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Behaviour of Steel Tubes with Circular Cutouts – A Numerical Study

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Abstract

In this paper, simulation and analysis of steel tubes of various lengths and diameters with circular cutouts have been studied using the Finite Element (FE) method and the effect of cutout position, Length-to-Diameter(L/D) ratio and Diameter-to-Thickness(D/t) ratio on the buckling and post-buckling behaviour of steel tubes have been presented. The provision of a circular cutout in a steel tube shows a reduced stress concentration compared to cutouts of other shapes due to the even distribution of stresses. For 495 FE models, linear and non-linear analysis was performed using ABAQUS/CAE 2020 and the results of steel tubes with varying cutout positions were compared. A very good correlation was observed between numerical simulation and theoretical investigation. Weibull reliability analysis was performed using Minitab software. Finally, based on the numerical and theoretical results, formulae for predicting the buckling load of steel tubes with circular cutouts have been proposed.

Key words : *Steel tube, Circular cutout, FE Analysis, Reliability Analysis*

Introduction

Circular steel tubes are widely used in many industrial applications such as pipeline construction, wind turbine towers, foundation piles, and columns in tall buildings[1]. Cutouts are provided in steel tubes for easy installation of columns and also to relieve the stress induced in the column. Several researchers have carried out investigations on tubes with cutouts. Han et al. investigated the quasi-static and dynamic crushing behaviours of aluminium and steel tubes with cutouts. Empirical equations describing the mean and peak crushing forces of aluminium and steel tubes with cutouts were developed using linear and non-linear regression methods[2]. Shariati et al. carried out numerical and experimental investigations on the buckling of steel cylindrical shells with elliptical cutouts subjected to axial compression and concluded that a good correlation was observed between numerical simulation and experimental results and also proposed a formula for finding the buckling load of this structures[3]. Shariati et al. investigated the buckling of steel cylindrical shells with an elliptical cutout and proposed equations in the form of buckling load reduction factor[4]. Ghazijahani et al. studied the influence of cutout on circular steel hollow sections under cyclic loading and proposed optimal cutout diameters at which the stress concentration is significantly relieved[5]. The structural behaviour of shells with cutouts under compression was also studied. The main focus of the study was tubes with a door-shaped cutout under axial loading. The height and shape of the cutout were found to have no significant effect on the capacity[6]. Subramanian et al. numerically analyzed GFRP stiffened composite plates with rectangular cutouts to determine the type and size of reinforcement required for restoring the lost strength and stiffness.[7]. Shareef et al. carried out an experimental investigation to study the impact of holes on the buckling of Rectangular Hollow Steel (RHS) columns and the experimental results indicated

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the typical failure mode for all the tested hollow specimens was local buckling. The test results indicated that increasing hole dimension leads to a reduction in ultimate loads of tested column by up to 75%[8]. Qingxin et al. studied the influence of circular cutouts on infilled steel tubes and proposed an equation to predict the ultimate strength of concrete-filled steel tube stub columns with cutouts[9]. Nabati et al. studied the effect of CFRP strengthening on circular steel tubes with rectangular cutouts under axial load. It was found that utilizing CFRP in certain locations with specific dimensions and layers transfers the stress concentration from critical areas and CFRP has a significant effect on redistributing stresses and directing critical stresses to areas where the tubes can withstand higher stresses to recover capacity[10]. Kursun et al. concluded that the critical buckling load for all types of fiber orientation angles is maximum for specimens without a hole and lowest for specimens with a 40mm hole diameter for laminated composite plates[11].

The experimental and numerical investigations of the steel tubes with cutouts subjected to axial compression have been carried out by Shariati et al., Ghazijahani et al., and Shareef et al. Compared with the extensive studies carried out on steel tubes with cutouts, very limited research has been conducted on the circular hollow sections with cutouts in the steel tubes[3,5,6,8]. Understanding the impact of circular cutouts located at various locations of circular tubes of varying length and size is needed for maintenance purposes, a passage for electrical wires and hydraulic lines, and to reduce the self-weight of the circular tubes. The objective of this paper is to understand the influence of cutouts on the buckling of circular hollow steel tubes. In this paper, the results of the linear and non-linear analysis carried out on axially loaded steel hollow tubes with and without cutouts using the ABAQUS CAE/2020 finite element software are reported. Steel tubes with varying D/t ratios and L/D ratios were studied. A parametric study has been carried out varying the dimensions and position of cutouts as shown in **Table 1**.

Table. 1. Dimensions and Notations of Steel Tubes Investigated

Diameter of steel tube (D)	Thickness of steel tube (t)	Length of steel tube (L)	Diameter of cutout (a)	Position of cutout (H)
D_1 - 100mm, D_2 - 150mm, D_3 - 200mm	t_1 - 1mm, t_2 - 2mm, t_3 - 3mm, t_4 - 4mm, t_5 - 5mm	L_1 - 450mm, L_2 - 900mm, L_3 - 1350mm	a_0 - 0, a_1 - 0.1D, a_2 - 0.2D, a_3 - 0.3D, a_4 - 0.4D, a_5 - 0.5D	H_1 - $\frac{L}{2}$, H_2 - $\frac{L}{3}$

Numerical analysis

The numerical simulations were carried out using the general finite element program ABAQUS/CAE 2020.

Element formulation of the specimens

For modeling the steel tube linear element S4R which is a four-noded doubly curved rectangular element with six degrees of freedom per node was used. The refinement of mesh size is about 3mm as shown in **Figure 1.**

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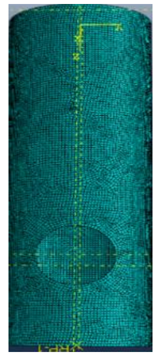

Figure 1. Meshed FE Model

Analytical process

The linear eigenvalue analysis is carried out to predict the buckling load and deformed buckling mode shapes. Buckling usually occurs in the primary mode shapes. For this, the subspace solver method is used. However, this is not enough to find the load – end-shortening behaviour of steel tubes, therefore an additional geometric non-linear analysis was performed. A non-linear static analysis is required if there is any static value in which the stiffness of the entire structure changes during the loading. This way of simulation must be solved incrementally to know the changes in stiffness. The Static-Riks method is used for non-linear analysis to investigate the post-buckling behaviour of the steel tube and to study the influence of geometric deformation.

Validation of FE Model

Shariati et al. carried out numerical and experimental investigations on the buckling of steel cylindrical shells with elliptical cut-outs subjected to axial compression[3]. The stress-plastic strain curves used for this study are taken from Shariati et. al[3]. The assigned sectional properties and element types are given in **Table 2**. All degrees of freedom at the bottom plate and the upper plate except in the direction of the longitudinal axis were constrained.

Table. 2. Assigned Sectional Properties and element type

Part	Steel
Modelling Space	3D
Type	Deformable
Basic Shape	Shell
Feature Type	Extrusion
Section Category	Shell
Section Type	Homogeneous
Element Type	S4R Shell Element S8R5 Element

Table. 3. Specimen Details and Comparison of Results

Model Designation	Cutout Size	Location of cutout	Element Type	Buckling Load (N)		$\frac{F_{Shariati}}{F_{FE}}$
				Shariati et. al	FE Model	
D42-L420-Perfect	-	-	S4R	23285.2	23298.6	0.99

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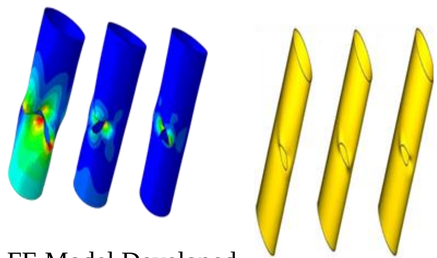
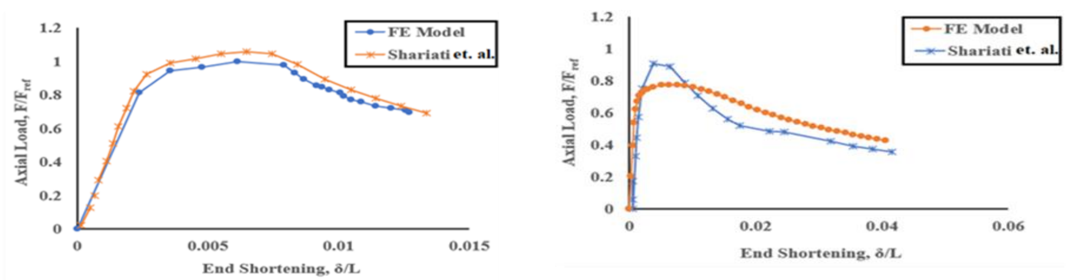
D42-L420-Perfect	-	-	S8R5	22792.8	21544.3	1.05
D42-L120-Lo60-8-17.6	8 x 17.6	0.5	S4R	19760.8	17998.8	1.09
D42-L120-Lo60-8-17.6	8 x 17.6	0.5	S8R5	19120.4	17585.0	1.08



(a). FE Model Developed by the Authors (b). Shariati et. al.

Figure 2. Buckling Mode Shapes

Table 3 shows the comparison of FE model results with the results obtained by Shariati et al[3]. The coefficient of variation is found to be 1.05. **Figure 2** shows the three eigen buckling mode shapes for the specimen with a shell length of 120mm and diameter of 42mm with an elliptical cutout of size 8×17.6mm. The load-end shortening curves for a cylindrical shell with and without cutout are shown in **Figure 3**. Shariati et al. used buckling of a reference cylindrical shell (F_{ref}) for making the buckling load dimensionless[3], which is defined as $F_{ref} = \pi D t \times \sigma_y$; where F_{ref} – reference load, D – diameter, t – thickness of the shells, σ_y – yield stress.



(a). D42-L420-Perfect (a). D42-L120-Lo60-8-17.6

Figure 3. Load-End Shortening Behaviour of Cylindrical Shells with and without Elliptical Cutout

Results of Numerical Analysis

Linear Analysis

In the case of steel tubes without a cutout, increasing the diameter of the steel tube, the buckling load increases as shown in **Figure 4(a)**. The reduction in the buckling load with the increase of the diameter of steel tubes from 100mm to 200mm for long, intermediate, and short lengths of steel tubes with a thickness of 3mm was about 70%, 69% and 68% respectively. Steel tubes with a larger diameter are more resistant to buckling.

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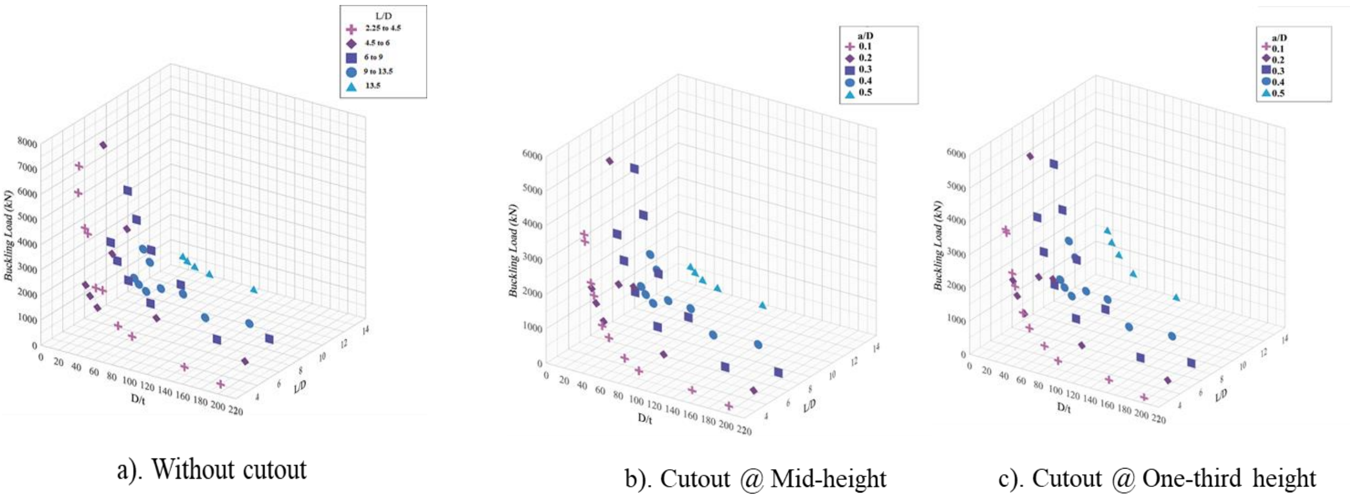

Figure 4. Buckling Load of Steel Tubes

Figure 4(b) shows that when D/t decreases, buckling load increases by 71.8%, 47.68%, 36.84%, and 26.84% in relation to the thickness of steel tube from 1mm to 5mm, and when L/D increases, buckling load decreases by 72.48%, 50.16%, 38.73%, and 27.58% in proportion to the size of the cutout varying from 0.1D to 0.5D at the mid-height position of the steel tube. Buckling load decreases by 20%, 25%, 33.33%, and 67.8% as D/t increases for different thickness ranging from 1mm to 5mm, and buckling load increases by 19%, 35%, 47%, and 69% as L/D decreases for the size of the cutout at the one-third position of the steel tube as shown in **Figure 4 (c).** Buckling occurs locally first in steel tubes with cutouts, followed by crushing.

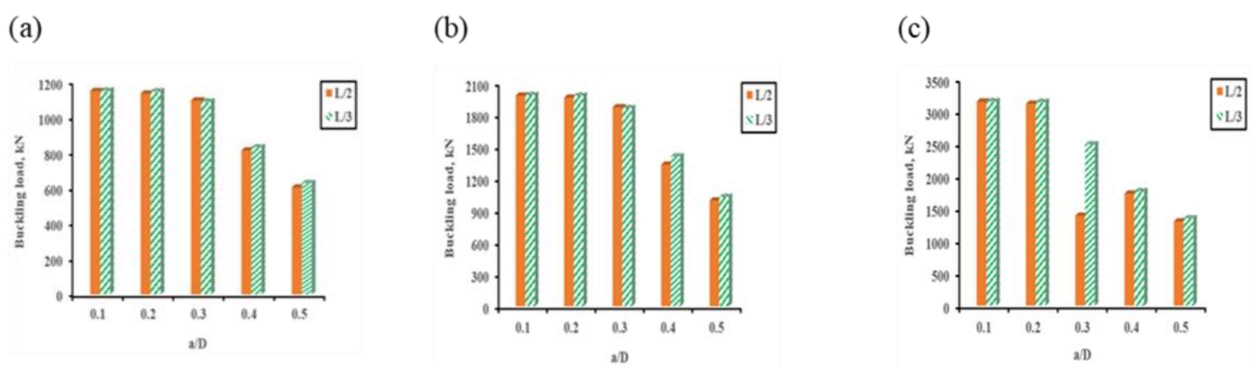

Figure 5. a/D vs Buckling load

Figure 5 (a-c) shows that changing the position of the cutout from the steel tube's mid-height to the one-third height increases the buckling load by 5%. Buckling load decreases by 47.9%, 37.5%, 26%, and 20% as the cutout size increases from 0.1D to 0.5D, respectively.

Non-Linear Analysis

In this section, the results of the non-linear analysis of the steel tube with and without circular cutouts placed at various positions are discussed. **Figures 6 (i) &6 (ii)** show the load - end-shortening behaviour of the models. The axial stiffness of the cutout size ranging from 0.1D – 0.2D was raised by reducing the size of the cutout, however, the stiffness of the cutout size ranging

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from 0.3D – 0.5D was unaffected. **Figure 6 (i) (a)** demonstrated an excellent plastic response after yield, proving the effect of the cutout in improving post-yield ductility. **Figures 6 (i) (e–h)** exhibited better post-yield ductility, whereas **Figure 6 (i) (g)** indicated a steeper load reduction after the peak load. Even though, **Figures 6 (i) (e-h)** had shown a mild transition of deformations from the steel to the cutout area, which increased ductility. The stiffness was reduced dramatically in the specimens with larger cutout sizes. Even so, the ductility of long columns is significantly smaller than in short columns. The load–end shortening curves of steel tubes with cutouts at the position of L/2 and L/3 are compared in **Figure 6 (i) (a-h)**. As can be seen from the graph the slope of the linear part of load-end shortening curves is higher in the position of the cutout at L/2 where the a/D ratio is small. The position of cutout does not matter until a/D is 0.3. The results indicate that increasing the thickness enhances the steel tube buckling resistance and increases the ultimate load. Despite the smaller diameter-to-thickness ratio, steel tubes retain the same stiffness. If there is an increase in the a/D ratio, the ultimate load decreases, and also if there is a smaller L/D ratio, the ultimate load increases. Furthermore, if there are a decrease in the D/t ratio, the buckling load increases, and if there is increasing the diameter of the steel tube, the buckling load also increases. A smaller D/t ratio with a higher L/D ratio attains the lowest ultimate load. The maximum ultimate load is achieved by the steel tube with a 0.4D cutout.

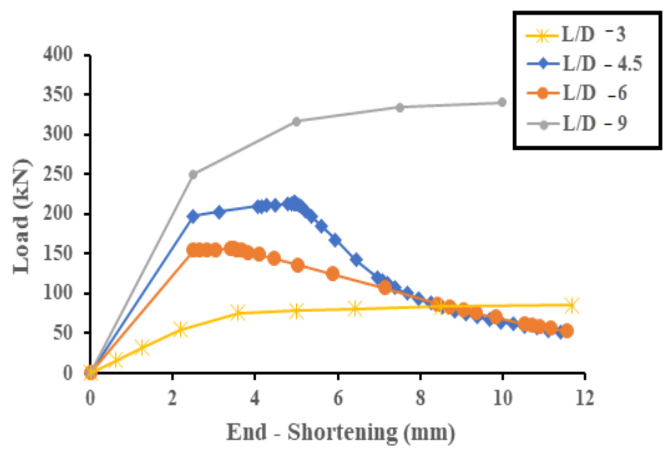

Figure 6 (i). Load-End Shortening Behaviour of Steel Tubes without Circular Cutout

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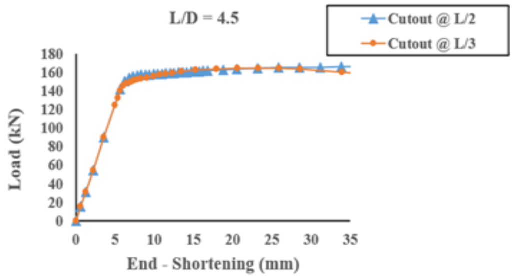
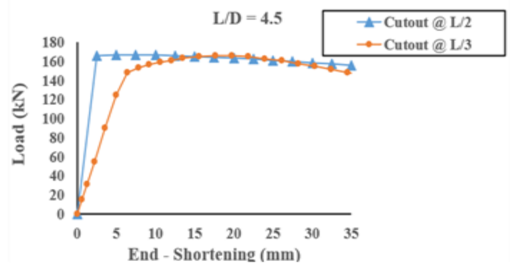
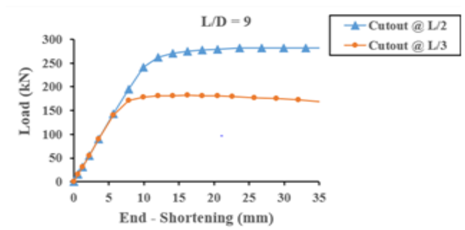


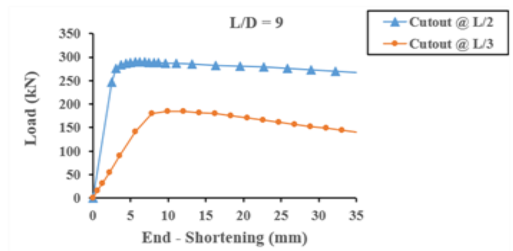
. $D_1 - t_3 - L_1 - a_1$; $D/t = 33.33$ & $a/D = 0.1$



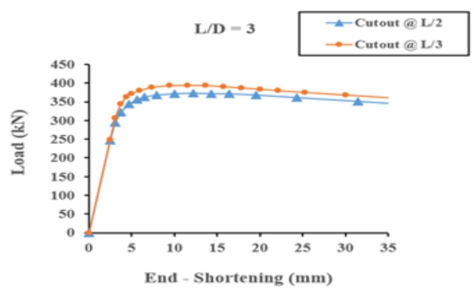
(b). $D_3 - t_3 - L_2 - a_1$; $D/t = 66.67$ & $a/D = 0.1$



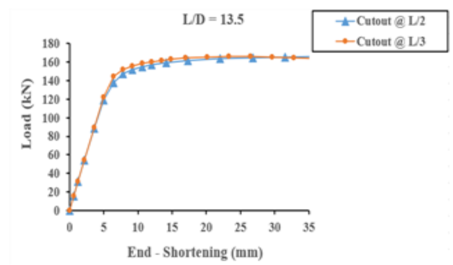
(c). $D_1 - t_2 - L_2 - a_2$; $D/t = 50$ & $a/D = 0.2$



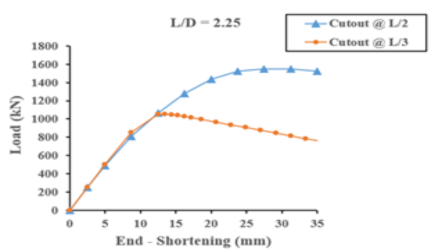
(d). $D_2 - t_2 - L_3 - a_2$; $D/t = 75$ & $a/D = 0.2$



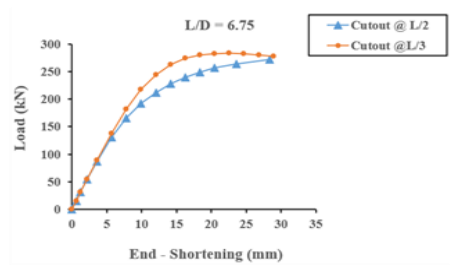
(e). $D_2 - t_4 - L_1 - a_3$; $D/t = 37.5$ & $a/D = 0.3$



(f). $D_1 - t_4 - L_3 - a_3$; $D/t = 25$ & $a/D = 0.3$



(g). $D_3 - t_5 - L_1 - a_4$; $D/t = 40$ & $a/D = 0.4$



(h). $D_3 - t_2 - L_3 - a_5$; $D/t = 100$ & $a/D = 0.5$

Figure 6 (ii). Load-End Shortening Behaviour of Steel Tubes with a Circular Cutout

Comparison with Available Design Specifications

The numerical results are closely correlate with EC3, AISC, AUS, and IS within a margin of 68%, 70%, 62% and 60% respectively. The comparison of results indicates that the predicted ultimate load for steel tubes without cutout from all the codes is much higher compared to the numerical values. [12-16] However, for a smaller L/D ratio with a decrease in D/t ratio, the steel tubes without cutout prediction of ultimate load by the codes are fairly good.

Stress Concentration

It occurs when internal force lines are denser near the hole. **Lurie et al. (1959)[17]** investigated the stress state around a circular hole in a circular cylindrical shell under internal pressure by a perturbation method in terms of a curvature parameter β defined as $\beta^2 = \frac{a^2[12(1-v^2)]^{\frac{1}{2}}}{8Rh}$ where a is the radius of a circular hole; v is the Poisson's ratio; R is the radius of the shell; h is the thickness of the shell. The theoretical stress concentration factor (K_t) was taken from the Peterson charts for the design factors for stress concentration. If the cutout size increases, stress concentration factor decreases by 7.7%, 4.4%, 4.1% and 4.3% respectively.

Reliability Analysis

Reliability analysis is done by using Minitab software which introduces reliability analysis tools that can be used to perform tasks that range from checking the distribution of values by the Right censoring method. In this analysis, the ultimate load of numerical analysis, and codal values of steel tubes without cutout have been taken in terms of kN to find the distribution of the ultimate load values in various forms of various distributions such as Weibull, Lognormal, Exponential, and Normal. Based on the value of Anderson-Darling goodness of fit the appropriate distribution for the present analysis is chosen. Overall, among the four distributions, Weibull and lognormal distribution show a good correlation compared to other distributions. So, we consider Weibull distribution analysis. The estimated load values are found to be more than 90% reliable based on the reliability analysis. The reliability confidence curve is shown in **Figures.7(a-e).**

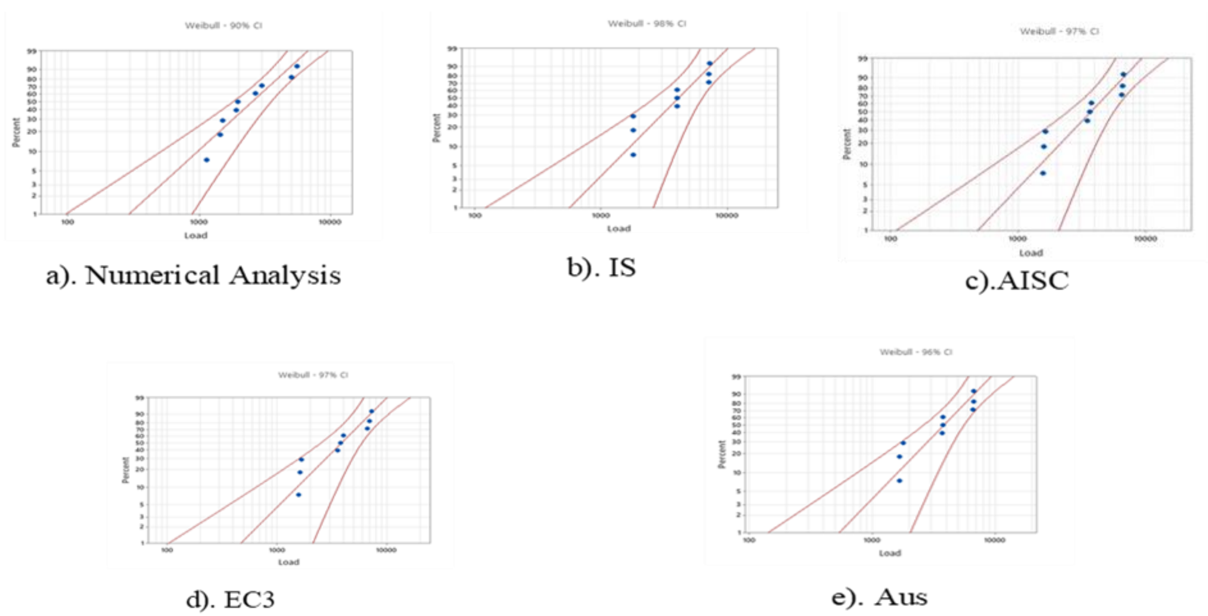


Figure 7. Reliability Confidence Curve

Predicted Equations

Marc[18] allows the use of the eigenvalue method for non-linear buckling analysis based on the incremental stiffness matrices. The buckling load is estimated by

$$P_{buckle} = P_{beginning} + \lambda\,(\Delta p) \quad (1)$$

where

P_{buckle} - Buckling Load

$P_{beginning}$ - Load applied at the beginning

λ - Eigen value

Δp - Load increment

Based on the equation (1) which was created by **Marc**[17], the formula was modified to calculate the buckling load for short, intermediate, and long steel tubes with circular cutouts with an accuracy of 88%. The graph was plotted between the results of buckling load from the proposed equation and FE results as shown in **Figure 8 (a-b)**.

$L \leq 450$mm,

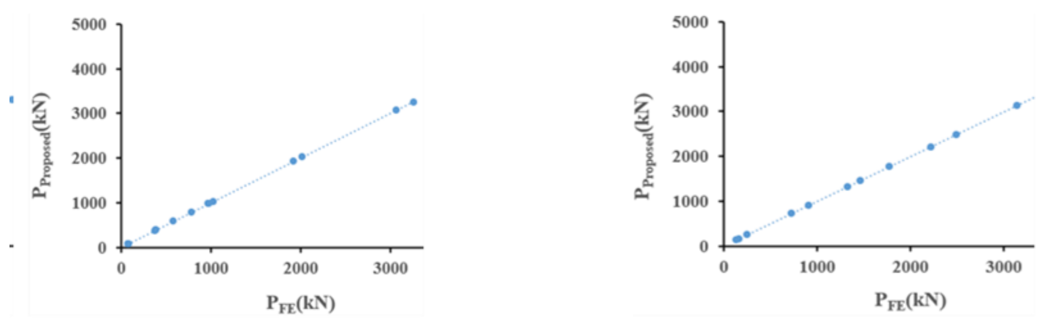
$$P_{Cutout} = 1.12\,[P_{applied} + \lambda\,(\Delta p)] \quad (2)$$

$L > 450$mm and < 900mm,

$$P_{Cutout} = 2.24\,[P_{applied} + \lambda\,(\Delta p)] \quad (3)$$

$L > 900$mm and < 1350mm,

$$P_{Cutout} = 3.36\,[P_{applied} + \lambda\,(\Delta p)] \quad (4)$$



(a). Cutout @ Mid-height (b). Cutout @ one-third height

Figure 8. P_{FE} vs $P_{Proposed}$

Conclusions

In this study, we used numerical analysis to determine the buckling load of steel tubes with circular cutouts of varying D/t, L/D and a/D ratio. The following conclusions were found in this study:

- Changing the position of small sized cutouts (0.1D to 0.5D) from mid-height to one-third height only margin <5% influence the buckling load.
- Increasing the size of cutouts for 0.1D to 0.5D substantially reduces the buckling load by about 48%.
- Decreasing the D/t ratio from 200 to 20 increases the buckling load by upto 70% irrespective of cutout size and location.

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- The FE model developed using ABAQUS is found to closely simulate the buckling behaviour of with and without cutouts. The results are found to be 90% reliable.
- The proposed equation for the prediction of buckling load of steel tubes with circular cutouts is found to give reasonable results with an accuracy of 88%

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