International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 05 | May-2018 www.irjet.net p-ISSN: 2395-0072

Fracture Behaviour of Cold Rolled Close Annealed Steel Sheets with Defects

Anu K P[1], Dr. EM Somashekaran Nair[2]

[1]M.tech Student, Dept. of Civil Engineering, SCMS School of Engineering and Technology, 0484 2450330, Kerala, India
[2]Professor, Dept. of Mechanical Engineering, SCMS School of Engineering and Technology, 0484 2450330, Kerala, India

---***---

Abstract - *The structures are vulnerable to cracking. Of these, plate sections are most important. Cold Rolled Close Annealed (CRCA) sheets are the commonly used materials now a days. The defects chosen for the study are cracks and holes. In the case of cracks, straight, edge and inclined cracks and for holes, specimens with varying diameter were provided. All the specimens were tested in Universal Testing Machine (UTM). The load deflection diagram and failure load were determined. Then, the same experiment was conducted on similar specimen with weld at the crack tip. A comparative studies on the specimens with and without weld has done. Comparison of crack initiation angle obtained experimentally and theoretically by strain energy density criterion was also done.*

Key Words: **CRCA, Strain Energy Density, Plastic Radius, Angle of propagation, Theories of Failure.**

1. INTRODUCTION

Fracture mechanics is a branch of mechanics which deals with the study of propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the materials resistance to fracture. In this study, Cold Rolled Close Annealed (CRCA) steel sheets are used. These are the materials commonly used now a days as structural element for the construction of automobile body, trusses, etc.

Tobias Backers and Ove Stephansson explained that when crack tip intensity factor becomes equal to critical value, crack initiation takes place[13]. This value depends upon external loading, geometry of the specimen and crack dimension. Arun Krishnan and L. Roy Xu, has done an experimental study on the crack initiation from notches connected to interfaces of bonded bi- materials[2]. For notch angle 90° it was observed that, a concentration of fringes occurred at the crack tip due to high stress gradient. M.R.M Aliha and M.R Ayatollahi, was based on maximum tangential stress criterion (MTS)[7]. Generalised form of this criterion was used for predicting the crack initiation angle under mixed mode loading. C.S Chen and C.R Myers (2002), presented a continuum phase – field model of crack propagation[3].

In this study, CRCA specimens with cracks and holes were studied. Cracks selected are straight, edge and inclined. The holes of varying diameter are also selected as the defect.

2. EXPERIMENTAL INVESTIGATION

Tobias Backers and Ove Stephansson (2012),explained that when crack tip intensity factor becomes equal to critical value, crack initiation takes place[12].

CRCA specimens with various crack specifications are tested. The specimens tested are

- Without crack - 1 specimen
- Cracked specimens- 1cm, 2cm and 3cm crack on one side
  - 1cm, 2cm 1nd 3cm crack on both the sides
  - 15°, 30°, 45°, 60° and 90°
- With weld - 1cm, 2cm and 3cm crack on one side
  - 1cm, 2cm 1nd 3cm crack on both the sides
  - 15°, 30°, 45°, 60° and 90°
- Specimens with hole- 4mm, 6mm, 9mm and 10mm dia.

The size of the specimen selected is 200 x 100 x 1mm. The specimens before and after testing are given below.

Fig - 1: Un cracked, 1cm and 2cm on both sides, 2cm and 3cm on one side

Fig - 2: 15°, 30°, 45°, 60° and 90° inclined crack

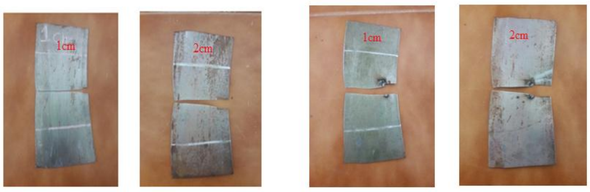

Fig - 3: 1cm, 2cm crack and 1cm and 2cm crack with weld after testing

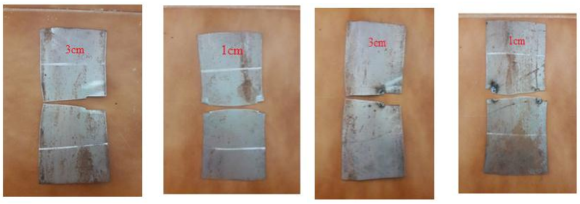

Fig - 4: 3cm crack on one side and 1cm crack on both sides with and without weld after testing

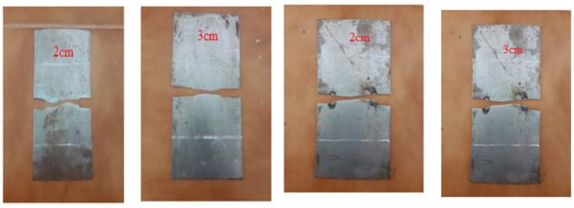

Fig - 5: 2cm and 3cm crack on both the sides with and without weld after testing

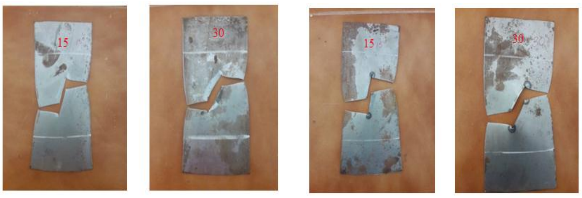

Fig - 6: 15° and 30° inclined crack with and withot weld after testing

Fig - 7: 45° and 60° inclined crack with and without weld after testing

Fig - 8: 90° inclined crack with and without weld after testing

From the figures given above, it was noted that there is a variation in the cracking of specimens with and without weld. When a weld is present, we can see a twisting nature. It is because when welds are provided the material behaves as a brittle material rather than an elastic material.

2.1 Load v/s Deflection Diagram

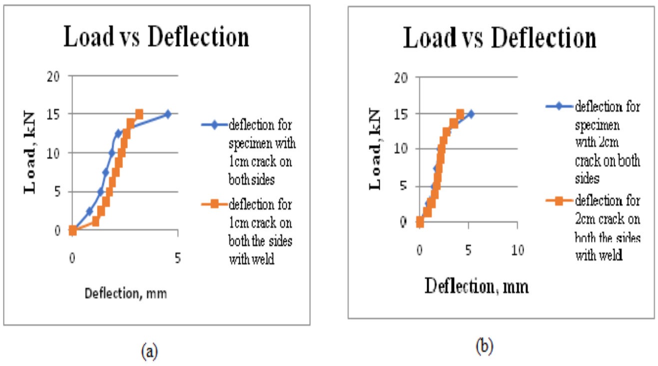

Chart-1: Comparison of load-deflection diagrams of specimens with (a) 1cm crack on both the sides with and without weld, (b) 2cm crack on both the sides with and without weld

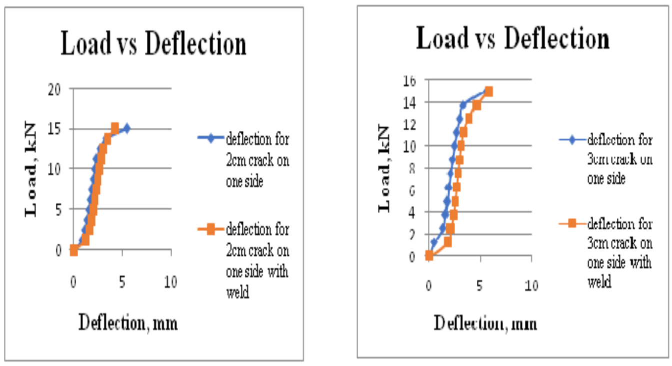

Chart-2: Comparison of load-deflection diagrams of specimens with (a) 2cm crack on both the sides with and without weld, (b) 3cm crack on both the sides with and without weld

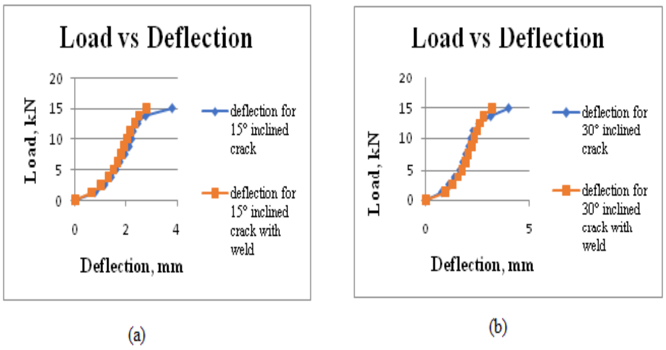

Chart-3: Comparison of load-deflection diagrams of specimens with 15° and 30° inclined crack with and without weld

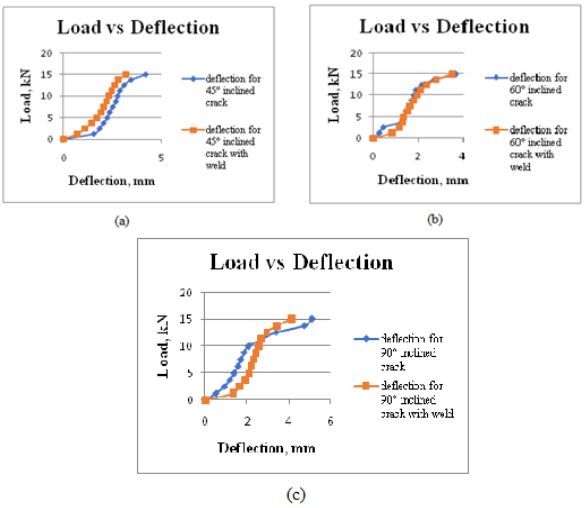

Chart-4: Comparison of load-deflection diagrams of specimens with 45°, 60° and 90° inclined crack with and without weld

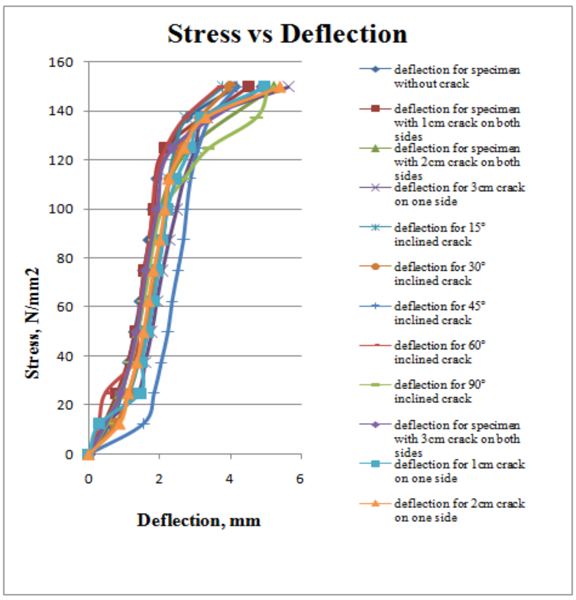

Chart-5: Load Deflection diagram for Specimens with and without crack having weld

From the charts 1-4, it was seen that the area under load - deflection graph for specimens without crack is more than that with crack. It is because, when cracks are present, some of the energy will be used for crack growth. Hence, strain energy decreases. Similarly, when weld is provided, strain energy further reduces. Some of the strain energy is used to break the weld.

The deflection is reduced and failure load is slightly increased when weld is present.

2.2 Failure Load

The failure load is given below in the table;

Table-1: Failure Load for Cracked Specimen

Specimen	Load (kN)	Specimen	Load (kN)
Without crack	36		
1cm crack on both the sides			
Without weld	21.4	With weld	24
2cm crack on both the sides			
Without weld	17.8	With weld	19.25
2cm crack on one side			
Without weld	19.4	With weld	21
3cm crack on one side			
Without weld	17	With weld	18
15° inclined crack			
Without weld	24.5	With weld	26
30° inclined crack			
Without weld	19.9	With weld	20.75
45° inclined crack			
Without weld	19.7	With weld	19.5
60° inclined crack			
Without weld	17.9	With weld	17.75
90° inclined crack			
Without weld	15.6	With weld	18.5

2.3 Effect of Holes

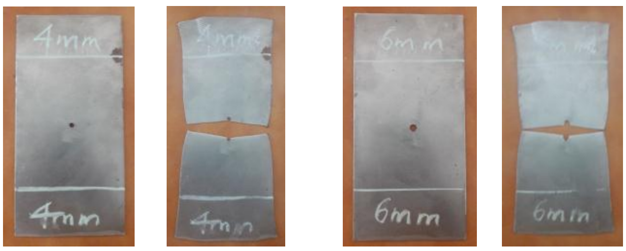

Fig-9: Specimen with 4mm and 6mm holes before and after testing

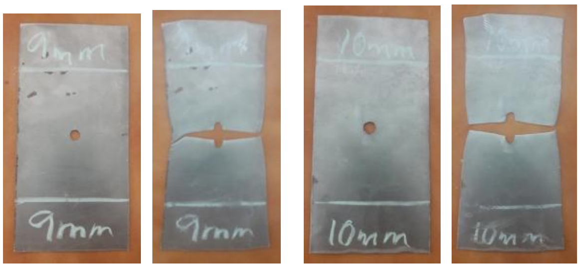

Fig-10: Specimen with 9mm and 10mm holes before and after testing

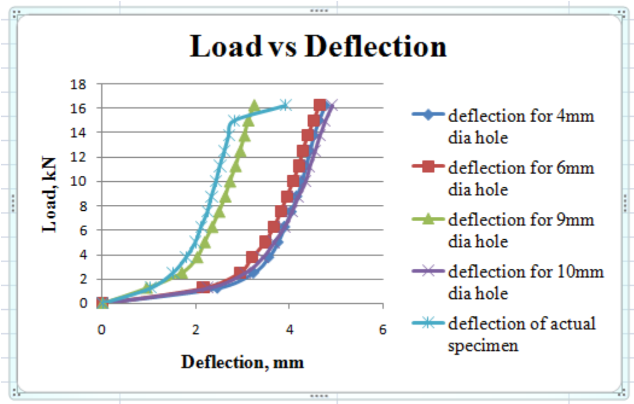

Chart-5: Load v/s Deflection Diagram

Table-2: Failure load for specimens without Hole

Specimens	Failure Load (kN)
Without hole	36
4mm diameter hole	34.5
6mm diameter hole	34.25
9mm diameter hole	34
10mm diameter hole	33.5

3 THEORIES OF FAILURE

In mixed mode fracture, it is known that the crack initiation angle depends on the loading angle. It is also known that the loading angle alters the shape and size of crack tip plastic zone. Several investigations have proposed fracture criterion on predicting crack initiation angle based on crack tip plastic zone in mixed mode fracture. Recently Bian and Kim have proposed a minimum plastic zone radius theory for crack initiation angle in mixed mode. This kind of study needs detailed information about the crack tip plastic zone shape and size in a fractured specimen estimated by numerical method such as FEM.

Different types of crack initiation theories are available. Some of them are as follows[5]:

- Maximum Tangential Stress Criterion
- Maximum Principal Stress Criterion
- Maximum Strain Criterion
- Strain Energy Density Criterion

3.1 Plastic Zone Radius Theory

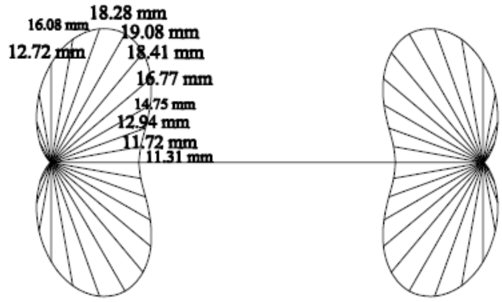

Fig-11 Plastic Radius for Specimen having 2cm crack on both the Sides

The figure above shows the Plastic Radius for the specimen having 1cm crack on both the sides. The Plastic Radius is calculated using the following equations.

$$r = \frac{k_1^2}{2\pi\sigma_{yy}^2} cos^2\left(\frac{\theta}{2}\right)\left[1+\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]^2$$

Where,

r = Plastic radius
k_1 = Stress Intensity Factor
θ = Any angle at which plastic radius has to be calculated

σ_{yy} = Yield stress of the material

$$k_1 = \sigma\,(\sqrt{\pi a})\,sin^2\,(\beta)$$

Where, σ = Stress at Failure load
a = Length of Crack
β = Angle at which the crack is inclined from vertical

Plastic Radius can also be found out by,

$$r_p = \frac{k_I^2\,(1+\nu)}{6*\pi*E*W_d}\left(f_x^2 + f_y^2 - f_x * f_y + 3f_{xy}^2\right)$$

Where,
r_p = Plastic Radius in mm
k_1 = Stress Intensity Factor
ν = Poisson's Ratio
E = Modulus of Elasticity
W_d = Distortional Strain Energy
f_x, f_y and f_{xy} = Functions of θ

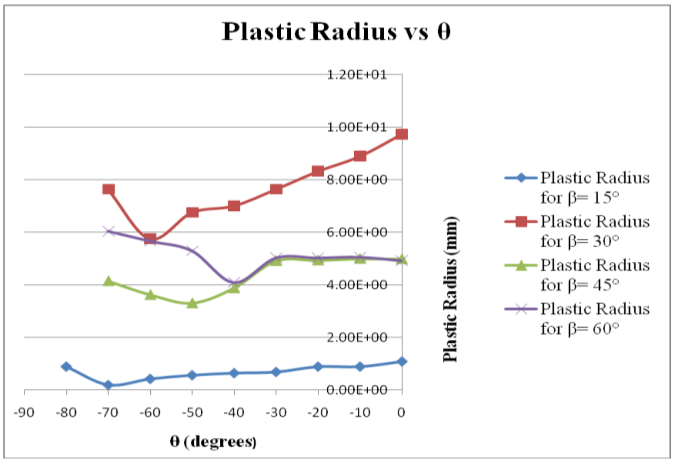

Chart-6: Plastic Radius vs θ for each β

The above graph shows the plastic radius vs θ for inclined angles. The graph gradually decreases and again increases. A minimum value was obtained in each case. Interestingly, it was noted that, the plastic radius was minimum for the same angle of propagation of crack obtained experimentally.

According to the Plastic Zone Radius Theory, in a cracked specimen, the further propagation of crack occurs through an angle where the plastic radius is minimum. Here also the result was obtained. That is, the minimum value for plastic radius was obtained at the propagation angle. Hence, it was clear that the CRCA specimen satisfies Plastic Zone Radius Theory

3.2 Energy Density Criterion

From the experimental evaluation it was clear that, when a cracked specimen is loaded, the further propagation of crack will not be through the same line as the crack. But it will takes an another path which makes an angle, θ with the crack. It can be determined using a protractor after the test was conducted[1]. The angles obtained are tabulated below. Siddharth Sumon, et al (2017), has numerically investigated crack propagation in Zircaloy-4 using XFEM. The study was based on strain energy density theory[11].

Table-3: Propagation Angle for Each Angle of Inclination

Angle of inclination of crack, β	Angle of Propagation, θ
15°	70
30°	60
45	50
60	40

The Strain energy can be calculated by using the following equation,

Total Strain Energy = Distortional Strain Energy + Dilatational Strain Energy

$$W_t = W_d + W_v$$

Where,

$$W_d = \frac{\sigma_1^2 - \sigma_1 * \sigma_1 + \sigma_2^2}{6G}$$

$$W_v = \frac{1-2\nu}{6E}\left[\frac{E * Wd}{1+2\nu} + (\sigma_1 * \sigma_2)\right]$$

Where,

σ_1, σ_2 = Principal stresses
ν = Poisson's Ratio
E = Modulus of Elasticity
G = Bulk Modulus

Where,

$$G = \frac{E}{2(1+\nu)}$$

Using the above equations, the distortional strain energy, dilatational strain energy, total strain energy and product of principal stresses were plotted against 'θ' for each 'β'. The results are given below.

Strain energy density consists of two components - Volumetric or Dilatational and Distortional for volume change without any change in shape. Distortional component is responsible for shear deformation or change in shape.

The variation of Distortional Strain energy density with 'θ' is given below.

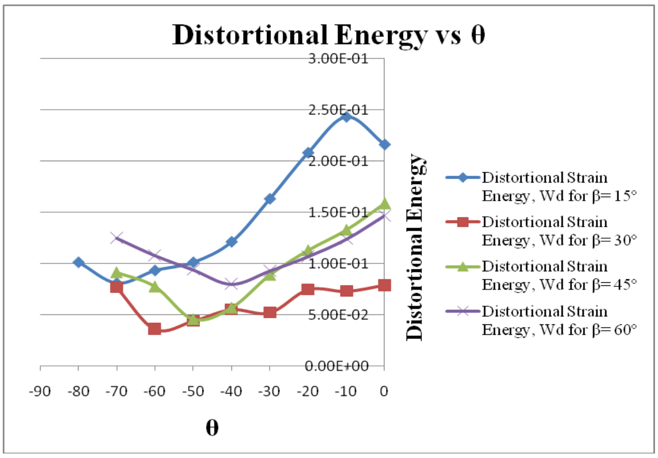

Chart-7: Distortional Energy v/s θ Graph

Distortional energy density was calculated for 'θ' corresponding to each 'β'. From the graph, it was noticed that at some angle the distortional energy is minimum. This angle is same as the crack propagation angle obtained experimentally.

Hence, it was clear that, the crack propagates when the distortional energy becomes minimum.

According to this criterion, the crack propagates when Distortional Energy Density becomes minimum.

The variation of Dilatational strain energy density vs θ was shown below. Dilatational energy is responsible for the volume change. Here there is no variation in the volume. The graph shown below does not give any relation between strain energy and θ for each β. The graph varies irregularly. No results are obtained through this criterion.

Hence, it was clear that the CRCA specimen does not follow Dilatational energy density criterion.

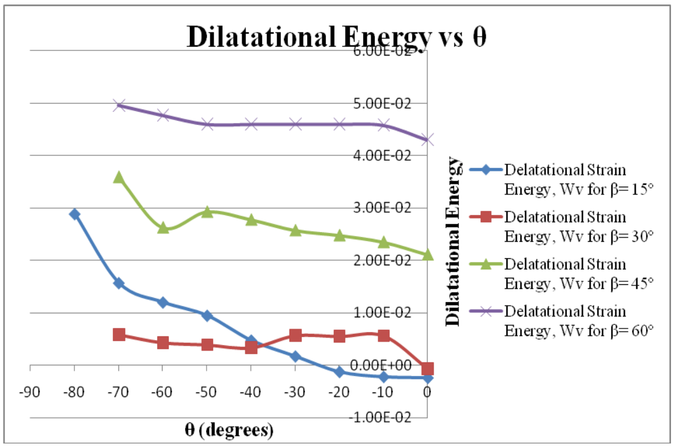

Chart-8: Fig. 5.5 Dilatational Energy vs θ Graph

Total strain energy is the sum of Distortional energy and Dilatational energy. From the calculations it was clear that Total strain energy depend on the value of Distortional strain energy. The graphs are also similar. As in the case of Distortional energy, it was noted that the crack propagates when the Total Strain energy becomes minimum. The total Strain energy does not depends on the value of Dilatational Strain Energy.

According to the Total Strain Energy Density criterion, A crack propagates when Total Strain Energy becomes minimum.

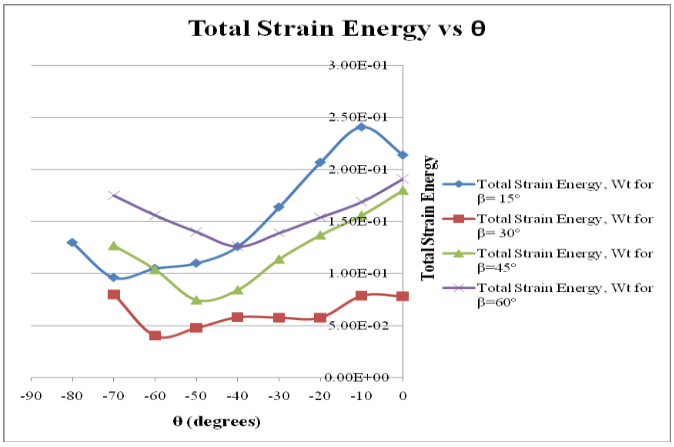

Chart-9: Total Strain Energy vs θ Graph

3.3 Maximum Principal Stress Criterion

Principal stresses were calculated by using the basic equations. Then their product was calculated for all θ corresponding to each β. Then they are plotted against θ.

The graph shows that at particular value of θ, the product of principal stresses become maximum. That value of θ was noted. It was again found that, this θ value matches with the propagation angle.

Hence, it was clear that the crack propagates when the product of principal stresses becomes maximum.

According to this theory, further crack propagates through an angle where the product of principal stresses becomes maximum. Thus, CRCA specimen satisfies Maximum Principal Stress Theory.

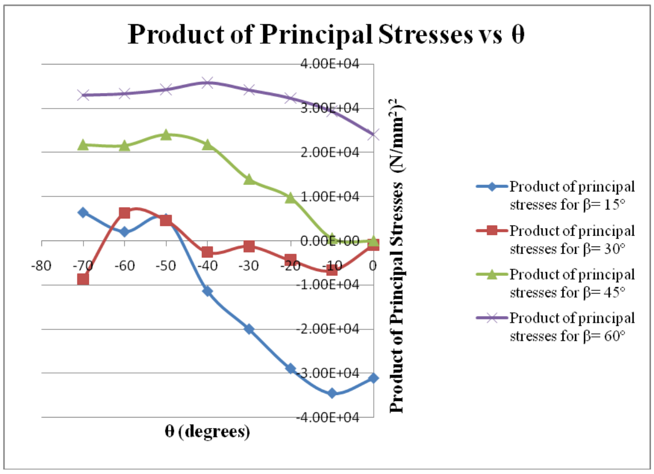

Chart-10: Product of Principal Stresses v/s θ Graph

4 RESULTS AND DISCUSSIONS

The experimental and theoretical study has done. The specimen used is Cold Rolled Close Annealed Steel Sheets. Straight, edge and inclined cracks and holes were selected as the defects. For cracks, weld was provided at the crack tip to find the difference in the failure load.

The results obtained through experimental study was listed below,

4.1 Load Deflection Graph

Load deflection graph for each case was drawn. Comparison between without and with crack and without weld and with weld was made. From the graph it was clear that, the area under load deflection graph is more for specimens without crack. This is because when cracks are present, strain energy is decreasing upon loading. When cracks are present, some of the total energy is used in growing the crack. Some of the energy is lost as surface energy which helps in further growth.

In uncracked specimen, total energy is equal to the strain energy. While in cracked specimen, total energy is the sum of strain energy and surface energy.

While comparing with and without weld specimen, the deflection is more for specimen without weld. The strain energy was further reduced when a weld was present. It is because, some of the energy was utilized to break the weld. Hence strain energy will be reduced.

4.2 Failure Load

The maximum failure load was obtained for specimen without crack. As crack was present, the failure load gets reduced.

Minimum failure load was obtained for straight crack at the centre. About 56.66% variation was observed. When weld was provided at the crack tip, a slight increase in the load carrying capacity was noticed.

Similarly when holes are present, no much variation in the failure load was observed. Only 5% variation was noticed. It was because, the cracks have sharp edges, It will be more vulnerable to cracking. But in holes no such sharp edges are present. Hence no such variations are found.

4.3 Crack Propagation angle

After the experiment was conducted, it was clear that the further propagation of crack was not through the same straight line. There is some variation in the crack propagation angle. It was measured using a protactor. This angle was then compared using theoretical investigation including different theories

4.3.1 Plastic Zone Radius Criterion

Plastic radius was drawn for straight and inclined cracks. For straight cracks, the crack propagates through $\theta = 0°$. Based on plastic zone radius theory, a crack propagates through an angle where the plastic radius was minimum. By drawing plastic radius also we obtained the minimum value at $\theta = 0°$.

For inclined crack also, by drawing plastic radius vs θ graph, minimum value is obtained at the same angle which was obtained as the crack propagation angle in the experiment. Hence, this theorem was applicable for the specimen.

4.3.2 Distortional Energy Density Criterion

Distortional energy was calculated for each β corresponding to θ. And a graph was plotted against θ. At some particular value of θ, it was noted that, the distortional energy was minimum. This angle and crack propagation angle obtained from the experiment are the same. Hence, this theorem was also applicable.

4.3.3 Total Energy Density Criterion

Similar to distortional energy, a graph of total energy was also drawn vs θ. In this case also, it was noted that, it was at the same angle the total strain energy was minimum. Hence, this criterion was also applicable

4.3.4 Maximum Principal Stress Criterion

Product of principal stresses in each case was determined. this values are plotted against θ fo each β. In this case, it was noticed that at some value of θ, the product becomes maximum. Interestingly, this angle was also the same as obtained in the previous case.

In all these cases, we can find that the crack propagation angles are the same as obtained experimentally.

5. CONCLUSIONS

Cold Rolled Close Annealed steel sheets were tested. Specimens without and with crack was tested. For cracked specimens, weld was provided at the crack tip and its effect was studied. Specimens with holes are also studied. Theoretical analysis was also done to determine the crack propagation angle and to know which all theories are applicable.

Results obtained through the study are listed below;

- From the load deflection diagram, it was clear that, the strain energy was more for un-cracked specimen. It was because, when cracks are present, some of the energy will be used for crack propagation. When weld was present, the energy further reduced. The reduced energy is used to break the weld. The total deformation obtained when weld was present is less

- In the case of failure load, minimum failure load is for 90° inclined crack at the centre. Failure load gets reduced when cracks are present rather than holes. Reduction in failure load is about 56.6% for cracks and that for holes is only about 5%. It was because of the presence of sharp crack tip.

- The material obeys distortional energy density criterion, total strain energy density criterion, plastic zone radius criterion and product of principal stress criterion. The material does not obey dilatational strain energy density criterion.

ACKNOWLEDGEMENT

Valuable informations are provided by Dr. EMS Nair. I express my sincere gratitude to him. The tests has been conducted in Material testing lab of SCMS School of Engineering and Technology, Karukutty. I extend my sincere gratitude to all my teachers and friends who helped me to complete my work successfully.

REFERENCES

1. Arun Krishnan and l. Roy Xu (2013), An Experimental study on the crack initiation from notches connected to interfaces of bonded bi-materials, Engineering Fracture Mechanics, 111, 65-76.

2. C.S Chen and C.R Myers (2002), Fracture in mode I using a conserved phase-field model, Physical Review E, vol. 65.

3. J. Alfaiate, et al. (2005), Mixed mode fracture in concrete and masonry, Dept. of Civil Eng. and Geosciences, Delft University of Technology, Delft, The Netherlands.

4. M.R.M. Aliha and M.R Ayatollahi (2012), Analysis of fracture initiation angle in some cracked ceramics using the generalized maximum tangential stress criterion, International Journal of Solids and Structures, 49, 1877-1883.

5. Siddharth Suman, et al. (2017), 3D simulation of hydride-assisted crack propagation in zircaloy-4 using XFEM, International Journal of Hydrogen Energy, 1-6.

6. Tobias Backers and Ove Stephansson (2012), ISRM Suggested Method for the Determination of Mode II Fracture Toughness, Rock Mech Rock Eng, 45, 1011-1022.

7. YS Jenq and S.P Shah (1988), Mixed-mode fracture of concrete, International Journal of Fracture, 38, 123-142.