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Stress Analysis of Weld Penetration Problem in Butt Welded Joints

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ABSTRACT

Butt – welded joints have wide applications in industry as well as in offshore constructions. The assessment of butt welded joints is a major industrial problem for two reasons. Firstly these butt welds tend to be regions of weakness in a structure due to stress concentration effects as stresses associated with welds are more variable due to inherent presence of defects. Secondly it is difficult to predict their material properties. Thus these welds are the critical links in a fabricated structure.

Many of the fatigue failures occur in these butt - welded joints involve fatigue cracking from severel imperfections that are actually inherent parts of the joint. One of the imperfections in butt welds is referred as the LOP (lack of penetration) which is considered as a crack from fracture mechanics point of view. In the present work this is the subject of concern in butt welded joints. Lack of penetration occurs in most of the cases, as a gap remains between two joined plates of butt welded joints due to incomplete penetration of the weld metal i.e. weld metal fails to reach the root of the joint which is inevitable considering both the cost of edge preparation and machining time in to account. The LOP crack may initiate a crack when the welded joint is subjected to loading. States of stress at these highly stress concentration regions are evaluated by two important fracture parameters namely stress concentration factor and stress intensity factor.

The SIF & SCF are discussed for different lack of penetrations defects with respect to different weld parameters to study the stress state. These include plate thickness, weld size, weld toe angle, and weld shape, gusset thickness and weld leg length for different butt welds.

Relation between SIF range and crack length at toe and LOP root in butt welded cruciform joints is computed. Slit leg length with respect to slope angle of weld is also discussed for different butt – welded cruciform joints. The present work also discusses the stress concentration factors for both load carrying and non-load carrying butt – welded cruciform joints with different toe angles, different weld leg length to plate thickness ratios, different gusset thickness and depth of weld penetration. Both SCF and SIF are obtained for different butt – welded joints with varying defect lengths (LOP) to plate thickness ratios to find an "acceptable" defect length beyond which stress concentration increases rapidly, with the help of FEA package. Few comparisons are made with the previous existing experimental results. Hence present work becomes the first approach for approximation of typical weld penetration defects.

Keywords: *- butt-weld joints, lack of penetration, fracture mechanics, gusset thickness, stress intensity factor (SIF), stress concentration factor (SCF)*

Nomenclature

a	defect length
b	plate thickness
djj	double J joint
dvj	double V joint
E	young's modulus
FEA	finite element analysis
G	shear modulus
H	leg length
K	stress intensity factor
K_N	stress concentration factor
LCJ	load carrying joint
LOP	lack of penetration
γ	poisons ratio,
NLCJ joint	non load carrying
2p	total weld penetration
sjj	single J joint
svj	single V joint
T_p	plate thickness
W	width
Δk:	stress intensity factor range
θ	toe angle
σ_{max}	maximum stress
σ_0	nominal stress

Introduction:

Butt weld joints have wide variety of applications in the industries and engineering constructions such as bridges, boilers, pressure vessels, automobile industries, offshore structures, etc due to higher strength of these joints. The inherent presence of discontinuity like lack of penetration (LOP) is quite common in butt welded joints because of insufficient penetration, which is considered as a crack from fracture mechanics point of view.

The weld defects constitute a group of stress raisers. Fracture mechanics provides basis for quantifying the behavior for crack or crack like defects during both the crack initiation and propagation phase. The important parameters of fracture mechanics are the stress concentration factor and stress intensity factor, which are measure of the magnitude of stress occurring in the highly stressed region like weld toe, lack of penetration.

The ratio of the maximum stress and the nominal applied tensile stress is denoted as the stress concentration factor, $\mathbf{K_t}$**.** the fundamental principles of fracture mechanics is that the stress field ahead of sharp crack can be characterized in terms of a parameter **K**, the stress intensity factor.

Accurate analysis in presence of such crack (LOP) is required to determine the stress state at these highly stress concentration regions. Number of analytical procedures as well as experimental procedures is available to evaluate stress parameters like

ANSYS is one o the widely used FEM packages with a wide range of advantages such as easy modeling, require less time and automatic mesh generations. Present work becomes the first approach for approximation of typical penetration defects adequacy of the finite element analysis is closer to the experimental analysis. Hence it is advantage to use finite element analysis for the determination of stress concentration factors and the stress intensity factors.

The present work discusses the effect of lack of penetration on important fracture parameters like SCF and SIF with respects to different weld parameters like slope angle, gusset thickness, weld leg length, weld size, plate thickness and weld shape using FEM package and few comparisons are made with previously existing experimental results.

For design of welded joints the independent variables considered are weld leg length, plate thickness, defect length(LOP), gusset thickness and weld toe angles.

In the present analysis, the influence of stress concentration factor and stress intensity factor for weld penetration problems in single-V, double-V, single-J, double-J butt welded joints have been determine d using FEA with varying defect length to plate thickness ratios. There exists proportionality between SCF and defect length i.e. larger the defect lengths higher the stress concentration factor. Hence it is important to find out the optimal defect length considering the cost of edge preparation (matching cost), expensiveness of the joining process. Based on the nature of the graphs the optimum defect lengths are determined. Present work becomes the first approach for approximation of typical penetration defects. It shows that, for typical defect profiles, an “acceptable” defect length exists beyond which stress concentration increases rapidly.

The influence of weld shape, weld size in both load carrying and non-load carrying cruciform butt welds over the stress concentration factor (SCF) is computed. The limit of linearity between toe angles and SCF is determined. The results are represented in the form a graph.

The effect of varying gusset thickness and the depth of weld penetration are studied in non-load carrying cruciform butt-welded joints. Comparisons are made for specimens with gussets welded on either side of the main plate i.e. opposite each other and specimens with similar gusset on one side only. The stress concentration factor at both the toe and the root tend to vary with increasing gusset thickness. The summaries of the results obtained are represented in the form of graphs.

Butt welded cruciform joint containing both the weld toe region with thumbnail crack embedded in the stress concentration region and also lack of penetration is analyzed. For a cruciform joint with 45^0 toe angle, the SIF for a crack emanating from the region has been calculated and the relation between SIF range Δk and the normalized crack length a/t_p is obtained. SIF range as a function of lack of penetration is also computed for the same stress values. The lack of penetration has been normalized by dividing the same by the width W. The SIF for the toe crack is found to be higher than that for the lack of penetration. The toe crack will start growing unless the lack of penetration is long enough to have SIF higher than that of the toe crack. Region between the toe failure and LOP failure is also computed.

Stress intensity factor of lack of penetration is also computed with varying slit length, leg width and slope angle in butt welded cruciform joint.

Determination of Stress Concentration Factor:

The ratio of the maximum stress and the nominal applied tensile stress is denoted as the stress concentration factor, $\mathbf{K_t}$, where $\mathbf{K_t}$ can be expressed by equation:

$$S.F.C = \frac{Maximum\ \ Stress}{Nominal\ \ Stress}$$

The stress concentration factor is a simple measure of the degree to which an external stress is amplified at the tip of a small crack.

Stress Concentration Considerations:

It is important to remember that stress amplification not only occurs on a microscopic level (e.g. small flaws or cracks) but can also occur on the macroscopic level in the case of sharp corners, holes, fillets, and notches.

Stress raisers are typically more destructive in the brittle materials. Ductile materials have the ability to plastically deform in the region surrounding the stress raisers, which in turn evenly distributes the stress load around the flaw. The maximum stress concentration factor results in a value less than found for the theoretical value. Since brittle materials cannot plastically deform, the stress raisers will create the theoretical stress concentration situation.

Stress intensity factor, K is used in fracture mechanics to more accurately predict the stress state ("stress state") near the tip of a crack caused by a remote load. When this stress state becomes critical a small crack grows and the material fails. The load at which this failure occurs is referred to as the fracture strength. The experimental fracture strength of solid materials is 10 to 1000 times below the theoretical strength values, where tiny internal and external surface cracks create higher stresses near these cracks, hence lowering the theoretical value of strength. Unlike "stress concentration", stress intensity, K, as the name implies, is a parameters that amplifies the magnitude of the applied stress that includes the geometrical Y (load type). These load types are categorized as Mode-I, -II, or –III as shown in figure 1.

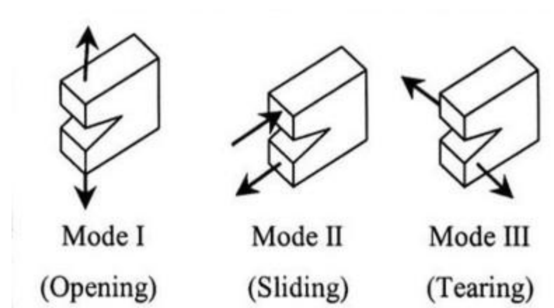

FIGURE 1.Basic modes of loading

The mode-I stress intensity factor, KI is the most often used engineering design parameters in fracture mechanics. Typically for most materials if a crack can be seen it is very close to the critical stress state predicted by the "Stress Intensity Factor".

The value of stress intensity factor, K is a function of the applied stress, the size and the position of the crack as well as the geometry of the solid piece where the cracks are detected. The stress distribution at the vicinity of the crack tip is shown in the figure 2. The tensile stress in X and Y directions, and the shear stress in the X-Y plane can calculated in terms of K and position can be written as:

Mode-I

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}(1 + \sin\frac{\theta}{2} \sin\frac{3\theta}{2})$$

$$\sigma_x = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}(1 - \sin\frac{\theta}{2} \sin\frac{3\theta}{2})$$

$$\tau_{xy} = \frac{K}{\sqrt{2\pi r}} (\sin\frac{\theta}{2} \cos\frac{\theta}{2} \cos\frac{3\theta}{2})$$

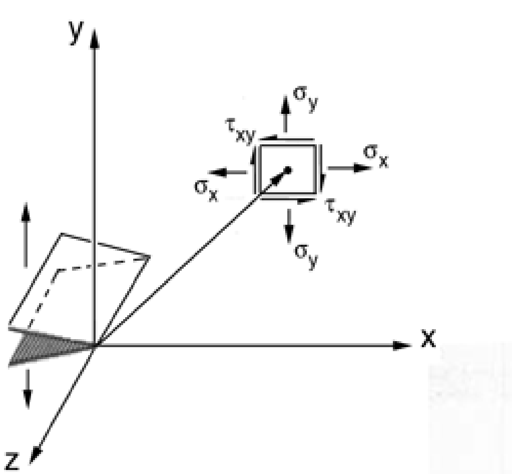

FIGURE 2.distribution of stress in the vicinity of crack tip

Relation between SCF and SIF:

From fracture mechanics and traditional elasticity, it is usual to express the stress at the tip of a crack as

$$\sigma_{max} = K_N \sigma_{net}$$

Where K_N = elasticity stress-concentration factor

σ_{net} = nominal stress at the cracked section based on the net area

For an infinite plate with uniform stress σ

$$K_N = 1 + 2(a/\rho)^{1/2}$$

Where a = ½ crack length

ρ = characteristic (fictious) radius at the crack tip.

This relationship is based on the elasticity solution for an elliptical hole of semi-major axis a, and radius at the tip ρ.

Hence:

$$\sigma_{max} = \sigma_{net}\,[1 + 2\left(\frac{a}{\rho}\right)^{\frac{1}{2}}]$$

For a small circular hole in an infinite plate a = ρ and K_N= 3; i.e. $\sigma_{max} = 3\,\sigma_{net}$

For an "infinitely sharp", crack width a>>ρ

$$K_N \approx 2\sqrt{a/\rho}$$

The stress intensity factor $K = \sigma\sqrt{\pi a}$ controls the rate of crack extension i.e. da/dN = G (k). Paris [8] following the arguments, points out that da/dN = G $(\sigma\sqrt{a})$.

Hardrath and McEvily [9] reduced this to show that $K_N\,\sigma_{net}$ is of the same from as the stress intensity factor K. if ρ is small compared to a

$$K_N = 1 + 2(a/\rho)^{1/2} \approx 2\sqrt{a/\rho}$$

Therefore $\sqrt{a} = \frac{1}{2} K_N \sqrt{\rho}$

And $K = \sigma\sqrt{\pi}a = \frac{1}{2} K_N \sigma_{net} \sqrt{\pi\rho}$

This relationship between K_N σ_{net} and K provides some justification for the present study. So the relationship between K_N and K with the variation of K_N with the flaw size would be valuable in predicting the initiation period of the fatigue life.

SOLVING FRACTURE MECHANICS PROBLEMS:

Solving a fracture mechanics problem involves performing a linear elastic or elastic-plate static analysis and then using specialized post-processing commands or macros to calculate desired fracture parameters. Two main aspects of the procedures are

- ❖ Modeling the Crack Region
- ❖ Calculating Fracture Parameters

Modeling the Crack Region:

The most important region in a fracture model is the region around the edge of the crack. The edge of the crack is referred as a crack tip in a 2-D model and crack front in a 3-D model, which is illustrated in figure 3.

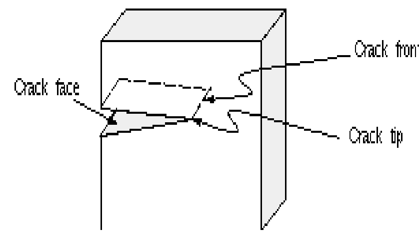

FIGURE 3.crack tip and crack front

In linear elastic problems, it has been shown that the displacements near the crack tip (or crack front) vary as$\sqrt{r}$, where r is the distance from the crack tip. The stresses and strains are singular at the crack tip, varying as$\frac{1}{\sqrt{r}}$. To pick up the singularity in the strain, the crack faces should be coincident, and the elements around the crack tip (or crack front) should be quadratic, with the midside nodes placed at the quarter points. Such elements are called singular elements. Figure 4 shows examples of singular elements for 2-D and 3-D models.

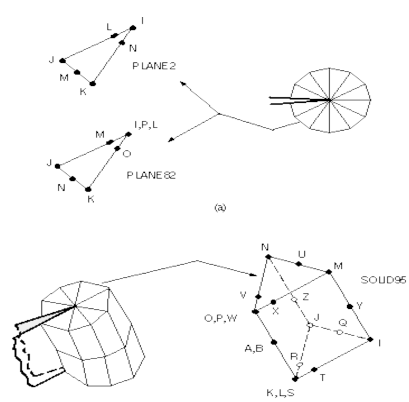

FIGURE 4.Singular elements

Calculating Fracture Parameters

The displacement at and near a crack for linear elastic materials given by *Paris P.C and Sih, G.C* [10] are

$$u = \frac{K_I}{4G}\sqrt{\frac{r}{2\pi}}\left[(2k-1)Cos\frac{\theta}{2} - Cos\frac{3\theta}{2}\right] - \frac{K_{II}}{4G}\sqrt{\frac{r}{2\pi}}\left[(2k+3)Sin\frac{\theta}{2} + Sin\frac{3\theta}{2}\right] + 0(r)$$

$$v = \frac{K_I}{4G}\sqrt{\frac{r}{2\pi}}\left[(2k-1)Sin\frac{\theta}{2} - Sin\frac{3\theta}{2}\right] - \frac{K_{II}}{4G}\sqrt{\frac{r}{2\pi}}\left[(2k+3)Cos\frac{\theta}{2} + Cos\frac{3\theta}{2}\right] + 0(r)$$

$$w = \frac{2K_{III}}{G}\sqrt{\frac{r}{2\pi}}Sin\frac{\theta}{2} + 0(r)$$

Where

u, v are the displacements in a local Cartesian co-ordinate system.

r, θ are the co-ordinates in a local cylindrical co-ordinate system as shown in figure 5.

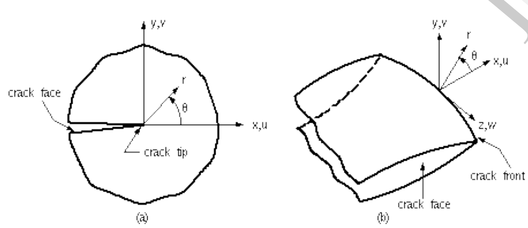

FIGURE 5.local coordinate system

G is the shear modulus

$$= \frac{E}{2(1+\vartheta)} \text{ For plane stress}$$

K_I, K_{II}, K_{III} are the stress intensity factors relating to deformation shapes.

$$K = \frac{3\vartheta}{1+\vartheta} \text{ For plane stress}$$

ν = is Poisson's ratio

0(r) is the terms of order r or higher

Evaluating the above two equations at θ = +/- 180^0 and dropping the higher order terms yields

$$u = \frac{K_{II}}{2G}\sqrt{\frac{r}{2\pi}}(k+1)$$

$$v = \frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}(k+1)$$

$$w = \frac{K_{III}}{2G}\sqrt{\frac{r}{2\pi}}(k+1)$$

For the full crack model

$$K_I = \sqrt{2\pi}\frac{G}{1+k}\frac{|\Delta v|}{\sqrt{r}}$$

$$K_{II} = \sqrt{2\pi}\frac{G}{1+k}\frac{|\Delta u|}{\sqrt{r}}$$

$$K_{III} = \sqrt{2\pi}\frac{G}{1+k}\frac{|\Delta w|}{\sqrt{r}}$$

Δu, Δv and Δw are the motion of one crack face with respect to the other.

Finite Analysis Approach and Assumptions:

- Determination of stress concentration factor and stress intensity factor involves the analysis of stress in a particular model under consideration, which is a typical structural static analysis.
- The model assumed to be made of Mild Steel withYong's Modulus 2e5 MPa and Poisson's ratio of 0.3
- As the stress distribution is the main objective of the analysis, "plane stress" option is chosen.

- Geometric modeling is done according to the dimensions and geometric ratios. Concentration key points are created at the tip of the crack models as shown in figure 6 for knowing the nodal displacement in calculation of SIF.

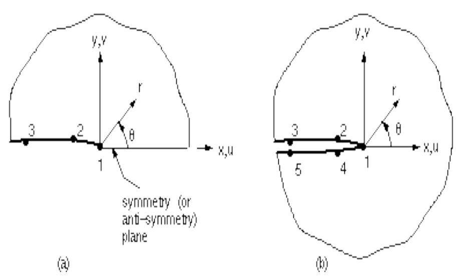

FIGURE 6.Path definition of half crack and full crack model

- Element type selection: to pick up the singularity in the strain, the crack faces should be coincident, and the elements around crack tip should be quadratic, with the midsize nodes placed at the quarter points. Such elements are called singular elements.
- PLANE 82 is a higher order version of the 2-D, four-node element (PLANE42). It provides more accurate results for mixed (quadrilateral-triangular) automatic meshes and can tolerate irregular shapes without as much loss of accuracy. The 8-node element is defined by eight nodes having two degrees of freedom at each node. Translations in the nodal x and y direction as shown in figure 7. The element may be used as a plane element or as an axisymmetric element. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The meshed model with concentrated key point and path is shown in figure 8.

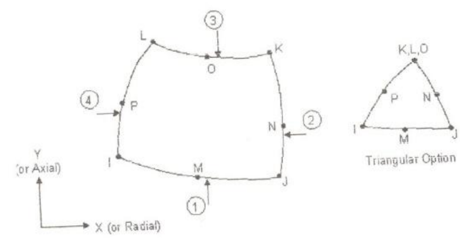

FIGURE 7.geometry of PLANE 82

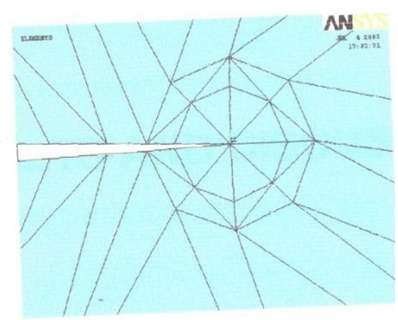

FIGURE 8.Meshed part of a crack tip with concentrated key point

Results and Discussion:

Stress analysis of double v butt-welded joints:

Double V butt-welded joints have been analyzed by varying defect length to plate thickness ratio i.e. varying a/b ratio to find out an acceptable level penetration defect lengths. Figure 9 shows the ANSYS stress output diagrams of double V butt-welded joints at different defect length to plate thickness ratios.

The values obtained are plotted in the figure 10. It is observed that the graph has a “knee” at defect length-to-plate thickness ratio around 0.2. Below the "knee", the stress concentration factor changes very little with change in defect length but for lengths beyond the knee i.e. ratios larger than 0.2, the stress concentration increase rapidly with defect length. It may constitute to the acceptable level of penetration defects. These observations are conformity with photo elastic tests conducted by *C.P. Burge, L.W.Zachary and W.F.Riley [4]*. Stress intensity factor has also been computed for double V butt-welded joint at the same defect length to plate thickness ratios. The values obtained are represented in figure 11 and have the similar trend as that of the stress concentration factor.

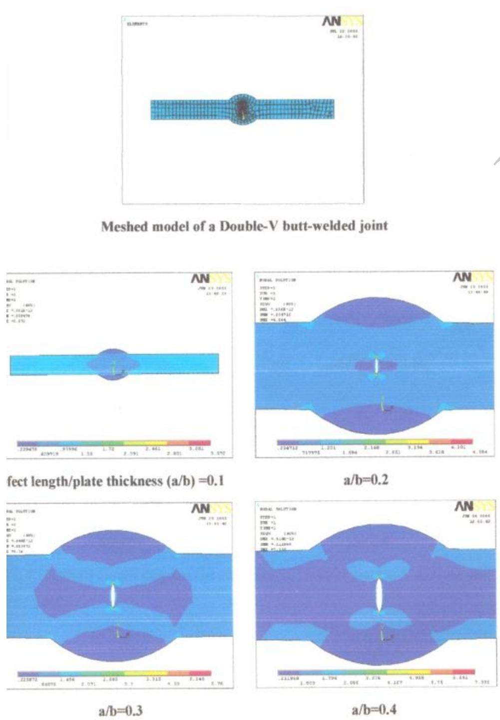

FIGURE 9.ANSYS output diagrams at different a/b ratios of double V butt welded joints

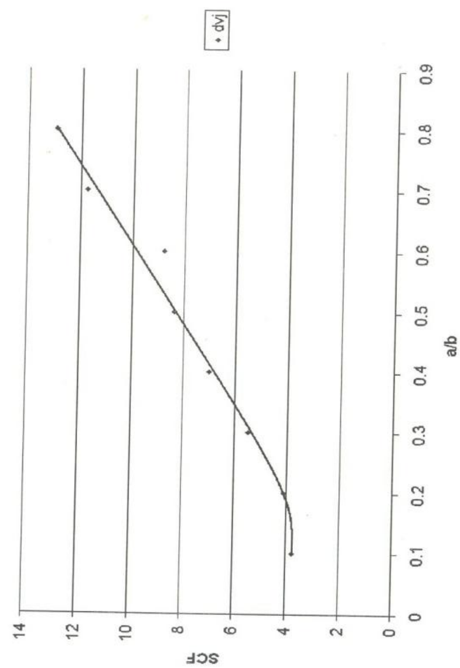

FIGURE 10.graph between SCF and a/b ratio

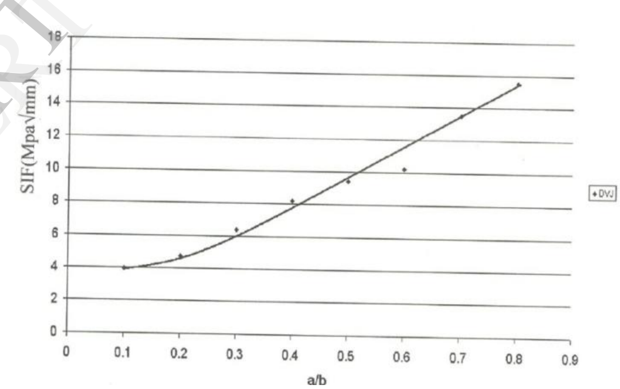

FIGURE 11.graph between SIF and a/b ratio

Effect of gusset thickness and depth of weld penetration in butt cruciform joints:

The effect of gusset thickness and the effect of the depth of weld penetration are analyzed in ANSYS for Non-load carrying cruciform butt-welded joints. Also comparisons are made for specimens with gussets welded on either side of the main plate i.e. opposite each other and for cruciform butt welded joints by removing one gusset i.e. specimens with similar

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gussets on one side only. The thickness of the gussets considered is 9.6mm & 38mm respectively.

Analyzed ANSYS output diagram for specimens with 9.6mm thick gusset on both sides and on one side are shown in figure respectively and for specimens with 38 mm thick gussets on both sides and on one side are shown in figure respectively.

The stress concentration factor at both the toe and the root vary with increasing gusset thickness the summary of the results obtained are represented in the form of graphs in figure 12 showing the relation between SCF, ratio of total weld penetration to gusset thickness and lack of penetration to weld leg length for butt welded joints respectively.

In non load carrying joint the stress concentration at the weld root is of minor important, particularly when the gussets are 9.6mm. The stress concentration factor at the weld toe is seen to be independent of the depth of penetration of the weld when the gusset is 9.6mm, but SCF to some extent depend when the gusset is 38mm thick. A gusset attached to one side of the plate gives better results than having a pair attached opposite each other the stress concentration factors at both the toe and root increase with increasing gusset thickness as shown in figure. The results obtained have the similar trend with that of the photo elastic result of *Cherry [6]* except for joint with gusset of 38mm either side in the region of ratio of lack of penetration to weld leg length.

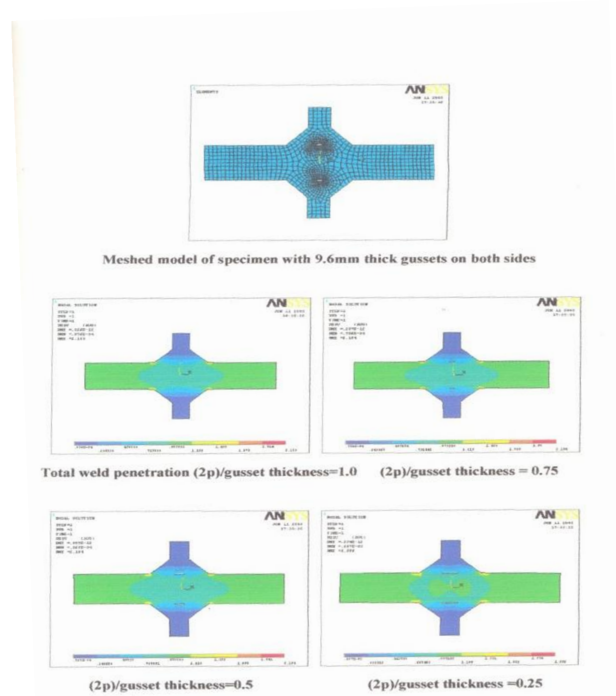
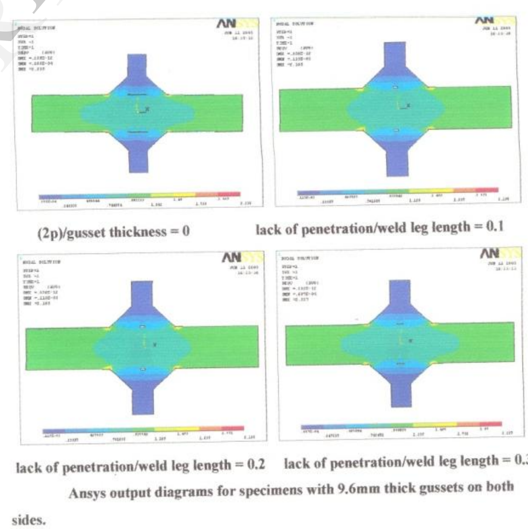
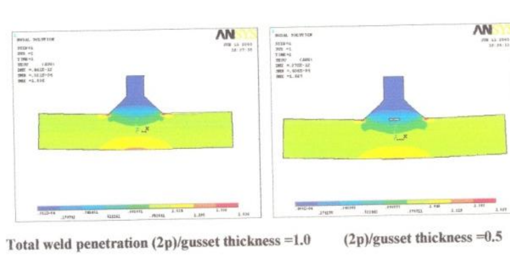
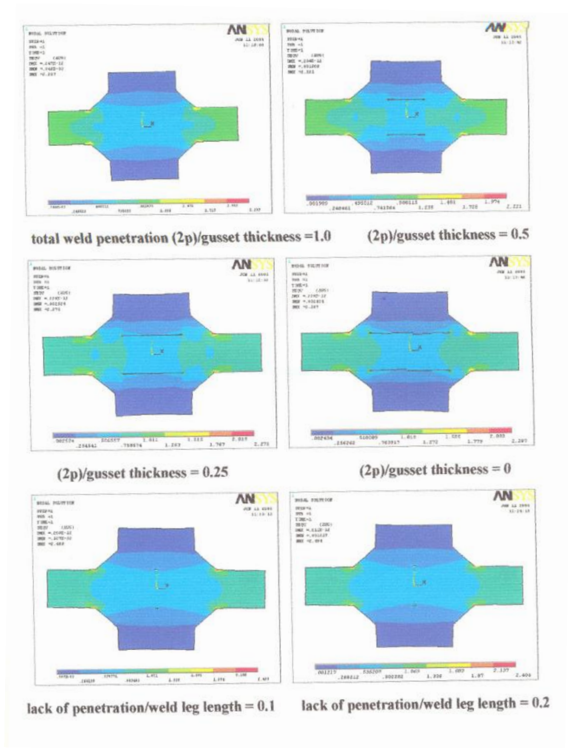
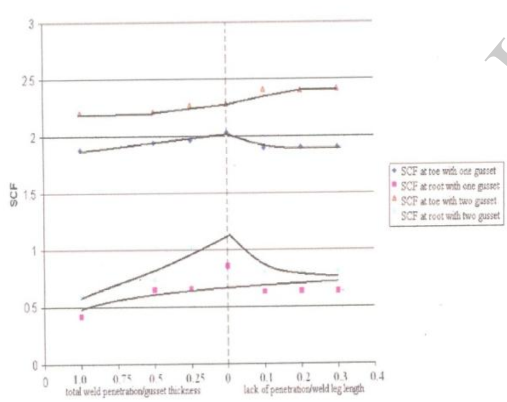


FIGURE 12. 9.6mm gussets on both sides





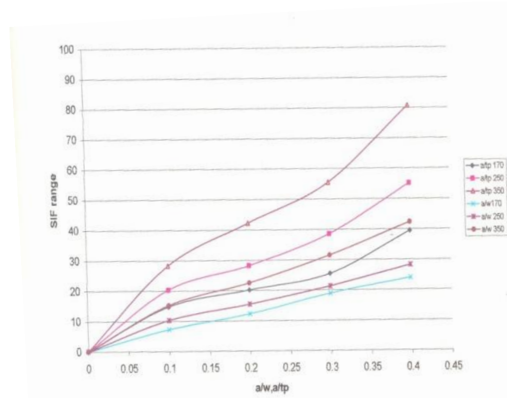




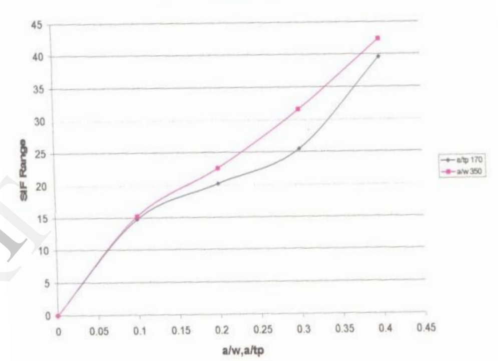
Graph drawn between SCF, ratio of total weld penetration to gusset thickness and lack of penetration to weld leg length.

RELATION BETWEEN STRESS INTENSITY FACTOR RANGE AND CRACK LENGTH

The cruciform joint containing both weld toe region with thumbnail crack embedded in the stress concentration region and also the LOP is analyzed. The results obtained are represented in the figure



Relation between SIF range Δk, a/t_p and a/w



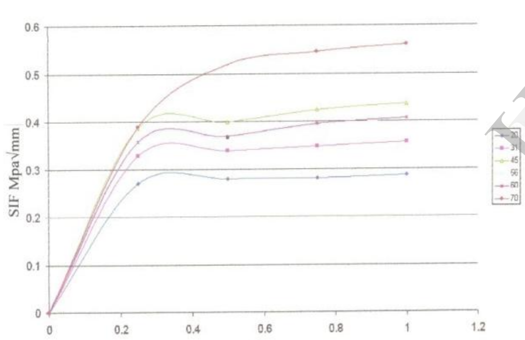
Region between the toe failure and LOP failure

For a cruciform joint 45^0 toe angle, SIF for a crack emanating from this region as calculated the relation between SIF range Δk and normalized crack length a/t_p is computed. SIF range Δk as a function of LOP crack i.e. a/w is also computed for the same stress values as shown in figure. It has been observed that the SIF for the toe crack is higher than that for the LOP crack. The toe crack will start growing unless the LOP crack is long enough to have SIF higher than that of the toe crack. Region between toe and LOP failure is shown in the figure. The obtained results have the same trend with that of *Y.Tobe & F.V. Lawrance [7]*

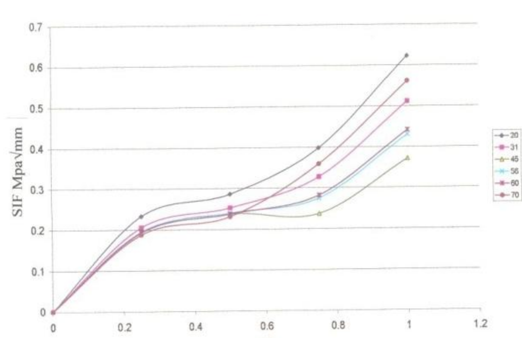
INFLUENCE OF SLIT LENGTH AT VARYING LEG WIDTH AND SLOPE ANGLE ON STRESS INTENSITY FACTOR IN CRUCIFORM BUTT WELDED JOINT

The cruciform joint with varying slit length (LOP), leg length and weld toe angles is analyzed the toe angles considered are 20^0, 31^0, 45^0, 56^0, 60^0 and 70^0 with leg length 2.4b and 1.6d. Based on the analyzed models in the relation between SIF, slit length, leg width and toe angle are represented in the graphs

Figure shows the effect of varying slit length toe angles on stress intensity factor at the toe based on analyzed models with leg width of 2.4b and 1.6b respectively.

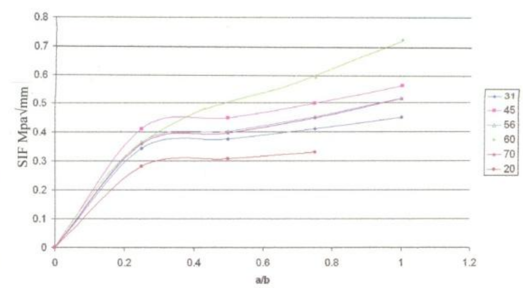


Stress intensity factor of LOP in cruciform butt welded joint at the toe with slit length of 2.4b and varying slope angles.

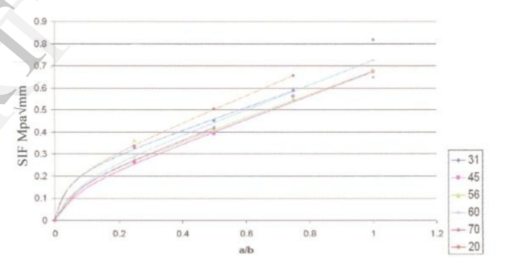


Stress intensity factor of LOP in cruciform butt welded joint at the root with slit length of 2.4b and varying slope angles.

Figure shows effect of varying slit length and toe angles on the stress intensity factor at the root based on the analyzed models with leg width of 2.4b and 1.6b respectively.



Stress intensity factor of LOP in cruciform butt welded joint at the toe with slit length of 1.6b and varying slope angles.



Stress intensity factor of LOP in cruciform butt welded joint at the root with slit length of 1.6b and varying slope angles.

The analyzed output results at the root with leg length 1.6b (figure) have the same trend as that the previous existing results that is the value of SIF decreases with increase in the toe angle of 31^0, 45^0 and 56^0 respectively. The trend is reversed at the toe region for cruciform butt welded joint of leg width 1.6b (figure) for toe angles of 31^0 and 45^0. For weld leg length of 2.4b there is a variation in order of SIF values as 310, 56^0 and 45^0 respectively after a/b ratio of 0.6. It is observed that below a/b ratio of 0.6 the trend is same. Toe angles 20^0, 60^0 and 70^0

for both leg width of 1.6b and 2.4 b are also considered.

At the toe region for the cruciform butt welded joints with leg length of 2.4b it is observed that there is no variation in SIF values with increase in a/b ration beyond 0.2. For leg length of 1.6b there is a slight variation in SIF values beyond a/b ratio of 0.2.

SCOPE FOR FUTURE WORK

- The present work can be extended further for failure analysis of weld joint under fatigue loading
- Design load reduction factor can be obtained for different design conditions.

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