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Evaluation of η_{pl} for Circumferential through Wall Cracked Bimetallic Weld Pipes by FEA

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Abstract—*The bimetallic welds (BMWs) play a critical and crucial role in the primary heat transport piping system of nuclear reactors. In nuclear power plant bimetallic welds between austenitic stainless steel and ferritic low alloy steel are used. This paper is concerned with the assessment of J-integral and η_{pl} function for straight bimetallic weld pipes. The η_{pl} function is used for experimental assessment of J-integral. There is no empirical relation is available in literature to calculate η_{pl} factor for bimetallic weld pipes.*
FE Model is constructed for homogeneous weld pipes made up of stainless steel. The FE Model is approved by comparing the η_{pl} factor for homogenous weld pipe obtained using FEA and analytically. In bimetallic weld pipes the circumferential through wall crack is at center of weld which is subjected to pure bending. Finite element analyses have been carried out on bimetallic weld pipes to calculate η_{pl} factor for four point bend loading. The investigation was accomplished for various crack sizes of straight bimetallic weld pipes.
Key words: J-integral, bimetallic, crack, pipe, η_{pl} factor.

1. Introduction

The design of the pressurized water reactor (PWR) and the boiling water reactor (BWR) consists of many bimetallic weld joints in the piping and vessels nozzles. The heavy section low alloy steel components are usually connected to stainless steel (SS) primary piping systems. In various industries like nuclear power plants the pressure vessels are made up of low alloy steel and these pressure vessels are connected to the stainless steel piping using bimetallic weld joints. In bimetallic weld pipes, at weld zone some flaw or crack may be present. These flaws may grow further and get unstabilized. In this fracture assessment study, work is done on static crack. Bimetallic weld pipes are weaker in the weld zone, thus structural integrity assessment of welded pipe is necessary. For experimental fracture assessment Load-line-displacement (LLD), J-integral, strain energy and η_{pl} factor are required parameters.

The J-integral was proposed as a new parameter to characterize the fracture behavior of cracked structures for an elastic plastic material by Rice [2]. The J-resistance curve plays an important role in structural integrity assessment of welded pipe. Chattopadhayay [3], Zahoor and Kanninen [4], Suneel K. Gupta et al. [5], have contributed to establishing procedures for experimental evaluation of the J-integral. Several experimental tests have been conducted on straight homogenous weld pipes to obtained load and plastic load-line-displacement data. Area under the curve load versus plastic load-line-displacement represents the plastic strain energy. For experimental evaluation of plastic J-integral, the η_{pl} factor is multiplied to the plastic strain energy. The η_{pl} factor is calculated for homogenous weld pipes from empirical relation which is given by Zahoor and Kanninen. These eta factor are mainly indented for nominally homogeneous material pipes, it may not yield accurate result for bimetallic pipe joints having weld center crack. In view of that, in this work set of η_{pl} factor was evaluated for weld center cracked bimetallic weld pipe joint by varying the crack angle.

The pipe model is constructed in FE software for bimetallic weld between low alloy steel and stainless steel (SS). The J-integral evaluation in FE software is based on domain integral method by Shih [6]. For bimetallic weld pipes, load and plastic load-line-displacement data is obtained from FE software. The slope value of plot, plastic J-integral versus plastic strain energy gives η_{pl} factor. For different crack sizes (half crack angle 30.9, 35, 40, 45, 50 in deg.) of straight bimetallic weld pipes the η_{pl} factors were evaluated.

2. Theoretical background

The cracked pipe is to be loaded in four-point bending and the crack plane is located such that it experiences maximum bending. The J-integral can be expressed as

$$J = J_{el} + J_{pl} \quad (1)$$

The plastic part of J-integral is defined as

$$J_{pl} = -\frac{dU_{pl}}{dA} \quad (2)$$

Where, A is crack surface area and U_{p1} is the plastic part of the strain energy. For a pipe of outer radius R_o, mean radius R, thickness t and having a through wall crack subtending an angle 2θ at the center, the plastic J-integral given by Eq. (1) can be, expressed as,

$$J_{pl} = -\frac{1}{2Rt}\frac{dU_{pl}}{d\theta} \quad (3)$$

The plastic strain energy U_{p1} can be obtained from the area under the load versus plastic LLD ($P–\Delta_{pl}$) curve. Then, U_{p1} is calculated by,

$$U_{pl} = \int_0^{\Delta p1} \boldsymbol{P}\, d\Delta_{pl} \quad (4)$$

Zahoor and Kanninen [4], have derived an expression for determination of J_{p1} from $P–\Delta_{p1}$ curves obtained from pipe fracture tests. It is based on dimensional analysis and on an alternative but equivalent definition of the J integral given by Rice et al. The resulting expression for evaluating J_{pl} for a non-growing crack i.e. stationary is

$$J_{pl} = \eta pl \int_0^{\Delta p1} \boldsymbol{P}\, d\Delta_{pl} \quad (5)$$

The resulting expression for η_{pl} as derived by Zahoor and Kanninen is

$$\eta_{pl} = -\frac{1}{2Rt}\frac{h'(\theta)}{h(\theta)} \quad (6)$$

Where h'(θ) is the derivative of h(θ) with respect to θ. For the circumferentially through wall cracked pipe geometry, the h(θ)function is

$$h(\theta) = \cos\left(\theta/2\right) - 0.5\sin(\theta) \quad (7)$$

From above equations it is clear that η_{pl} factor is important parameter for the experimental evaluation of J-integral. Equation number (6) is intended for homogeneous weld pipes for calculating η_{pl} factor. There is no any observational empirical relation to calculate η_{pl} factor for bi-metallic weld pipes.

3. Finite element model

FE Model is constructed for homogeneous (SS) weld pipes in FE software. The geometrical details of homogenous and bimetallic weld pipes are given in table 1. The circumferential through wall crack is introduced at the center of weld zone as shown in Figure 1.

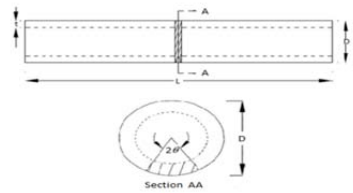

Figure 1. Straight weld pipes with circumferential through-wall crack.

Table 1. Geometry details of straight weld pipes.

Parameters	Homogeneous weld pipes	Bimetallic weld pipes
Outer Diameter D (mm)	325	325
Thickness t (mm)	25	25
Total length of pipe L (mm)	4008	4008
Outer span Z (mm)	3500	3500
Inner span L (mm)	972	972
Half-Crack Angle θ (deg.)	50	30.9,35,40,45,50

3.1 Weld zone and crack modeling

Constructions of weld zone and crack model are very complex due to the V-shape of weld and different material of weld from pipe material. The two stainless steel pipes are joining by V-shaped welding in case of homogeneous weld pipes. Through wall crack is created at the center of weld as shown in Figure 2. The orientation of crack is perpendicular to the length of pipe i.e. crack is circumferential. The transition volumes are created at weld zone for reduction in elements.

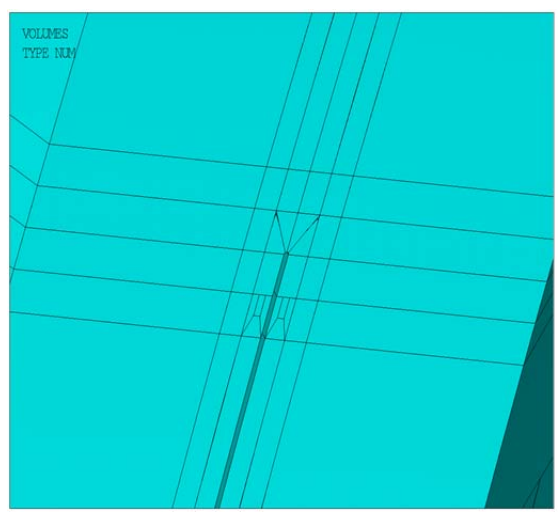

Figure 2. Crack model.

3.2 Weld zone and crack Meshing

To get J-integral value fine close contour (spider) meshing at crack tip is required. From symmetry consideration half of the through wall circumferential cracked pipe has been modeled. The symmetric boundary conditions were applied at the cut surfaces. Three dimensional 20-node SOLID-186 element type is used for meshing. Hexahedral Mapped meshing is used. Figure3 shows the weld zone meshing. The different size meshing is done on each transition volume created near the crack. Figure 4 shows fine meshing done near crack tip.

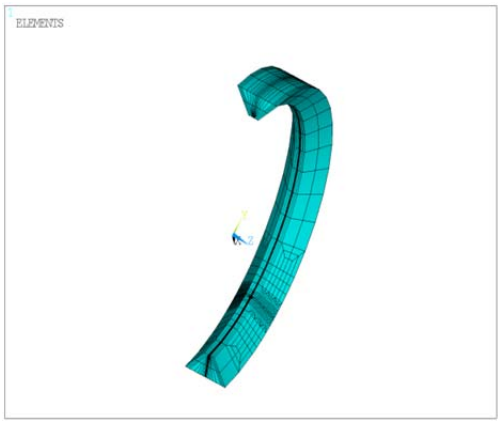

Figure 3. Weld zone meshing.

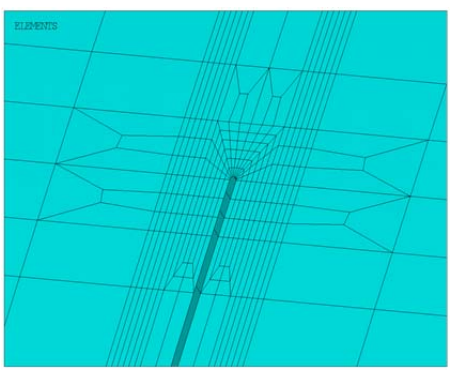

Figure 4. Fine mesh at crack tip.

In Bimetallic welded straight pipe specimen, one pipe is of low alloy steel and other pipe of stainless steel. These two pipes are welded using Inconel-182 as a filler material by Shielded metal arc welding process. The throughout circumferential crack is present at the center of weld zone. Pipe is considered as simply supported at both the ends. Schematic of loading and supports are shown in Figure5. In bimetallic weld case use same FE model and critical crack meshing that are used in homogeneous weld model. In this FE model only material properties are changing and model is shown in Figure 6.

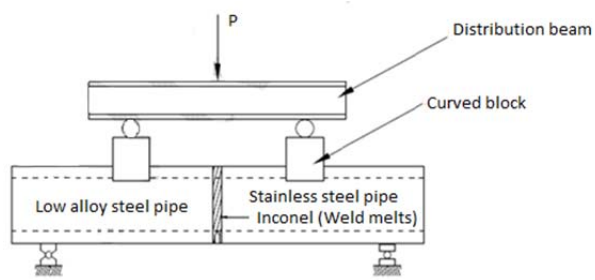

Figure 5. Typical loading arrangement of straight weld pipes.

Table 2. Details of pipe and weld material properties.

Properties	low alloy steel	Stainless steel 304LN	Invor weld material
Yield strength (MPa)	571	210	410
Ultimate Tensile strength (MPa)	693.81	545	668
Young's modulus (GPa)	227	194	182

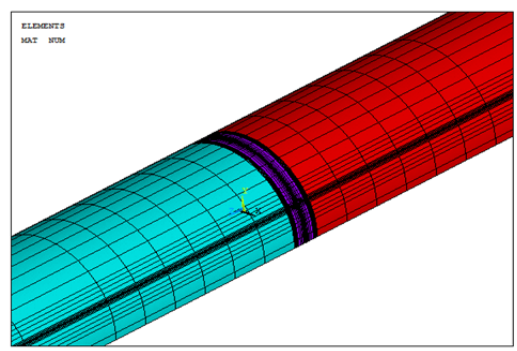

Figure 6. Bimetallic weld pipe model with meshing and material properties.

4. Finite element model validation for homogeneous weld pipes

Evaluation of η_{pl} for homogenous weld pipe from FE analysis:

For evaluation of η_{pl} factor requires plastic part of LLD, J-integral, strain energy. In these Finite element analyses LLD, J-integral, etc. have been evaluated and data have been further processed and plastic parts of various fracture parameters have been calculated. The crack-system plastic parts of LLD have been evaluated using below equation

$$\Delta_{pl} = (\Delta_{EP\,cr} - \Delta_{EP\,non\,cr}) - (\Delta_{E\,cr} - \Delta_{E\,non\,cr}) \qquad (8)$$

Where,
Δ_{pl}= plastic load-line-displacement due to crack.
$\Delta_{EP\ cr}$ = Total load-line-displacement due to crack.
$\Delta_{EP\ non\ cr}$ = Total load-line-displacement due to non-crack.
$\Delta_{E\ cr}$ = Elastic load-line-displacement due to crack.
$\Delta_{E\ non\ cr}$= Elastic load-line-displacement due to non-crack.

From above equation plastic parts of LLD have been evaluated and Plotting Load versus plastic LLD. The plastic strain energy U_{pl} obtained from the area under the load versus plastic LLD ($P–\Delta_{pl}$) curve.

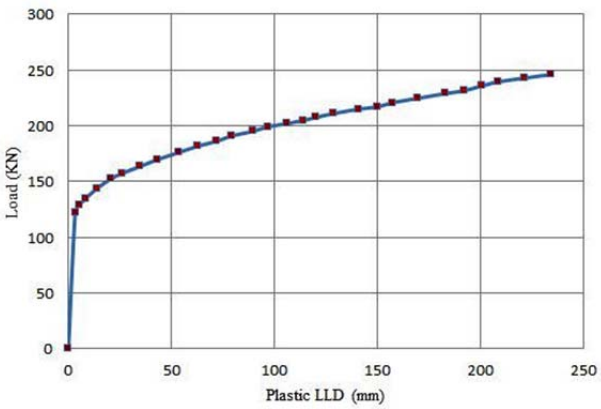

Figure 7. Plot of Load Vs. plastic LLD for, θ=50° (SS)

A typical finite element mesh used for evaluation of J-integral. A spider type mesh pattern was used to mesh the crack tip zone as shown in Figure 8. The crack thickness was modeled using eighteen elements. FE software gives different values of J-integral at different crack fronts, using trapezoidal rule J-effective is calculated.

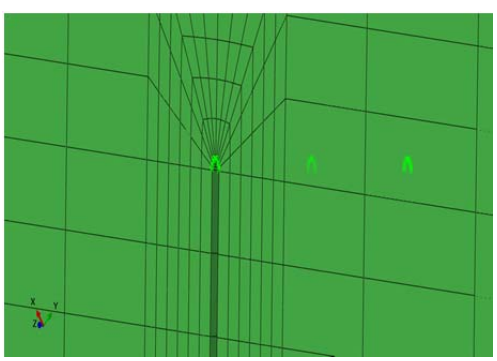

Figure 8. Crack tip mesh with crack fronts.

The plastic parts of J-integral have been evaluated as

$$J_{pl} = J - J_{el}$$

From above equation plastic and elastic parts of J-integral for crack tip have been evaluated from the finite element results.

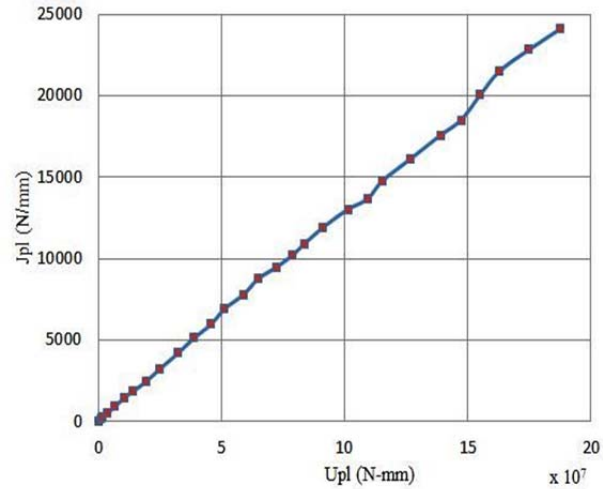

Figure 9. J_{pl} Vs Plastic strain energy U_{pl} θ=50° (SS)

Plotting plastic J-integral versus plastic strain energy and the slope of this plot gives η_{pl} value. The plastic η factor value also obtained from analytical method by using equation number 6. The plastic η factor obtained from FE analysis was nearly equal to the value calculated from analytical equation with error of 4.73 percent.

5. Results and discussion

5.1 Evaluation of η_{pl} for bimetallic weld pipe:

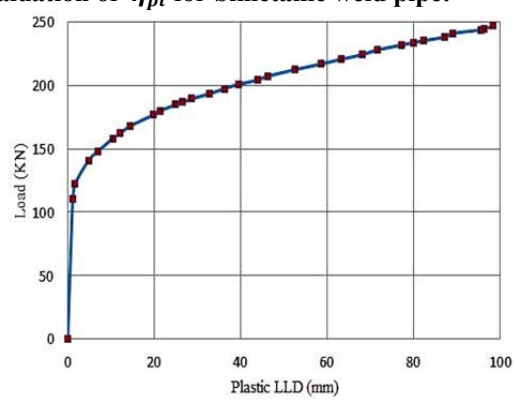

Figure 10. Plot of Load Vs. plastic LLD for, θ=50° (LAS-SS)

The results obtained from the finite element analysis are plotted in Figure 10 and Figure 11 for circumferential through wall cracked bimetallic weld pipes (θ=50°). These plot shows variation of load with respect to plastic load-line-displacement and plastic J-integral with respect to plastic strain energy (U_{pl}). The slope of plastic J-integral versus plastic strain energy (U_{pl}) plot directly gives the value of η_{pl} for bimetallic weld pipe.

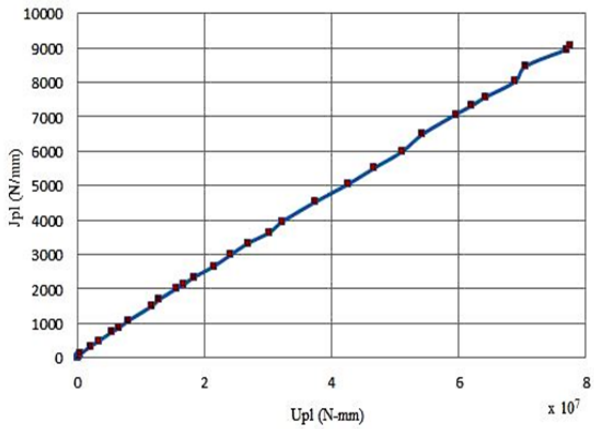

Figure 11. J_{pl} Vs Plastic strain energy U_{pl} for, θ=50° (LAS-SS)

5.2 Variation of η_{pl} with half crack angle for bimetallic weld pipes

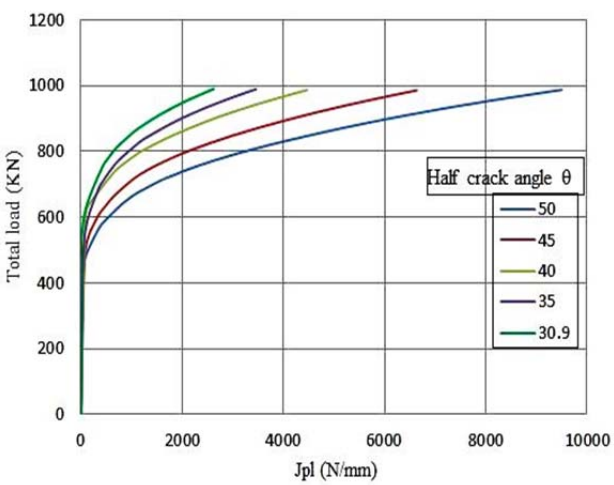

Figure 12. Total load Vs J_{pl} for, θ=30.9, 35,40,45,50 (deg.).

Load vs. J_{pl} obtained from FE analysis for different crack angle is plotted in Figure12. and J_{pl} vs. U_{pl} for different crack angle is plotted in Figure 13. These values will be utilized for evaluation of plastic eta factor.

The slope of J_{pl} vs U_{pl} plot will give η_{pl} factor. The values of η_{pl} factor evaluated for different crack angle is shown in Figure14. The η_{pl} factor value is increasing with half crack angle.

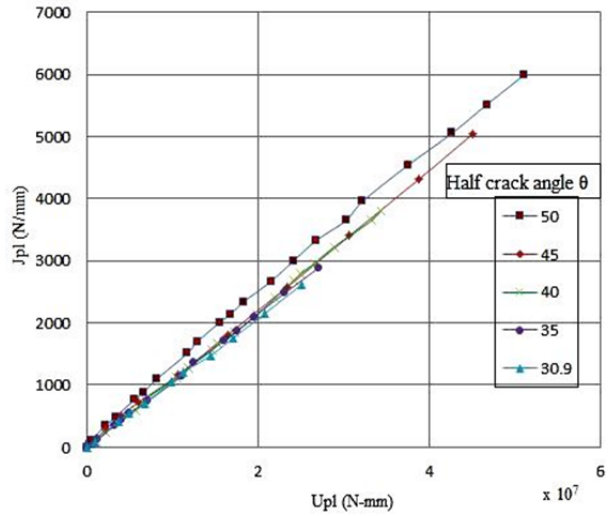

Figure 13. J_{pl} Vs Plastic strain energy U_{pl} for, θ=30.9, 35,40,45,50 (deg.)

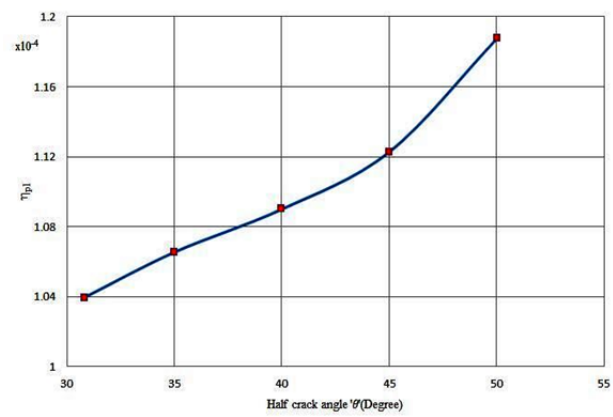

Figure 14. η_{pl} Vs Half crack angle θ=30.9, 35,40,45,50 (deg.)

5.3 Comparison of η_{pl} for Bimetallic and homogeneous weld pipes.

The η_{pl} factor obtained from FE analysis for homogeneous material pipe was nearly close to the calculated value from analytical equation. The η_{pl} factor for bimetallic weld pipes is less as compared to homogenous weld pipes. For bimetallic metal weld straight pipe η_{pl} factor depends upon pipe geometry, crack size and strength mismatch between weld and parent metals

The comparison of η_{pl} factor for bimetallic pipe weld and homogeneous pipe is shown in Figure15.

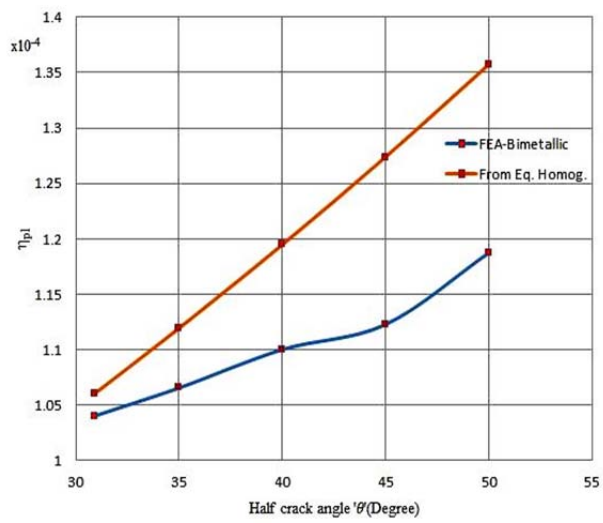

Figure 15. η_{pl} Vs Half crack angle for bimetallic (FEA) and homog. pipe (From Eq.)

The variation of the η_{pl} factor is shown in the form of normalized plot. The η_{pl} factor values for homogenous weld pipes from empirical relation were normalized with respect to the The η_{pl} factor values for bimetallic weld pipes from FEA. The normalized factor is denoted by "F"

And as shown below,

$$F = \eta_{plhomog.} / \eta_{pl\ bimetallic}\ (FEA)$$

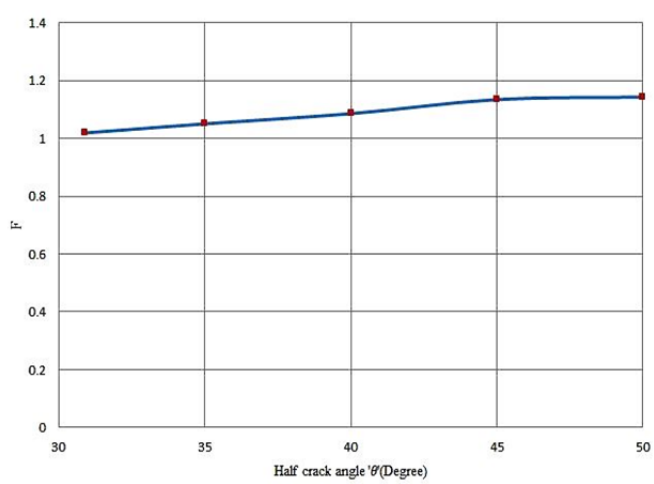

Figure 16. Normalized η_{pl} Vs Half crack angle.

6. Conclusions

- For homogeneous metal weld straight pipe plastic η factor is depends up on only model pipe geometry and crack size.
- For bimetallic weld straight pipe plastic η factor is depends upon model pipe geometry, crack size and strength mismatch between weld and parent metals.
- Effect of model pipe geometry, crack size and strength mismatch on η_{pl} factor increases with the increase in crack size.

7. Acknowledgements

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