l=0$ is relates to the concentrated load exerted on the middle of the width of the plate, a, and the position $l=a$ represents to the distributed load exerted on the entire the width of the plate.

In this investigation, the structural steel rectangular plates with 100 x 150 x 2.07 mm dimensions are used. These plates have square or circular cut outs. The side of the square cut out is considered to be $e=30$ *mm* and for having the same area of two types of cut out, the diameter of the circle is considered to be $D=33.84$*mm*. The lower edge of the plates has been placed in the support (both simply and clamped support) and opposite edge has been exerted through a simply support with various bands. The tests have been conducted for the width of loading of l= 15,30,50,75 and 100 mm. The right and left sides of plates aren't constrained. In these tests, the post buckling behavior of the plates has been fully studied, too.

The mechanical properties of the tested structural steel plates have been specified through the tensile test in accordance with the ASTM-E8 standard using an INSTRON8802 servo hydraulic machine. Based on the linear portion of true stress-strain curve resulted of this test, the value of elasticity module and yield stress was obtained $E=218$*Gpa* and σ_y =349Mpa, respectively. Moreover the Poisson's ratio value is considered to be $\nu=0.33$.

The data of the plastic region of the stress-strain curve has been used for analysis of the plastic behavior in ABAQUS software.

Numerical analysis: In Abaqus software, after defining the geometry, boundary conditions and the applied loading, we must mesh the perforated plate to analyze. This is achieved using the S8R5 quadrilateral non-linear elements. The S8R5 element is very suitable for the element arrangement of the thin plates and shells[3].

After meshing specimens, a linear buckling analysis for getting eigenvalues is performed in ABAQUS and the buckling mode shapes are obtained. Since in eigenvalue linear analysis, the plastic properties of the specimen are not taken into account, overestimates the real value for buckling load.

Since buckling usually occurs in smaller mode shapes, a linear analysis should be performed first for all specimens, to find the mode shapes with smaller eigenvalues. In this step, three primary mode shapes were obtained. We used all three primary mode shapes in analysis, because these mode shapes have more effects on buckling behavior.

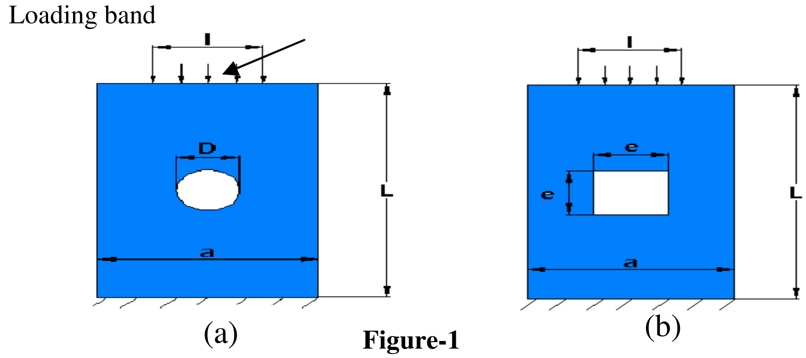
Effect of loading band on buckling behavior: In this part the effect of the loading band on buckling behavior of perforated plates has been numerically studied. Loading band is varied between 15 to 100 mm. The behavior of buckling load versus end shortening of plates (load-displacement curves) under various load bands for plates with no cut out and plates with square and circular cut outs with the simply and clamped supports have been displayed in figure 2 through 4, respectively. Note that all diagrams were presented in dimensionless using F_{ref} and height of plates, 150mm, for normalizing buckling loads and end shortening, respectively. F_{ref} is defined as follows:

$$F_{\mathrm{ref}} = at \times \sigma_y$$

Where F_{ref} is the reference load, the load required for the yielding of plates, a is the width of plates, t is the thickness, and σ_y is the yield stress. Therefore, the reference load of the specimens is calculated in this way

$$F_{\mathrm{ref}} = 100\,\mathrm{mm} \times 2.07\,\mathrm{mm} \times 349 \times 10^6\ \mathrm{N/mm}^2 = 72243\,\mathrm{N}$$

Load-displacement curves for plates with circular and square cutouts and perfect plate (with no cut out) for loading band l=100 mm with simply and clamp support are compared in figure 5 (a) and (b).



(a) (b)

Figure-1

The geometry of the plate and the type of the applied loading (a) The plate with circular cut out (b) The plate with square cut out

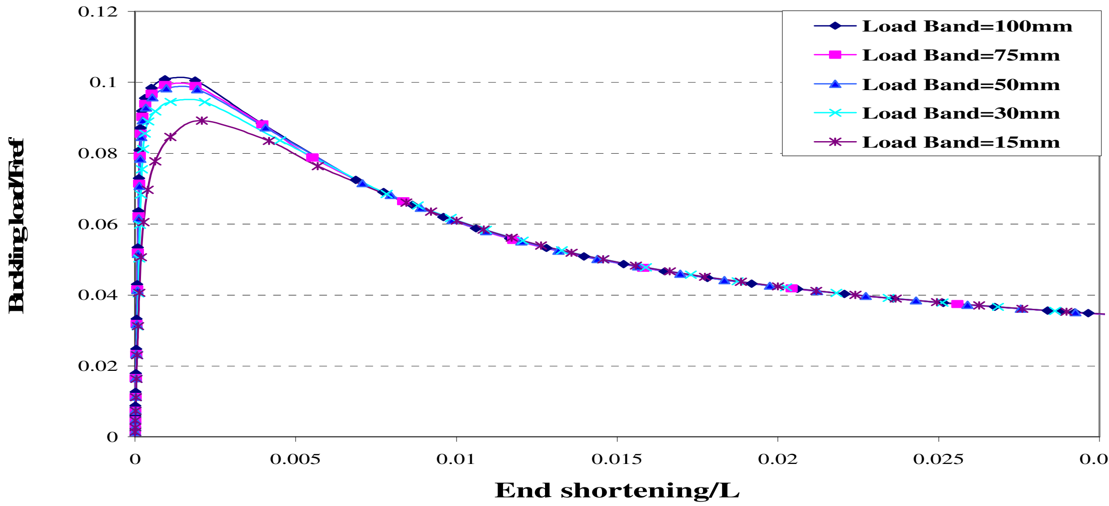


Figure-2

Load-displacement behavior of plate with no cutout and simply support at lower edge

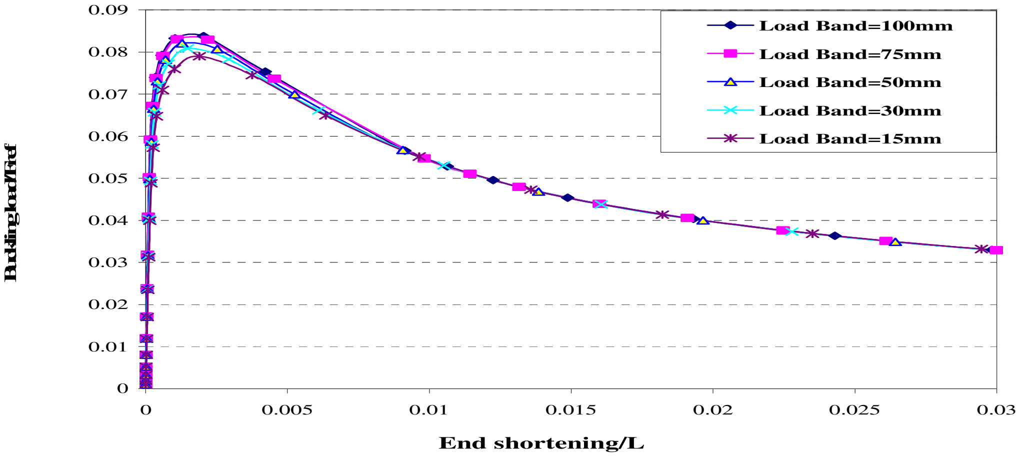


Figure-3

The behavior of the load-displacement of the plate with square cut outs and lower edge with simply support

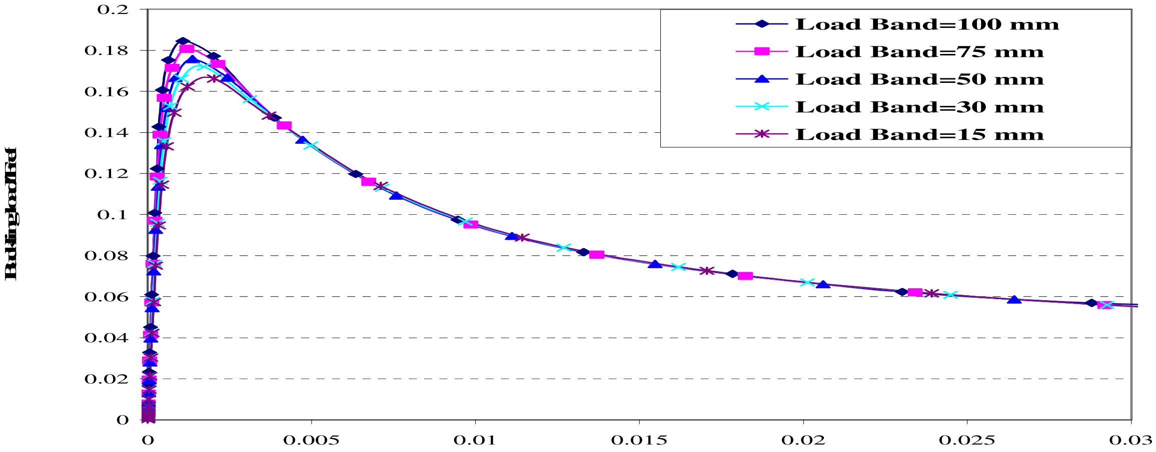
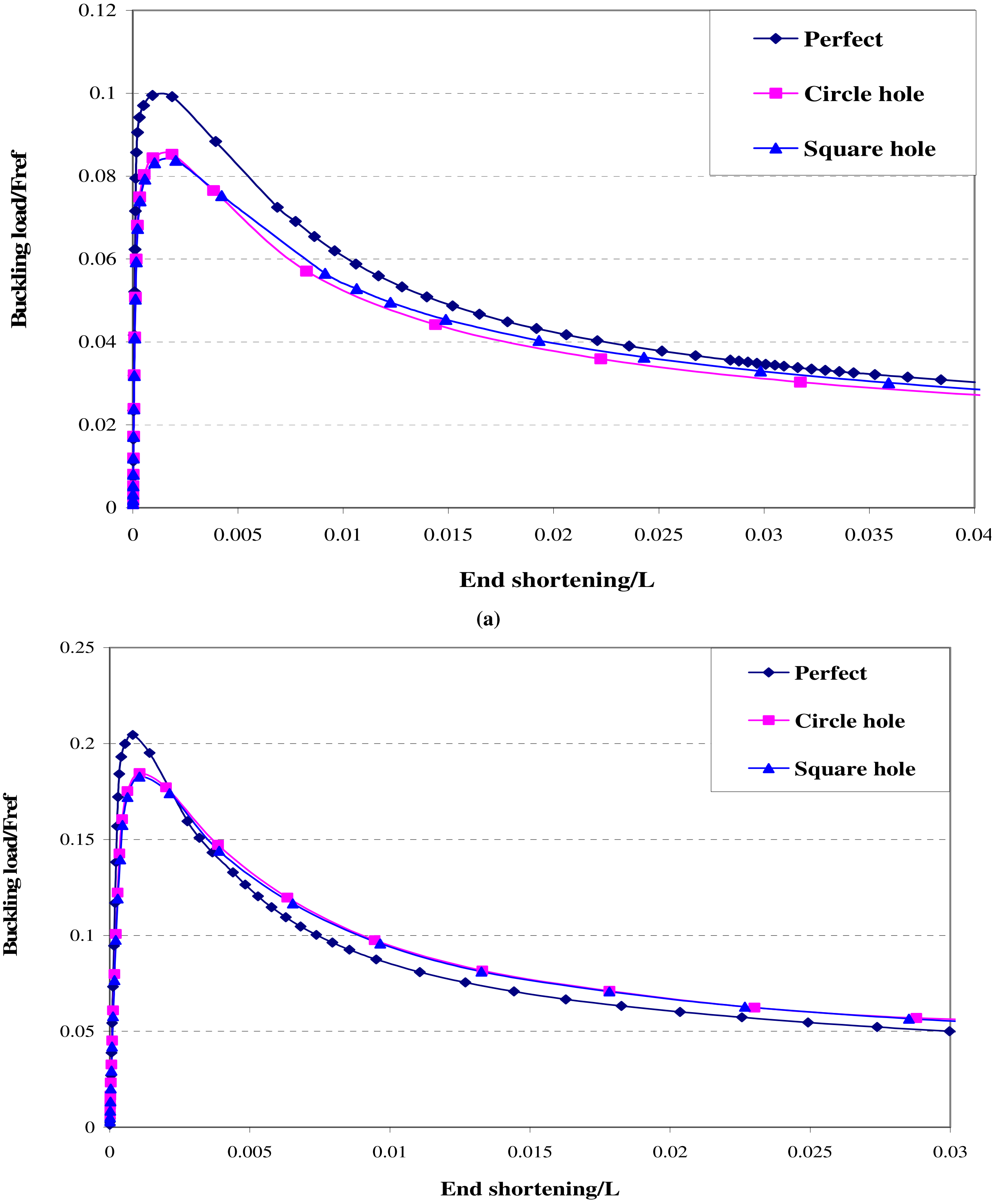


Figure-4

The behavior of load-displacement of the plate with circular cut out and lower edge with the clamped support



(a)

(b)

Figure-5

Comparison of load-displacement curves for plates with circular and square cutouts and perfect plate for loading band l=100 mm (a)- Simply support. (b)- Clamped support

Also the critical buckling loads of plates with and without cut out for different loading bands are given in tables (1) and (2)

Table-1
Numerical results of buckling load for plates with no cut out (perfect) and plates with circular and square cutouts under simply support at lower edge

Loading band (mm)	Critical buckling load with no cutout (kN)	Critical buckling load with circular cutout (kN)	Critical buckling load with square cutout (kN)
15	6.441	5.779	5.702
30	6.824	5.948	5.837
50	7.098	5.993	5.925
75	7.167	6.067	5.991
100	7.282	6.194	6.083

Table-2
Numerical results of buckling load for plates with no cutout (perfect) and plates with circular and square cutouts under clamped support at lower edge

Critical buckling load with square cutout (kN)	Critical buckling load with circular cutout (kN)	Critical buckling load with no cutout (kN)	Loading band (mm)
11.851	12.004	12.986	15
12.256	12.424	13.353	30
12.486	12.676	13.762	50
12.821	13.048	14.126	75
13.076	13.372	14.664	100

As shown in the curves, after the load of the plate reaches to the critical value, the buckling phenomenon is occurred and the plate is bent by a low force. Moreover it is observed that, as the load band increases, the ultimate value of the buckling load is also increased.

The changes of the buckling load in proportion to the loading band for two specimens with square and circular cut out have been numerically compared with two types of simply and clamped boundary conditions. These changes are also displayed in figure 6 The phrase "circle-simply support" indicates the specimen with the circular cut out which its lower edge has been placed inside the simply support and the phrase "square–clamp support" indicates the specimen with square cut out which lower edge has been placed inside the clamped support.

As indicated in figure 6, for one specific loading band and under the same boundary conditions, the buckling load of the specimen with circular cut out is a little higher than the buckling load of the specimen with square cut out. Owing to the less difficulties of manufacturing and creation of the circular cut out than the square cut- out and due to the higher buckling load of the specimen with circular cut out than the specimen with square cut out, it's recommended that use circular cut out for specimens which don't have any limitations on type of the geometry of cut out.

Furthermore, in this diagram, it is also observed that, the buckling load of each specimen with the clamped boundary conditions is so higher than the buckling load with simply boundary conditions. It's about twice bigger for each specimen, for this specific case study. Different experimental tests were conducted to confirm of the authenticity of the results obtained from the numerical method

Experimental results: The lower edge of the plates was placed in the simply or clamped support and their upper edge was placed in a simply support with various loading bands (figure 7). Also experiments are carried out under displacement control with speed of 0.01 mm/s.

Some results of experimental tests which were conducted on the rectangular plates with square and circular cut outs have been displayed in figure 8-9.

Results and Discussion

As shown in figure 8 and 9, the trend of the experimental diagrams is wholly similar to the trend of the numerical diagrams and upon the increase loading band; the buckling load is also increased. For better understanding of the results, the numerical and experimental quantities of the buckling load are compared in proportion to the boundary conditions and the various loading bands for the specimens having square and circular cut out in tables 3 through 6.

Table-3
The numerical and experimental critical buckling loads for plate with square cut out and the lower edge, simply support (average error = 8.05%)

Loading band(mm)	Numerical buckling load(kN)	Experimental buckling load (kN)	Numerical error (%)
15	6.124	5.702	6.89
30	6.317	5.837	7.59
50	6.486	5.925	8.65
75	6.590	5.991	9.08

Table-4
The numerical and experimental critical buckling loads for plate with circular cut out and the lower edge, simply support (average error =8.92%)

Loading band(mm)	Numerical buckling load(kN)	Experimental buckling load (kN)	Numerical error (%)
15	6.305	5.779	8.34
30	6.519	5.948	8.76
50	6.596	5.993	9.14
75	6.702	6.067	9.47

Table-5
The numerical and experimental critical buckling loads for plate with square cut out and the lower edge, clamped support (average error = 6%)

Loading band(mm)	**Numerical buckling load(kN)**	**Experimental buckling load (kN)**	**Numerical error (%)**
15	11.851	10.584	10.69
30	12.256	11.389	7.07
50	12.486	11.796	5.52
75	12.918	12.821	0.75

Table-6
The numerical and experimental critical buckling loads for plate with circular cut out and the lower edge, clamped support (average error for plates with cut out= 7.33%)

Numerical error (%)	Experimental buckling load (kN)	Numerical buckling load(kN)	Loading band(mm)
10.71	10.718	12.004	15
7.53	11.488	12.424	30
6.04	11.920	12.687	50
5.04	13.048	13.741	75

In figure 10, the ultimate value of the buckling load calculated from the numerical and experimental analyses for some various loading bands and the end of the clamped support have been compared with each other for circular and square cut outs.

Based on the experimental buckling loads of plates, formulas are presented here using Lagrangian polynomial for the computation of the buckling load of plates with circular and square cut outs subject to axial compression. To get these formulas with using Lagrangian polynomial method[19], the curves were passed through the buckling load values. In these formulas F and l are buckling load for plates with cutout and loading band, respectively. The general form of F is as follows:

$$F = A + Bl + Cl^2 + Dl^3 + ... \qquad (1)$$

The coefficients A, B, C, D, … are computed using Lagrangian polynomial. The formulas for computation of the buckling load of plates with circular and square cutouts are represented in equations 2 and 3, respectively. For plates with circular cut outs:

$$F = 3E(-0.05)l^3 - 0.004l^2 + 0.179l + 8.82 \qquad (2)$$

And for plates with square cut outs:

$$F = 2E(-0.05)l^3 - 0.003l^2 + 0.163l + 8.793 \qquad (3)$$

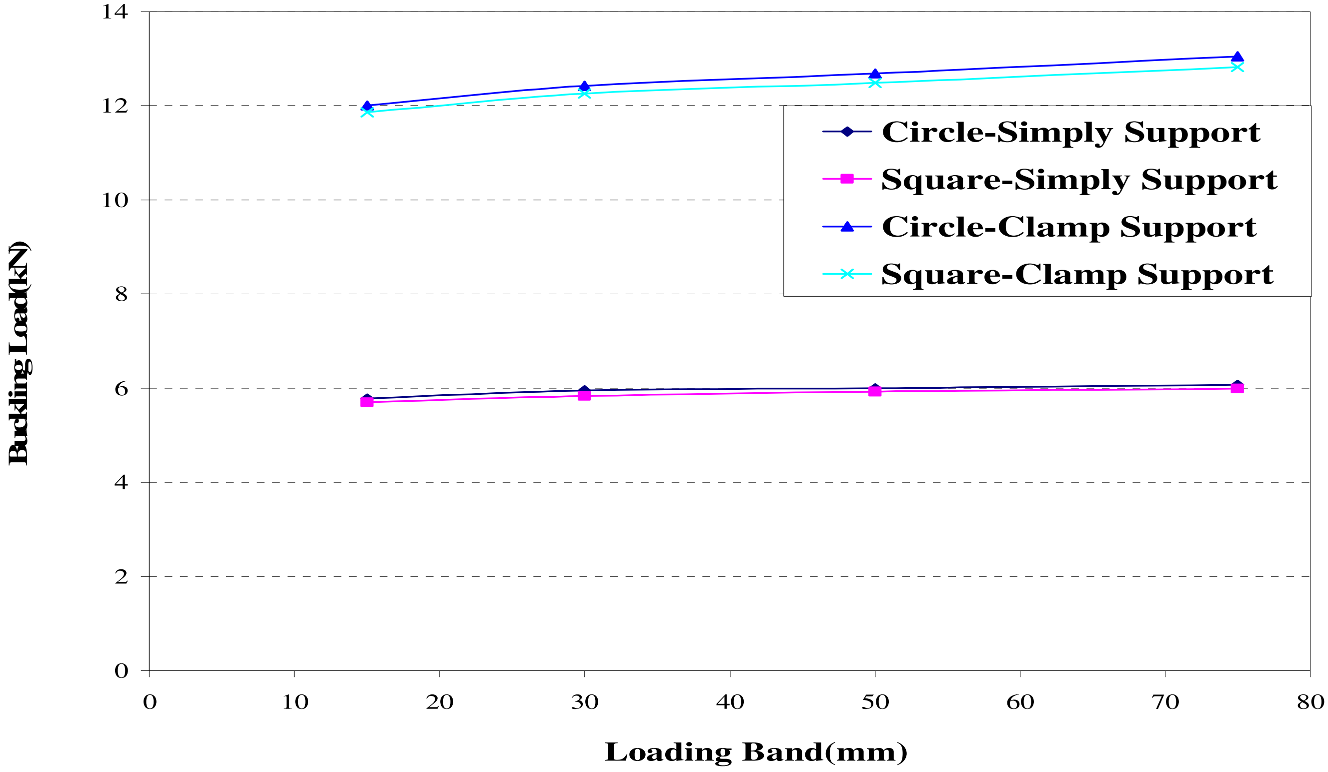


Figure-6
Changes of buckling load with loading band for various cut outs and supports

Figure-7
The setup of experimental tests (in this case, both of the supports are simply)

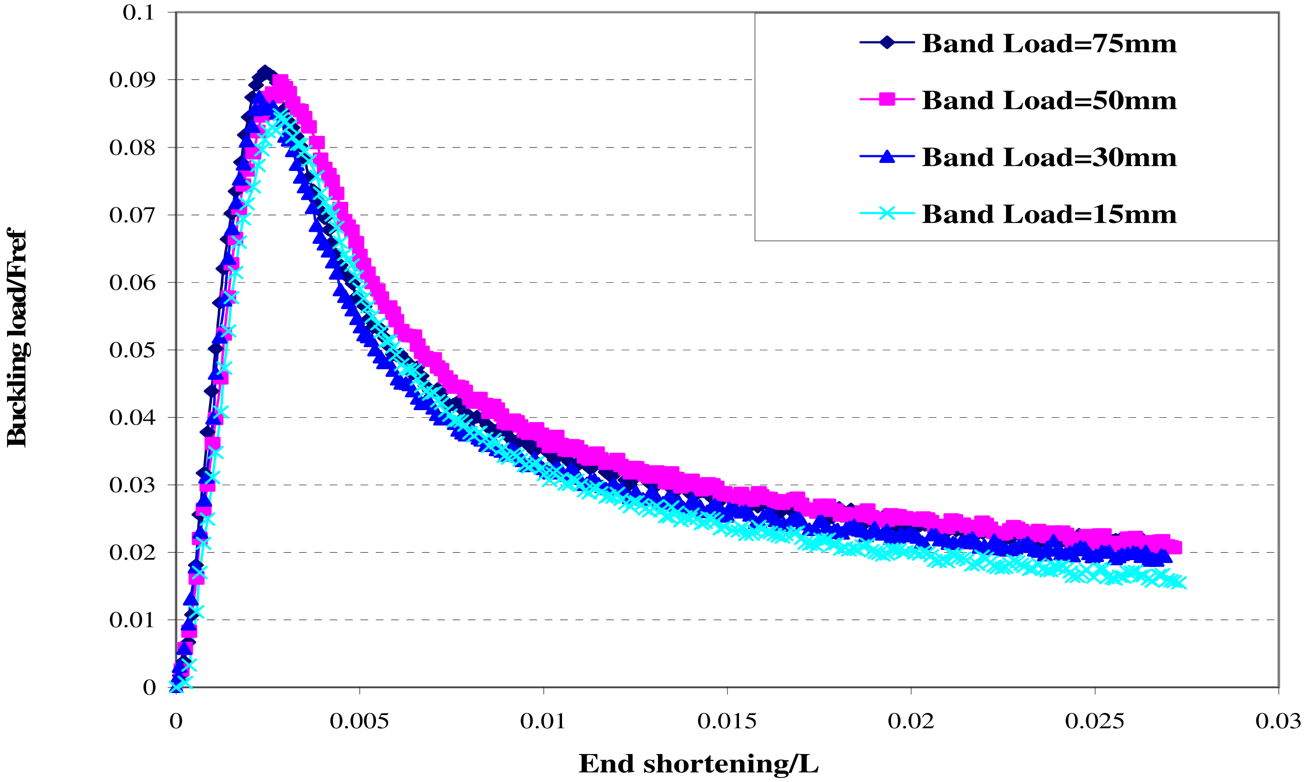


Figure-8
The behavior of the load-displacement of the plate with circular cut outs and lower edge with simply support from experimental tests

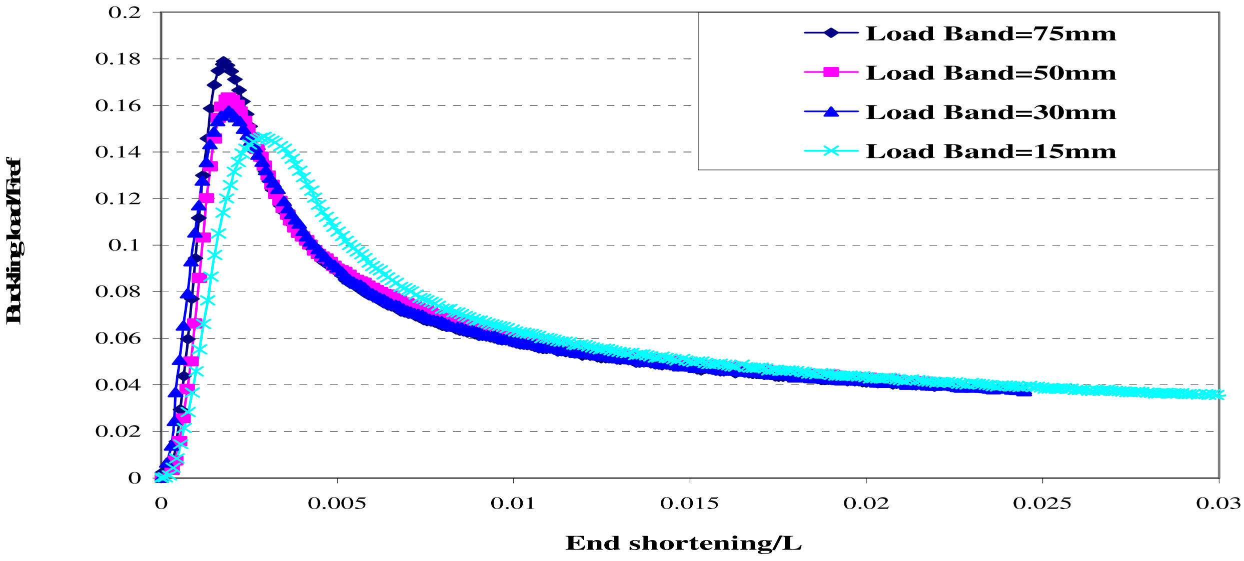


Figure-9
The behavior of load-displacement of the plate with square cut out and lower edge with the clamped support from experimental tests

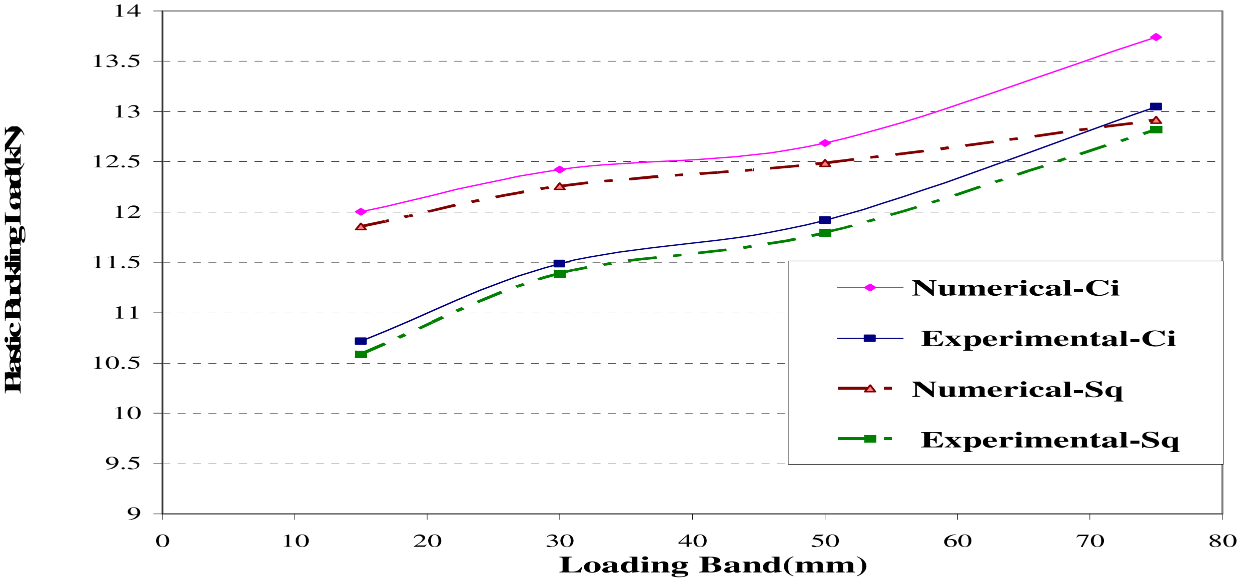


Figure-10
Effect of loading band on buckling load in numerical and experimental analyses of plates with circular and square cut outs and clamped support

Conclusion

We can conclude from the results obtained in this research that: when the buckling phenomenon occurs, the capacity of the load toleration is considerably decreased. The results show that, as loading band increases, the ultimate buckling load also increases. The buckling load of the specimen with circle cut out is a little more than the specimens with the square cut out with the equal surface area, therefore it's suggested that if there is no limitation in manufacturing process, the specimens with circular cut out are appropriate, because the Production of circular cut outs are very easier than square cut outs. The buckling load of the plates with the clamped support is about twice bigger than plates with simply support. Numerical and experimental results are in good agreement with each others.

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