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RESEARCH ARTICLE

Effect of Weld Parameters on Effective Notch Stress at Weld Root and Toe of Load Carrying Cruciform Joints

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Abstract

Cruciform joints in ships are prone to fatigue damage and the determination of type of weld plays a significant role in the fatigue design of the joint. In this paper, the effect of weld geometry on fatigue failure of load carrying cruciform joints in ships is investigated using Effective Notch Stress (ENS) approach. A fictitious notch of 1 mm radius is introduced at the weld root and toe and fatigue stress is evaluated. The effect of weld leg length (l) and weld penetration depth (p) on ENS at weld root and toe are determined. The critical weld leg length (l_{cr}) at which fatigue failure transitions from weld root to weld toe is investigated. An approximation formula for determination of the critical weld leg length considering weld penetration depth (p) is proposed.

Keywords Crack initiation; Critical leg length; Cruciform joints; Effective notch stress; Load carrying joint; Root failure; T-welded joint; Weld penetration; Weld root; Weld toe

1 Introduction

During the design life of a ship, various structural details in the ship are subjected to wave loads resulting in their fatigue failure. The welded joints are the locations that are highly susceptible to cracks due to accumulated fatigue damage. Out of numerous welded joints of different categories, cruciform joints are one of the complex joints in ships. Fatigue cracks which develop at weld toe are observable in nature and can be detected for further corrective measures. Unlike cracks at weld toe, cracks which develop at weld root are difficult to detect unless it penetrates to the plate surface. This aspect makes the joints which fails at weld root more critical due to difficulty in identification and subsequent repair measures.

Also, the occurrence of crack at weld toe or root is influenced by weld parameters which determines the type of weld design (i.e., fillet weld, partial penetration weld or full penetration weld). Thus, the understanding of transition of joint failure from weld root to toe is critical in design of welded joints. This is considered crucial in ship building industry as the type of weld plays a huge role in construction of ships. Due to a large number of cruciform joints present in ships, the choice of type of weld and weld size will have a significant impact on optimal design of a ship. Hence, it is of our interest to study these parameters that can cause a shift of crack initiating at weld root to crack at weld toe and determine the combination of these parameters to ensure that crack is not initiating at weld root, but at weld toe of the joint.

Kainuma and Mori (2006) examined various factors influencing fatigue strength of load carrying fillet welded cruciform joints. Influences of main plate thickness, weld size, weld penetration depth and weld shape on fatigue strength were examined by crack propagation analysis (Kainuma and Mori, 2008). They observed that the fatigue

Article Highlights

- Fatigue strength at weld toe and root of cruciform joint is investigated;
- Effective Notch Stress (ENS) method is applied to compute the fatigue effective stress;
- Effect of weld parameters – weld leg length and penetration on ENS is evaluated;
- Critical weld leg length at which fatigue failure transition from root to toe is computed;
- Approximation formula for evaluating critical weld leg length is proposed.

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strength increased with increase in weld penetration depth and decrease in plate thickness.

They also studied the effect of weld size on fatigue strength at weld root and toe of load carrying cruciform joints. Fatigue strength was also observed to vary inversely with weld size when weld size to plate thickness ratio was less than 0.5 and almost remained constant afterwards. The critical weld size ratio was obtained as 1.2 when the weld penetration is zero and decreased to 1.0 when weld penetration is introduced indicating a decrease in critical weld size with increase in weld penetration depth.

They also examined effect of different thicknesses of the main plates and cross-plate on weld root crack propagation and fatigue behaviour of load-carrying cruciform joints. It is observed that the fatigue strength decreases as the thickness ratio of attached plates increases. This reduction is more evident in case of smaller cross plate thickness. A constant fatigue strength is observed when both attached plates are of same thickness, irrespective of the attached and cross plate thickness.

Hong (2013) attempted to determine design master S-N curve for weld root failure using test data of around 800 specimens that had confirmed weld toe fatigue failure. SN curve was obtained for the weld root failure by downshifting the mean S-N curve for weld toe failure. The study concludes that the proposed Structural Stress Method (SSM), used for analysis of weld toe failure, can also be used for analysing weld root failure with a hypothetical cut along the given crack in the weld region.

Crack mechanics approach has been used by Petinov et al. (2006) to analyse the root cracking when the crack growth is in its initial stages. An approximate procedure to simulate fatigue failure at weld root is proposed and the results were found to conform with the empirical relations.

Song et al. (2017) studied the fatigue behaviour of cruciform weldments using concept of Strain Energy Density (SED). SED was determined at fictitious rounded notches of weld toe and root notches based on notch stress intensity factor (NSIF) and the results were verified with the results from Finite Element Analysis and analytical outputs using NSIF approach. They found that the critical weld size to thickness ratio (h/t) varies from 1.16 to 0.75, when weld penetration to thickness ratio (p/t) varied from 0 to 0.2. A formulation to approximately calculate stresses at the toe and root using NSIF method to find SED was suggested by Song et al. (2018). It was observed that numerically calculated NSIF and SED values showed good conformity with the predicted values from FE methods.

Lee et al. (2009) observed that the fatigue life increases with increase in the weld flank angle and weld toe radius. The weld throat thickness was found to have no significant influence on the fatigue strength. Alteration in the toe shape and size due to post weld treatment is also found to cause stress concentration in the root, consequently shifting the possibility of failure to root in welds with low penetration.

Study of the transitional behaviour of fatigue failure origin in load carrying fillet welded connections based on the concept of traction stress was carried out (Xing et al., 2016; Xing et al., 2017). An analytical fillet weld model is proposed, to establish a critical fatigue failure plane and compared with the finite element solutions of weld throat effective stresses, normal traction stress and transverse shear stress. It was found that, for 5 mm and 10 mm thick plates, critical weld size (s/t) without penetration was 1.16 and with an average penetration (p/t) of 0.2, critical weld size (s/t) changed to 0.85. The critical weld size varied from 0.7 to 1.0 when effect of joint misalignments was considered. The study concluded that critical weld throat failure plane angle increases with increasing weld size (s/t) and weld penetration depth (p/t). Maddox (2008) proposed a relation between critical weld leg length and plate thickness, in case of load carrying fillet weld, and found that the critical weld leg length ranges from 1.4 for plate thickness of 5 mm to 1.0 for plate thickness of 60 mm.

The current study aims at investigating the transition of failure of load carrying cruciform joints from weld root to toe based on the concepts of Effective Notch Stress (ENS) approach. This is achieved by evaluating the influence of various parameters such as plate thickness, weld leg length and weld penetration depth on ENS. Accordingly, an approximation formula for weld leg length will be developed at which the failure transitions from weld root to toe that can be used in preliminary design of welded cruciform joints.

2 Analysis of cruciform joints

2.1 Geometry and weld configuration

A typical cruciform joint as shown in Figure 1 is considered to study the effect of weld leg length and weld penetration depth on transition of fatigue failure from weld root to weld toe. In order to simplify the study, thickness

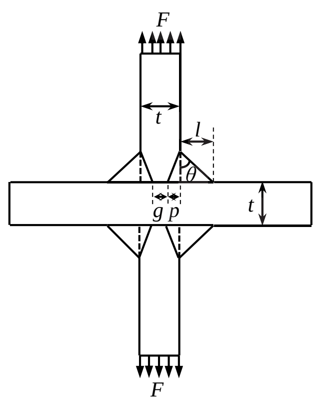


Figure 1 Typical load carrying cruciform joint along with weld configuration

of continuous plate and attached plate of cruciform joint are considered to be the same. Cruciform joints with plate thickness of 15 mm, 18 mm, 22 mm and 26 mm are considered as these thicknesses represent the scantlings used in ship building industry. The studies are carried out considering steel plates.

A partial penetration weld, as per Common Structural Rules for Oil Tankers and Bulk Carriers (CSR) of IACS (2021), is defined as the weld where the root face is to be taken between 3 mm and $t/3$ mm and a fillet weld is considered as weld with root face of t mm. In areas with high tensile stresses or areas considered critical, full or partial penetration welds are to be used. Examples of partial penetration welds are given in Figure 2. The present study considers the weld penetration depth, p, such that the root face varies from 't' mm to '3' mm as defined in CSR.

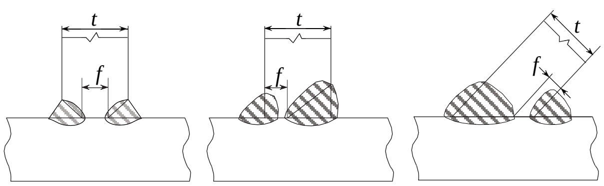


Figure 2 Partial penetration welds as defined in CSR

Accordingly, various parameters considered for the study are as follows:

- Weld leg length, l is varied from $0.2t$ to $1.0t$ with increments of 0.1.
- Weld penetration depth, p, is varied from 0 mm to '$(t-3)/2$' mm with increments of '$0.05t$' mm with an additional case of '$0.33t$' mm to account for $t/3$ root face.
- Weld toe angle is assumed to be 45° in all the cases.
- Uniform axial tensile load is applied at the free end of attached plates of cruciform joint such that the end of each plate has unit axial stress.

2.2 Effective notch stress approach

In the present study, fatigue stress at weld root and weld toe is evaluated and obtained using Effective Notch Stress (ENS) approach. This approach is based on the concept that any increase in local stress at the notch can be evaluated by averaging the stress using fictitious rounding at that notch (Radaj, 2013). The effective notch radius is introduced in such a way that the tip of the notch radius intersects with the root of the real notch. The radius of the fictitious notch, ρ_f, is considered as follows:

$$\rho_f = \rho + s \times \rho^* \tag{1}$$

where, ρ is the actual notch radius, s the factor for stress multiaxiality and strength criterion, and ρ^* the substitute micro-structural length.

In the present study, Radaj's approach (2006) for worst case is applied assuming an actual notch radius of zero, factor s is assumed to be 2.5 for plane strain conditions and the value of ρ^* is considered as 0.4 mm for cast steel in the welded zone so that the fictitious radius is 1 mm.

The weld is modelled using an idealized weld profile with constant flank angle of 45 degrees. Fictitious notch at weld root can be modelled by a keyhole notch or U-shaped notch among others as shown in the Figure 3. It is noted that U-shaped notch may lead to an underestimation of the fatigue stress (Fricke, 2013) and hence a keyhole notch is adopted in the present study.

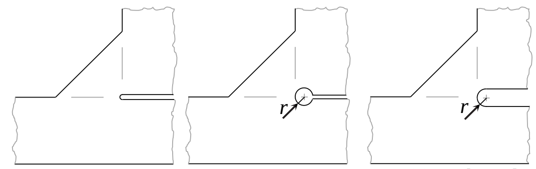


Figure 3 Rounding of the weld root of a non-penetrating fillet weld (Fricke, 2013)

Fictitious notch at weld root and toe are modelled as shown in Figure 4 in the present study.

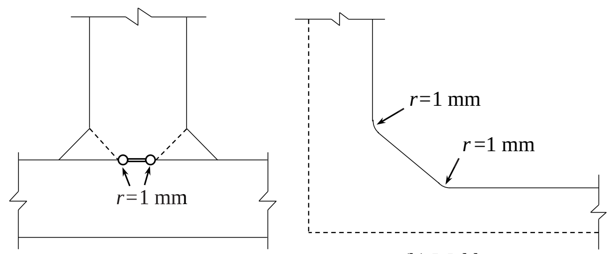


Figure 4 Fictitious notch of 1 mm radius for ENS Approach

Meshing at these notches is carried out as per the IIW guidelines (Fricke, 2008) with 40 divisions along the notch radius (i.e., element length = $2\pi/40$ = 0.157 mm).

Stresses (normal and tangential) along the circumference of the notch and shear stress at the surface of the notch are obtained and ENS is considered as maximum principal stress derived using these components. FAT 225 class SN curve is to be used to compute fatigue damage along with calculated ENS by Hobbacher (2006).

2.3 Finite element analysis

Finite Element (FE) analysis is carried out to investigate the effect of weld penetration, weld leg length and plate thickness on crack initiation points of the steel cruciform joint. ENS is computed by linear elastic FE analysis using two-dimensional plane strain elements. Fictitious notch of 1.0 mm radius is modelled at weld root and toe. A keyhole notch is modelled by introducing a root gap of 0.1 mm. Typical FE model showing fictitious notch at weld toe and root with fine mesh is shown in Figure 5.

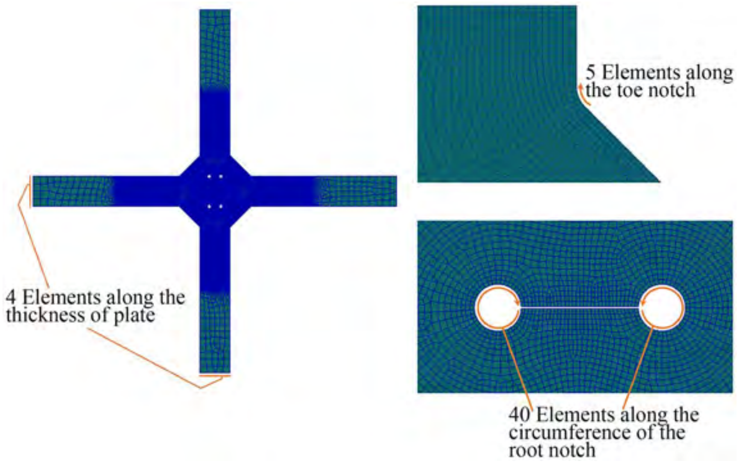


Figure 5 Typical FE model of the cruciform joint with very fine mesh at fictitious notches at weld root and toe

For FE analysis using elements defined with linear displacement function (i.e., 4 node quadrilateral elements), element size less than or equal to 0.15 mm (i. e., element length = $2\pi/40 = 0.157$ mm) is recommended in IIW guidelines (Fricke, 2013).

Meshing is done as per IIW recommendations such that there are 40 elements along the circumference of the root notch and 5 elements along the toe notch using 4 node quadrilateral elements. The weld surface is modelled as flat surface and weld profile is idealized as an isosceles triangle in all the cases. The Young's modulus of $E = 2 \times 10^6$ MPa and Poisson's ratio of $v = 0.3$ are considered for linear elastic material behaviour. The free ends of the continuous plates are provided with fixed boundary condition.

A cruciform fillet welded joint ($p = 0$) of 12 mm plate thickness is analysed and ENS at weld root and toe is computed. Results obtained are compared with results obtained by Fricke (2008). The comparison between results is shown in Table 1.

Table 1 Comparison of ENS at weld toe and weld root between present study and Fricke (2008)

ENS (N/mm^2)	Fricke	Present Study
Toe	4.62	4.61
Root	5.65	5.60

It was observed that the ENS obtained from the study are in good agreement with a difference of 1%. Accordingly, the FE models are developed for all other cases to determine the effect of various weld parameters.

3 Results and discussion

3.1 Effective notch stress (ENS)

2D Linear Elastic FE analysis are performed to calculate ENS at fictitious notch at weld root and weld toe. Modelling is carried out using MSC Patran and analysis is performed using MSC NASTRAN solver. Mesh convergence studies are deemed not required in this study as the meshing at the notches is carried out as per IIW guidelines and the results are validated with the same. ENS is defined as maximum principal stress along the circumference of the fictitious notch at weld root and toe. A number of analyses for different combinations of weld leg length to plate thickness ratio (l/t) and weld penetration depth to plate thickness ratio (p/t) as defined in 2.1 are carried out and ENS at weld root and toe is computed.

Typical contour of effective notch stress in a cruciform joint with $l/t = 1.0$ and $p/t = 0.33$ (i. e., $p = t/3$) for plate thickness of 22 mm subjected to axial load is shown in Figure 6.

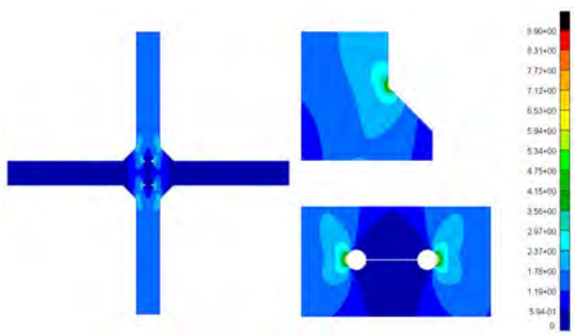


Figure 6 Typical ENS (N/mm^2) contour at weld root and weld toe

3.2 Effect of weld leg length and weld penetration depth

Variation of ENS at weld root and toe with weld leg length to thickness ratio (l/t) for each weld penetration to thickness ratio (p/t) for plate thickness of 22 mm is shown in Figure 7.

It is observed that in most of the cases, ENS at both

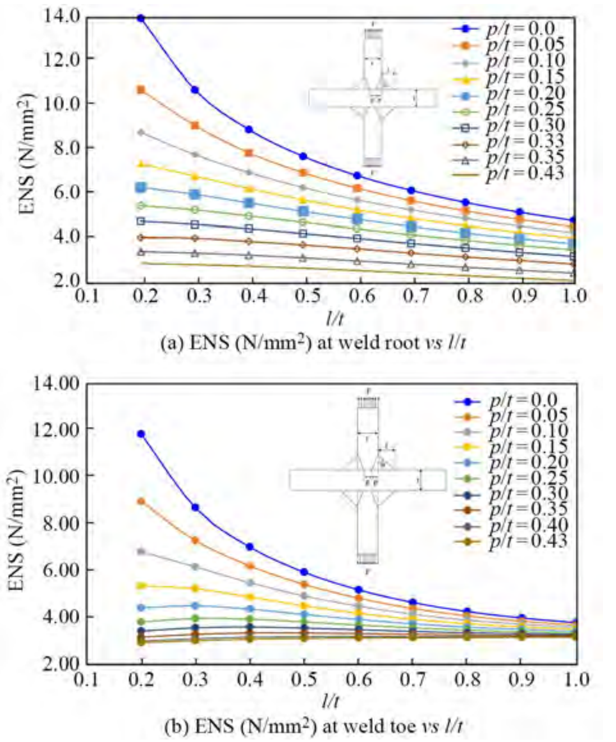


Figure 7 Variation of ENS (N/mm^2) with l/t for each p/t (t=22 mm)

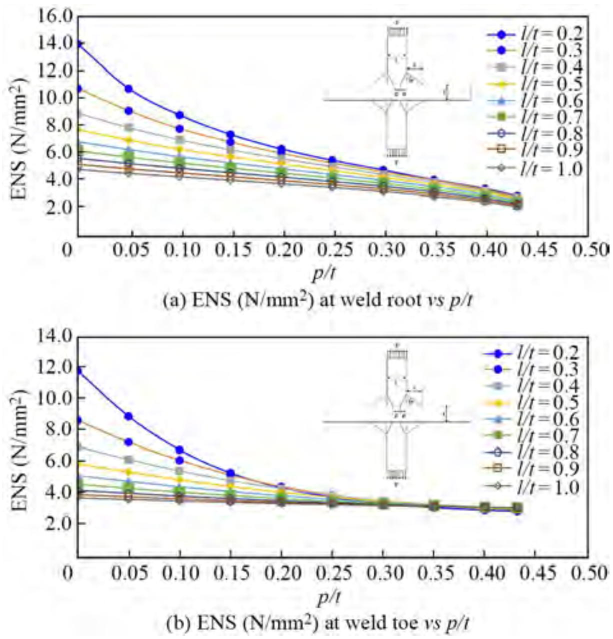


Figure 8 Variation of ENS (N/mm^2) with p/t for each l/t (t =22 mm)

weld root and toe decreases with increase in weld leg length (l) across the plate thickness. The rate of decrease of ENS with weld leg length is more pronounced in case of higher weld penetration. As the weld penetration increases the rate of decrease in ENS reduces. In cases with p/t>0.20, it is observed that the ENS at toe increases when 0.2<l/t≤0.3 and then decreases on further increase in l/t which may be attributed to very minimal effect of weld leg length at such high values of weld penetration depth. Variation of ENS at weld root and toe with weld penetration to thickness ratio (p/t) for each weld leg length to thickness (l/t) ratio for plate thickness of 22 mm is shown in Figure 8.

Similar to the variation of ENS with (l/t), ENS at both weld root and toe decreases with increase in weld penetration (p) across the plate thickness. Results related to ENS variation with l/t and p/t for plate thickness of 15, 18 and 26 mm are given in Appendix A. This variation of ENS with (l/t) and (p/t) is due to the fact that higher weld leg length and weld penetration results in a higher weld area participating in the load transfer between attached and continuous plate. This larger weld area results in decrease of stress concentration at toe and root resulting in decrease of ENS at root and toe.

It is further observed from Figure 6 that at higher weld penetration (p/t > 0.3), the variation of ENS at toe is relatively less compared to case of other weld penetration. Hence, it can be concluded that in case of partial penetration welds, the effect of weld penetration depth and weld leg length is relatively very minimal on ENS at weld toe. This observation is applicable across all plate thicknesses analyzed. Variation of ENS at weld root and toe with plate thickness for sample cases are shown in Figure 9.

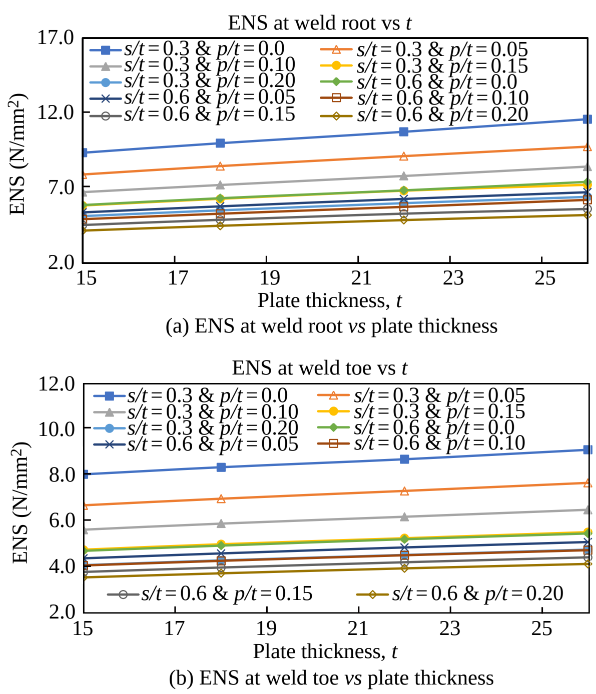
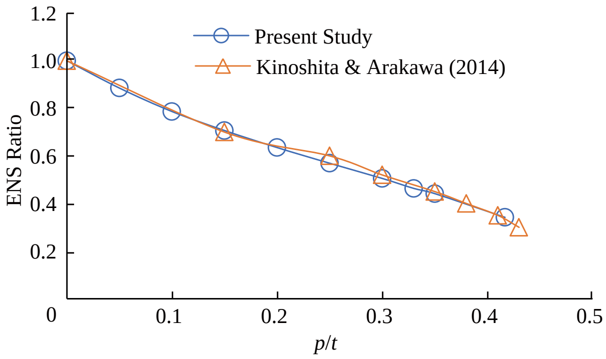
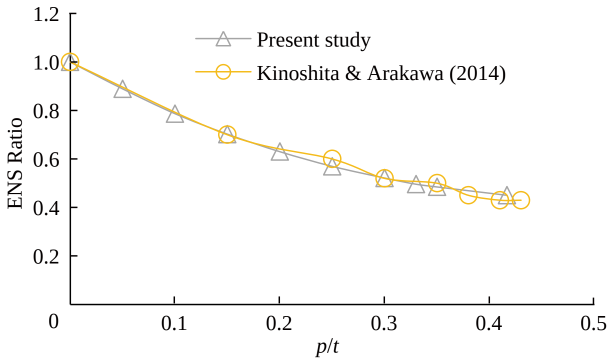


Figure 9 Variation of ENS with plate thickness for sample cases

It is also observed that ENS at both weld root and toe increase with increase in plate thickness indicating a decrease in fatigue strength at higher plate thickness.

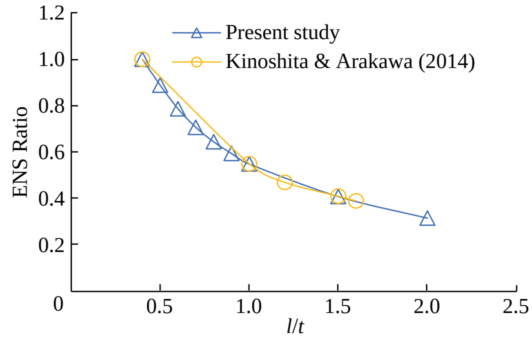


(a) ENS Ratio at root

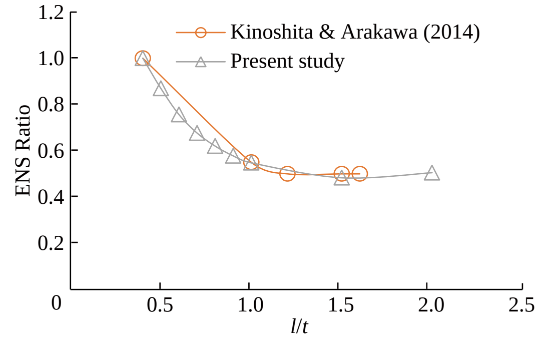


(b) ENS Ratio at toe

Figure 10 Comparison of ENS ratio ($ENS/ENS_{p=0}$) versus p/t between present study (t=18 mm) and Kinoshita & Arakawa, 2014 (t=17 mm) @ l/t=0.4



(a) ENS Ratio at root



(b) ENS Ratio at toe

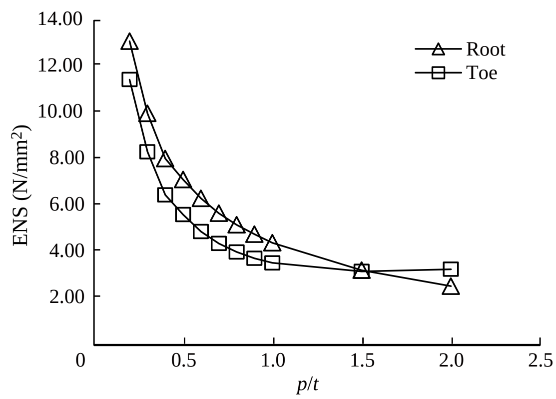
Figure 11 Comparison of ENS ratio ($ENS/ENS_{l/t=0.4}$) versus l/t between present study (t=18 mm) and Kinoshita & Arakawa, 2014 (t=17 mm) @ p=0

3.3 Explication of the results

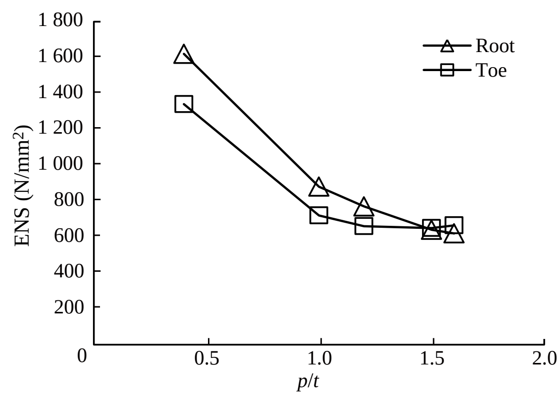
Results obtained from analyses are compared with published literature to check the validity of the procedure before developing any propositions. The results of ENS at toe and root are compared with Kinoshita and Arakawa (2014). ENS ratio ($ENS/ENS_{p=0}$) versus weld penetration to plate thickness ratio (p/t) are shown in Figure 10. Similarly, the comparison of ENS ratio ($ENS/ENS_{l/t=0.4}$) versus weld penetration to plate thickness ratio (p/t) is shown in Figure 11. It is observed that the results obtained from the present study are in good agreement with those obtained by Kinoshita and Arakawa, 2014. Slight deviation in ENS Ratio is noted in Figure 11 when l/t<1.0 which is due to additional data points considered in the present study.

Variation of ENS at weld root and toe with l/t for 18 mm thick plate is compared with results from Kinoshita and Arakawa as shown in Figure 12. The critical weld leg length ratio is obtained as 1.5 in both the cases. Further comparisons of variation of critical weld length ratio (l/t) with weld penetration ratio (p/t) is shown in Figure 13. Similar variation is observed in both the cases.

The results of ENS at toe and root are also compared with Mori and Ichimiya (1999). It is observed that the transition of fatigue failure from weld root to weld toe for plate



(a) Present study



(b) Kinoshita & Arakawa

Figure 12 Comparison of critical weld leg length ratio between present study (t=18 mm) and Kinoshita & Arakawa, 2014 (t=17 mm)

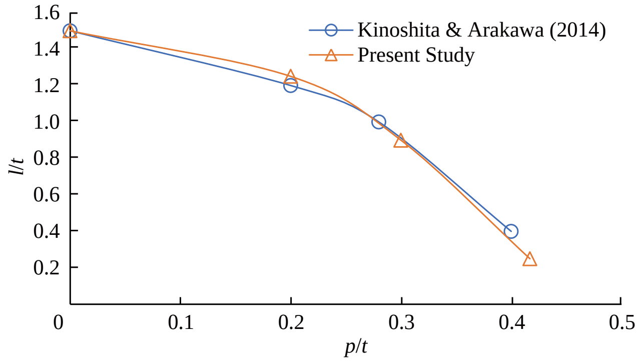


Figure 13 Comparison of plot of critical weld leg length ratio *l/t* versus *p/t* between present study (t=18 mm) and Kinoshita and Arakawa, 2014 (t=17 mm)

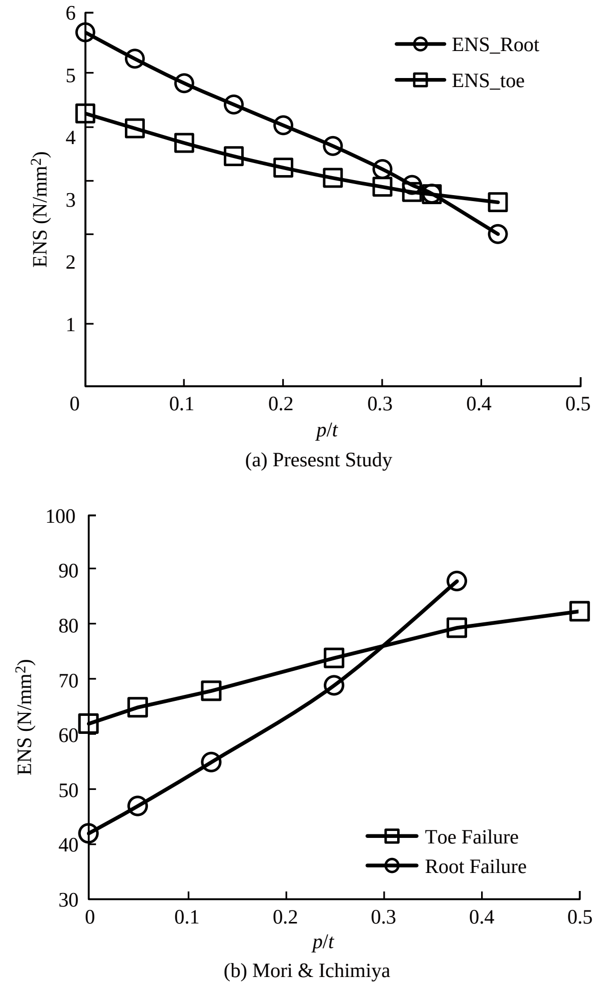


Figure 14 Comparison of Transition of root to toe failure between present study and Mori and Ichimiya (1999)

thickness of 22 mm and notch radius of 1.0 mm occurred at p/t = 0.35. Mori and Ichimiya predicted this transition at p/t = 0.3 using plate thickness of 20 mm and notch radius of 0.5 mm. As shown in Figure 14, it is understood that the results obtained from the present study are in good agreement with the results by Mori and Ichimiya, 1993.

3.4 Critical weld leg length for transition of root to toe failure

The ENS at weld root and toe is plotted against weld leg length to thickness ratio (l/t) for each weld penetration to thickness (p/t) ratio in Figure 7. It is observed that the ENS at weld root reduces and shifts below the ENS at weld toe beyond a certain value of l/t.

This behavior is also observed from the results of all other plate thicknesses studied indicating that there exists some value of leg length where the fatigue failure transitions from weld root to weld toe. After this specific weld leg length, (termed as critical weld leg length), the ENS at root will become lesser than the ENS at weld toe. Beyond this weld leg length, it can be safely assumed that toe failure will precede over the root failure.

Accordingly, critical weld leg length is defined as the leg length at which there is a transition of crack initiation from weld root to weld toe indicating a shift of fatigue failure from root to toe. The critical weld leg length to thickness ratios (l_{cr}/t) for a load carrying cruciform joint of 22 mm thickness and for $0 \leqslant p/t < 0.45$ are indicated in Figure 15.

It is observed from the results that in case of joints with 15 mm and 18 mm thick plates, the critical weld leg length ratio is 1.5 for $0 \leqslant p/t < 0.1$ when l/t is varied from 0.2 to 2. Similarly, it is observed that for joints with 22 mm and 26 mm plate thicknesses, no critical weld leg length was observed for $0 \leqslant p/t < 0.1$ when l/t is varied from 0.2 to 1. For higher plate thickness (22 mm and 26 mm), l/t is restricted to 1.0 as $l/t > 1$ is generally not common in ship structures (IACS, 2021). However, for all thickness, it is observed that the critical weld length ratio decreased with an increase in weld penetration (p).

Figure 16 shows the variation of critical weld leg length to thickness ratio (l_{cr}/t) and its relationship with p/t for various plate thickness.

It is observed from Figure 15 that critical weld leg length to thickness ratio, l_{cr}/t, does not vary for lower weld penetration ($0 \leqslant p/t < 0.1$). Non-linear relationship between l_{cr}/t and p/t was attempted for weld penetration in the range of $0 \leqslant p/t < 0.45$ (Refer Appendix B). However, as linear relationship is simpler to use at design stage of weld, a linear relationship is proposed.

The expression for l_{cr}/t in terms of p/t is given as below:

$$\frac{l_{cr}}{t} = \begin{cases} 1.50, & 0 \leqslant \frac{p}{t} < 0.1 \\ 2.0 - 3.90\left(\frac{p}{t}\right), & 0.1 \leqslant \frac{p}{t} < 0.45 \end{cases} \tag{2}$$

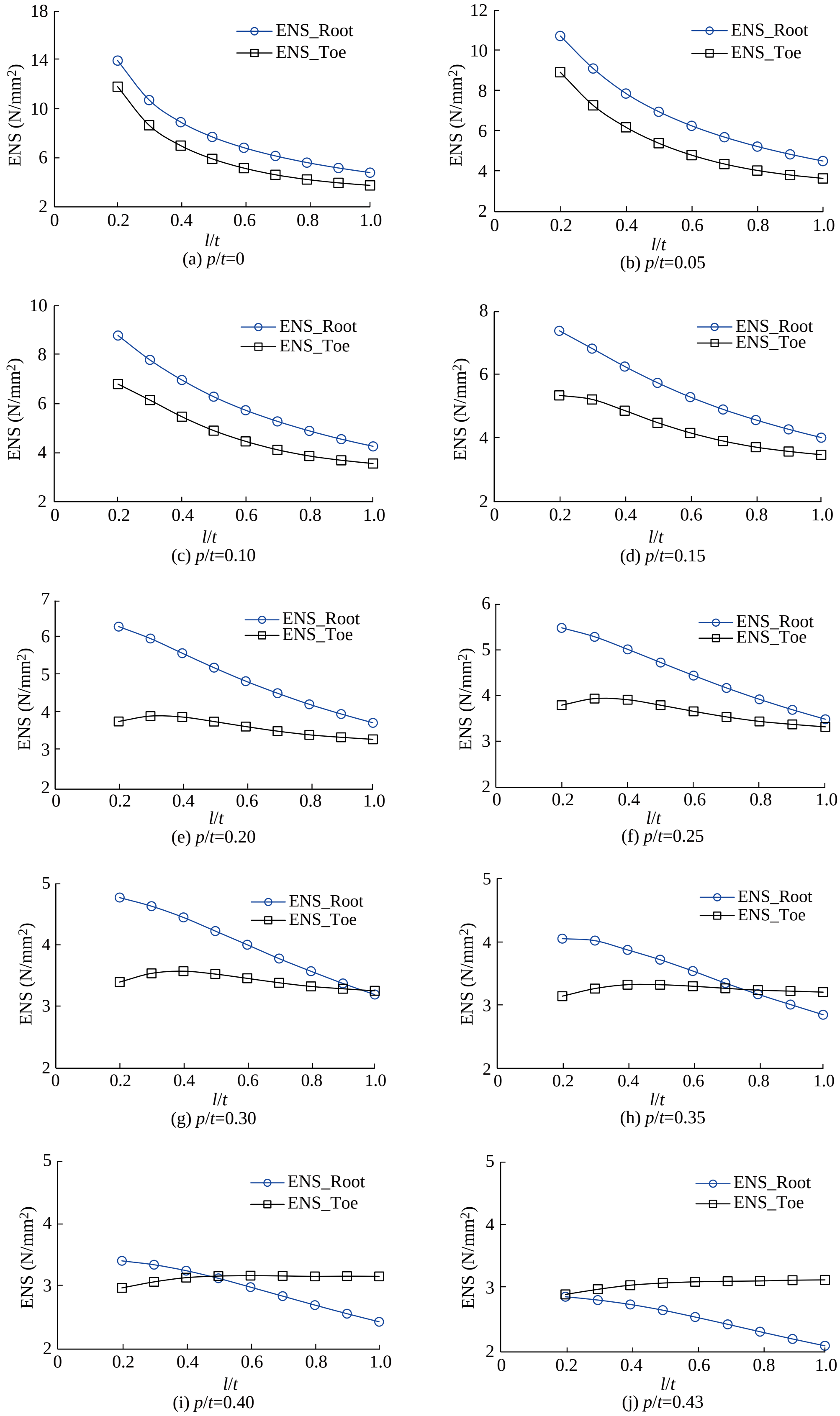


Figure 15 ENS (N/mm^2) at weld root and toe vs l/t indicating the critical weld leg length to thickness ratio (l_{cr}/t)

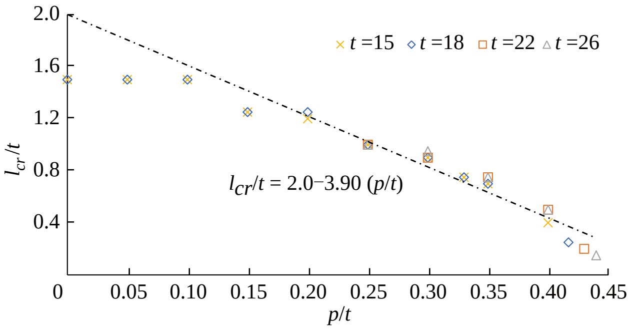


Figure 16 Critical weld leg length to thickness ratio (l_{cr}/t) for each p/t for various plate thickness

4 Conclusions

Load carrying cruciform joints subjected to axial load are investigated by varying plate thickness, weld leg length and weld penetration. Effect of these parameters on ENS at weld root and toe is studied.

The following points are identified:

1) It is observed that ENS at weld root and toe decreases with varying degree with increase in both weld leg length (l) and weld penetration(p).

2) It is further observed that at higher weld penetrations (p/t > 0.3), the ENS at toe is nearly constant in all cases with a maximum difference within 10% which indicates a very minimal effect of weld penetration depth and weld leg length on the ENS at weld toe for partial penetration welds.

3) It is observed that ENS at weld root and toe increases with increase in plate thickness, indicating lower fatigue strength at higher plate thickness.

4) Critical weld leg length at which transition from root failure to toe failure occurs is investigated. It is observed that critical weld leg length to thickness ratio, l_{cr}/t, does not vary for lower weld penetration ($0 \leqslant p/t < 0.1$).

5) For weld penetration in the range of $0.1 \leqslant p/t < 0.45$, relationship between l_{cr}/t and p/t is studied. An approximation formula is developed which can be used to predict the critical weld leg length at which there is a shift of fatigue failure from weld root to weld toe.

Using the proposed approximation formula for l_{cr}, the weld parameters can be determined to identify the location of crack initiation and subsequently type of failure of a load carrying cruciform joint. Accordingly, findings of the study can be used for design of the welds of load carrying cruciform joints.

The authors intend to extend these studies to the skewed cruciform joints, different thicknesses for continuous and attached plates and misalignment between the attached plates in the future for understanding effect of these weld parameters on crack initiation and fatigue failure of the load carrying cruciform joints in the ships.

Appendix A

Results of ENS at root and toe with weld leg length to thickness ratio (l/t) for each weld penetration to thickness (p/t) ratio for various plate thicknesses

1) Figure 17 for Plate thickness (t) = 15 mm

2) Figure 18 for Plate thickness (t) = 18 mm

3) Figure 19 for Plate thickness (t) = 26 mm

Appendix B

Figure 20 shows Non-linear relationship between l_{cr}/t and p/t for weld penetration in the range of $0 \leqslant p/t < 0.45$

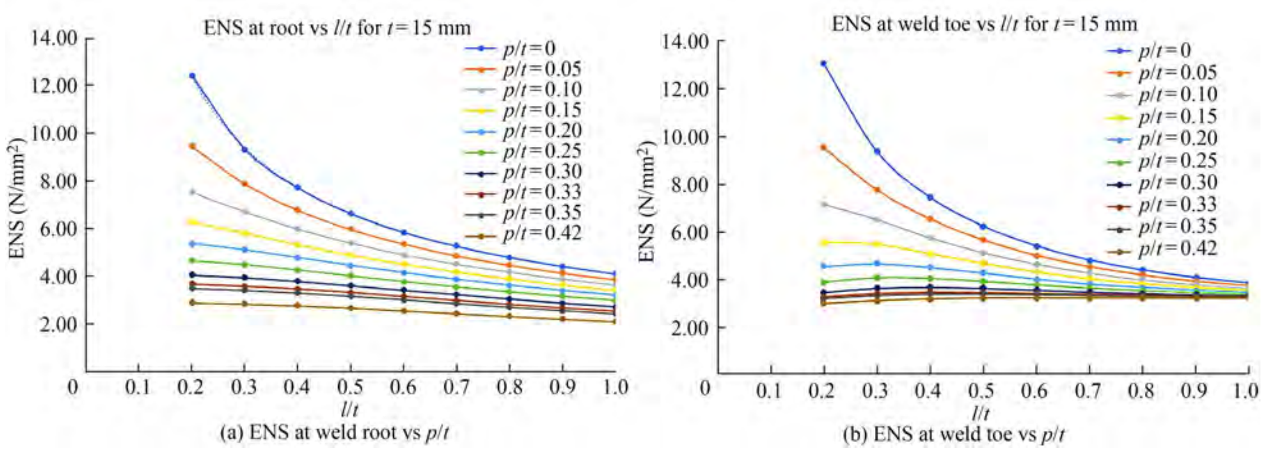


Figure 17 Variation of ENS (N/mm^2) with l/t for each p/t (t = 15 mm)

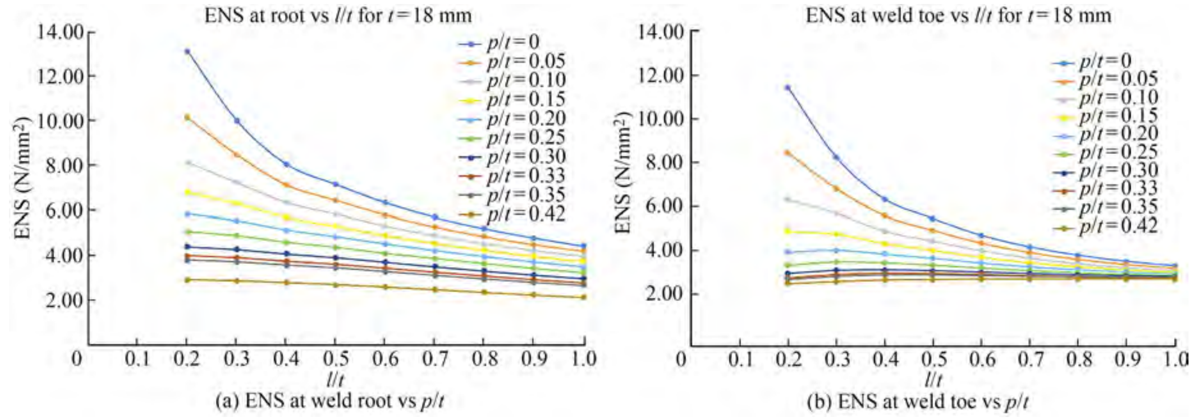


Figure 18 Variation of ENS (N/mm^2) with l/t for each p/t (t = 18 mm)

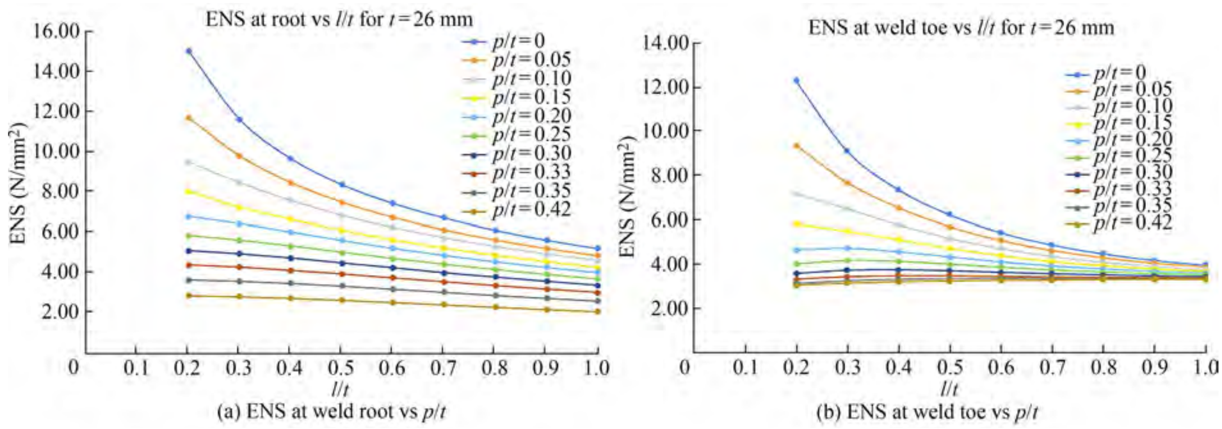


Figure 19 Variation of ENS (N/mm^2) with l/t for each p/t (t = 26 mm)

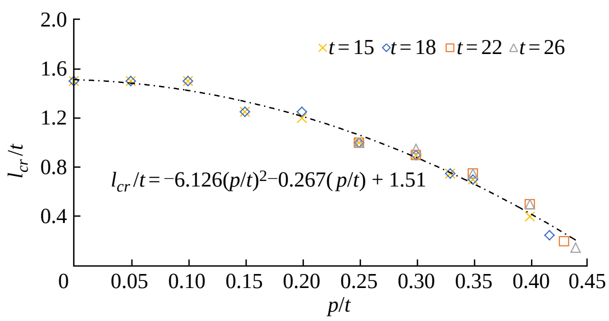


Figure 20 Critical weld leg length to thickness ratio (l_{cr}/t) for each p/t for various plate thicknesses

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