Experimental and numerical investigations on overall buckling of steel pipe truss with circular cutout on the compression element

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Abstract. Pitting corrosion, an extremely localized corrosion that leads to the creation of small holes in metal when a protective coating is damaged could trigger structural failure in platform structures. A single pit in a critical point, especially in compression element, can cause a great deal of reduction in overall buckling capacity of the structure. This study aims to indicate the effect of a circular cutout, representing a pitting corrosion on overall buckling capacity of steel pipe truss structure subject to static loading. Five models of truss structure having a circular cutout on their compression elements had been tested experimentally up to failure. The truss structures were made of steel pipes and contain only 2 elements as representation of part of real platform. The single cutout were located at 0.5L, 0.25L and 0.125L, where L is the length of the compression element. Two models without cutout had been used as control models. The overall buckling capacity of the truss were compared to similar truss based on the element buckling of compression element. The experimental test results, represented by nonlinear load deflection curves and their associated critical loads as well as buckling modes, had been verified numerically by eigenvalue and geometric nonlinear finite element analyses utilizing 3D solid elements on ABAQUS. The results showed that: (a) in the truss model with various hole positions, the overall buckling loads were slightly higher than that of element buckling loads: (b) the presence of cutout reduced the overall buckling capacity of the structure, (c) the capacity reduction factors depend on the cutout locations and (d) the lowest capacity reduction factor of 0.882 was associated with the presence of cutout at the middle of compression element.

1 Introduction

Tubular members are commonly found in offshore platform structures. In marine environment, the highest corrosion rate is in the splash zone and tidal zone, which is commonly protected by coating material. Pitting corrosion, an extremely localized corrosion that leads to the creation of small holes in metal when a protective coating is damaged could trigger structural failure in platform structures. A single pit in a critical point, especially in compression element, can cause a great deal of reduction in the overall buckling capacity of the structure.

Since the compression element with cutout is connected to other elements to form a structural system, the existence of hole will affect the overall buckling of the structure. History records a considerable number of buckling failures occurred in the tubular steel platform structure due to the combination of pitting corrosion and fatigue problems [1].

Some codes and design standards have provided a formula for buckling analysis in per-element (individual) basis, however the effect of hole or other localized defects has not been taken into account on the buckling capacity of the compressive elements as well as overall buckling capacity of the structure.

When defect like a hole resulting from pitting corrosion presence on the member, the Euler’s buckling formula given in Eq. (1), where \( P_{cr} \), E, I, k and L is respectively, the critical buckling load, modulus of elasticity, cross sectional moment of inertia, effective length factor which depends on the end support conditions, and length of the member, is no longer valid.
applicable due to its 1-Dimensional nature of formulation.

\[ P_{cr} = \frac{\pi^2 EI}{(kL)^2} \]  

(1)

Some experimental studies on the buckling capacity of tubular member with circular cutout at different location on the element have been reported, and the effect of diameter as well as number of holes on the buckling failure of the member element has also been carried out [1].

Several studies on the buckling capacity of tubular member with cutout have been conducted, both experimentally and numerically. Some of them used aluminum pipes with square holes [3], and the others used stainless steel pipe with ellipse holes [4]. Their results provided an empirical formula for predicting the buckling capacity of tubular member with cutout by introducing the reduction factor due to hole effects, with various hole shapes [5], [6], [7].

This study aimed to investigate the effect of a circular cutout (representing a pitting corrosion) that exist in compression member, on the overall buckling capacity of steel pipe truss structure subject to static loading. Effect of the hole positions in compression member, on the reduction of the overall buckling capacity of the structure was also investigated. The study was conducted using two approaches: (a) experimental approach that was conducted on physical model, and (b) numerical approach with nonlinear geometric finite element model utilizing 3D solid elements on Abaqus version 6.11-2.

In the following sections, a description of experimental model and numerical model of the truss structure being investigated is performed. The structure represents component and simplification of a typical jacket type offshore platform structure discussed in reference [1] that has been scaled 160 geometrically from the prototype.

2 Experimental Model

The truss structure model (Fig. 1) consists of 2 elements, one of them is compression and the other is tension. In the compression element there is a circular cutout with its position varied from 0.125L, 0.250L and 0.500L, where L is the length of the compression element.

The model has been derived based on \( n \)-Buckingham theorem to satisfy similarity requirements between the model and the prototype. The compression element has a slenderness ratio of 126.

2.1. Material Selection

The API 5L/A53/A106 Grade B of seamless pipes SCH40 and SCH80 have been used as specimens in this study. The material elastic modulus (E) as well as the yield strength were determined based on the laboratory test results, except that the Poisson's ratio was assumed to be 0.3 for steel. The support system uses JIS S45C steel material which equal to AISI 1045, UNSG 10450, ASTM A510, DIN 1.1191 or Assab 760, medium steel carbon classification.

2.2. Samples

The samples used in this experiment consisted of seamless steel pipe SCH40 and SCH80. Both have the same outer diameter (60.5 mm) but differ in thickness. The SCH40 has a thickness of 3.9 mm and the SCH80 has a thickness of 5.5 mm. A series of experimental tests conducted using several models with variations of hole positions. The holes are placed on the compression sides with a variation of 0.125L, 0.250L and 0.500L, where L is the length of the compression member.

Fig. 1 shows the two steel pipe members connected in 45° angle using welded joint. SCH80 material was used for the tension member, while SCH40 was used for the compression member with horizontal orientation. This compression member was the focus of observation in this study. The member slenderness ratio (L/r) of 126 has been determined to be the same as the individually tested compression member model.

![Fig. 1 The truss experimental model](image)

(a) compression member  (b) tension member

![Fig. 2 Pinned support at member ends](image)

Fig. 2 (a) shows the simple support that was used for the end of compression member. The support joint was placed on the loading frame as shown by Fig. 3 and Fig. 4. The same support system was used and applied on
both ends of the SCH40 member being tested individually. Fig. 2 (b) shows the pinned support provided at the end of the tension member. The tension member was designed referred to AISC 2010, chapter D and J (AISC, 2010).

There were two types of models tested in this study. The first model was the truss model that has been tested in a vertical plane, such that the orientation of the compression member was horizontal. The second model was an individual compression member that was tested vertically. Each model has a control sample, without the presence of a hole on the compression element. The variation of hole positions in both models was at 0.125L, 0.25L, and 0.5L, with L being the length of the compression member. The hole was circular in shape with diameter of 25 mm.

2.3. Setting Up

The test used a rigid steel loading frame in the Structural Laboratory of Civil and Environmental Engineering Department, Gadjah Mada University, Indonesia. Setting up of the experiment is shown in Fig 3. Hydraulic jack, load cells, LVDT’s and datalogger were used to simulate loading and monitor the response.

Two LVDT’s had been placed at the free node of the truss where the load was applied, and the other two were placed at the middle span of the horizontal compression member, at the opposite side of the cutout, to monitor the vertical and horizontal displacements.

A sufficiently stiff lateral bracing system was installed to prevent out of plane buckling of the truss. It consisted of 2L-50x50x5 steel profiles placed diagonally on both sides of the model (Fig 4).

The load was monotonically applied vertically at the free node, step by step until the structure reached its critical buckling load, p_{cr}, indicated by the occurrence of buckling mechanism (Fig 5), while the displacement at every loading step was recorded and plotted to get the load-deflection curve.
Fig. 5. Buckling mode of the truss structure and the cutout deformation after buckling

3. Numerical Analysis

Numerical analysis has also been conducted in this study by approaching the solution with nonlinear geometric finite element models utilizing 3D solid elements on Abaqus version 6.11-2. The models were shown in Fig. 6-a for the case of compression member without cutout, and in Fig. 6-b for the case of compression member with cutout.

The model was analyzed using 2 approaches to obtain the critical buckling load ($p_{cr}$): (a) buckling analysis, where the problem was formulated as eigenvalue problem written in Eq. 1, and the smallest eigenvalue was used, and (b) nonlinear analysis, where the nonlinear equilibrium equations (Eq. 2) were solved by Newton-Raphson method to get the load – deflection curve [2].

![Model without cutout on the compression element](image)

![Model with cutout on the compression element](image)

Fig. 6. The 3D solid Finite Element Model for the truss

The equations representing formulation of the problem in eigenvalue analysis and that of nonlinear geometric analysis were discussed in reference [2] and rewritten in Eq. (2) and Eq. (3), respectively.

$$\begin{align*}
[K_0] + p_{cr} [N_1] \{Q_0\} & = \{0\} \quad (2) \\
[K_0] + \frac{1}{2} [N_1] + \frac{1}{3} [N_2] \{Q\} & = \{P\} \quad (3)
\end{align*}$$

where $[K_0]$, $[N_1]$, and $[N_2]$ are the linear stiffness matrix, first order nonlinear, and second-order nonlinear tangent stiffness matrices of the structure, respectively. $\{Q\}$ and $\{P\}$ are, respectively, the displacement and load vectors, while $\{ΔQ\}$ is the incremental displacement, and $\{ΔP\}$ is the incremental load vector [2].

A variation on hole positions was at 0.125 $L$, 0.25 $L$, 0.375 $L$, and 0.5 $L$, where $L$ is the length of the compression element. The hole was taken to be 0.5 pipe diameter. As discussed in Ref. [2], to represent a hinge supports in 3D-solid model, the ends of the element connected to the supports were idealized to be a dome with relatively larger thickness.

The load -deflection curve resulting from nonlinear analysis and the critical buckling load ($p_{cr}$) obtained from eigenvalue analysis for the control model (truss structure without cutout on the compression element) as well as for the model with cutout with various positions were depicted in the same figure for...
obtaining buckling capacity reduction factors. Typical resulting buckling mode and associated cutout deformation obtained from geometric nonlinear analysis utilizing 3D solid elements were shown in Fig. 7.

![Typical buckling mode and cutout deformation](image)

Fig. 7. Typical buckling mode and cutout deformation obtained from nonlinear geometric analysis

### 4 Discussion Results

The resulting critical buckling loads for the truss structure with various cutout positions on the compression member, obtained experimentally and numerically (based on eigenvalue and nonlinear geometric analyses) are listed in Table 1.

From the experimental model tests, the critical buckling loads obtained were 114800 N, 114000 N, 105000 N, 103800 N, respectively, for cutout position at 0.125L, 0.250L, 0.375L, and 0.500L. The critical buckling load for the control model (without cutout) was 117600 N. Compared to the critical buckling load of the control model, the buckling capacity reduction factors, defined by the ratio of the critical buckling loads of the model with cutout position at 0.125L, 0.250L, 0.375L, 0.500L denoted by \( P_{cr} \) and that of the control model (without cutout, \( P_{cr}^{control} \)), were 0.976, 0.969, 0.893 and 0.882, respectively. The lowest buckling capacity reduction factor of 0.882 was associated with the presence of cutout at the middle of the compression element. This means that there was maximum reduction of 11.8% on the critical buckling load due to cutout on the compression element of the truss model. The capacity reduction factor of the truss model due to the existence of cutout is plotted in Fig. 8.

![Capacity reduction factors of the buckling load](image)

Fig. 8. Capacity reduction factors of the buckling load

When the compression members with various cutout position were tested individually as an element, the resulting critical buckling loads were obtained and plotted also in Fig. 8, denoted by L-3,65 for comparison with those of truss model, denoted by RL-3,65. From the figure it could be shown that, in this case, the overall buckling loads of the truss model were slightly higher than that of element buckling loads. It was about 2.5% higher when the cutout position was at 0.500L. The reason was that the boundary conditions at the ends of the compression member of the truss closed to hinge-fixed rather than hinge-hinge like that in the individual element.

Figure 9 shows relationship between the position of cutouts and the buckling capacity reduction factors obtained from experimental and numerical (eigenvalue and nonlinear geometric analyses). The results obtained from eigenvalue analysis were relatively bigger than those from experimental tests, while the results obtained from nonlinear geometric analysis were relatively smaller than those from experimental tests. Compared to the results of experimental tests, the differences were
3%, 3.5%, 9%, and 12%, respectively for cutout positions of 0.125L, 0.250L, 0.375L, and 0.500L. However, the trends were similar: the larger the distance of the cutout position from the end of the compression member (with maximum distance equal to 0.500L), the smaller the buckling capacity reduction factors would be.

![Fig. 9. Capacity reduction factors of the critical buckling load obtained from experimental and numerical](image)

The resulting critical buckling loads for the truss structure with various cutout positions obtained experimentally are plotted graphically in Fig. 10 in the format of load – deflection curves. Similarly, the critical buckling loads obtained numerically by nonlinear geometric analysis are plotted graphically in Fig. 11. From the resulting curves of load – displacement (Fig. 10 and Fig. 11), the critical buckling loads could be graphically determined by identifying the asymptote of each load – displacement curve, or by the maximum load that could be reached. The results had been written in the second column of Table 1. As shown in the table, the differences of the critical buckling loads between experimental and nonlinear geometric analysis were 2.9%, 2.7%, 10%, and 12%, respectively for cutout positions of 0.125L, 0.250L, 0.375L, and 0.500L.

![Fig. 10. The load - displacement curve obtained from experimental tests](image)

![Fig. 11. The load - displacement curve obtained from nonlinear geometric analysis](image)

Fig. 5 and Fig. 7 show the typical overall buckling modes of the truss model obtained experimentally and numerically by nonlinear geometric analysis. It was observed that the buckling modes were quite similar. The compression member buckled in single curvature, with the buckling mode corresponded with member bent away to opposite side of the cutout position. The deformed shape of cutout just after buckling occurred, as shown in Fig. 5 and Fig. 7 were also quite similar.

5 Concluding Remarks

Based on the results of experimental and numerical studies on the critical buckling of truss model with cutout presence at the various positions on the compression element, the following conclusion could be drawn:
1. for the truss model with various hole positions, the overall buckling loads were slightly higher than that of element buckling loads, with the maximum difference of 2.5%.

2. the presence of cutout reduced the overall buckling capacity of the truss structure,

3. the capacity reduction factors depend on the cutout positions,

4. the lowest capacity reduction factor of 0.882 was associated with the presence of cutout at the middle of the compression element, and

5. the typical overall buckling modes of the truss model corresponded to the compression member buckled in single curvature, with the compression member bent away to opposite side of the cutout position.

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