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Evaluation of Stress Intensity Factor of Welded Structural Steel Component

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Abstract

This project work is dedicated to study the influence of welding process on mechanical properties (such as ultimate tensile strength, hardness, and impact toughness) of welded structural steel component. In this work three grades of welded structural steel have been developed by using three different grades of electrodes such as E7016, E7018 and E7024. Comparative study has been made between the three grades of welded structural steel work pieces. Nondestructive test methods are used to find the quality of the weld. There after mechanical properties have been evaluated experimentally by preparing all specimens as per the ASTM standards. Based on the results of the tests carried out on the welded specimen using the three different grades of electrodes it is observed that the structural steel welded using E7016 grade exhibits better mechanical properties and hence crack resisting capability or fracture toughness(K_{IC}). The stress intensity factor for the structural steel welded using E7016 has been evaluated by using the data obtained from the fracture toughness test. The stress intensity factor thus obtained is validated by using FEM. Finally, mini hydraulic excavator bucket has been taken for the static stress analysis in the welded region.

Keywords: Welded Structural Steel; Fracture Toughness; Stress Intensity Factor; Finite Element Analysis.

1. INTRODUCTION

Fatigue failure is still a dominating cause for breakdown of welded structures in construction and mining equipment, trains, ships, agricultural machinery, bridges and off shore equipment, hence leading to substantial costs. Structural elements and components in these types of structures are continuously subjected to variable amplitude loading during operation [1]. The demand of a more sustainable society require structures with lower weight, better performance and in case of vehicles reduced fuel consumption. This will support the use of efficient and more accurate fatigue design methods and the design methods must be connected to quality requirements which can be understood and managed during production [2].

Eighty percent of the main structures and components in construction machinery are welded steel structures fabricated from steels of different grades**.** Figure 1.1 shows a typical component in an excavator that is welded. Many of the structures are complex with regards to both geometries and loading conditions. But welding without any improvement gives rise to local stress concentration and different types of defects. These features combined with high cyclic and complex service loading give rise to failure due to fatigue.

1.2 Main Areas of this Project

The main areas that are focussed in this project are:

- To evaluate the mechanical properties of welded structural steel.
- To evaluate the stress intensity factor of complex welded steel structure.
- Stress analysis of mini hydraulic excavator bucket by FEM.

Fig. 1.1 Examples of complex welded structure in excavator

1.3 Problem Definition

Welded Structural Steel (WSS) is mainly used to build complex welded structure in earth moving equipments. Design of such complex welded steel structures based on composition, resistance against corrosion, fatigue and other characteristics of the material used for construction of these structures are to be investigated to set further information to ensure reliability in service [2].

The welded structural steel is developed for the earth moving equipment applications. The Welded structural steel is obtained by welding the structural steel with the help of selected electrodes such as E7016, E7018 and E7024. The mechanical properties such as hardness, ultimate tensile strength, impact strength and bend strength of all such grades are compared.

Fracture toughness or crack resisting capability (K_{Ic}) is evaluated for the Compact Tensile (CT) specimen prepared by the selected WSS of EN19 grade.

Stress Intensity Factor is evaluated for the complex welded steel structure. Also the evaluated Stress Intensity Factor is validated by using the ANSYS software.

Finally, the stress analysis or the static analysis is done for the complex welded steel structure (Excavator bucket as shown in Fig 1.1) by FEM.

2. Experimental details

2.1 Selection of Proper Grade of Structural Steel

The material selected for experiment is EN19 steel. Chemical composition of the EN19 steel is given in Table 2.1. The dimension of work piece is 400mm x 100mm x 20mm. The EN19 grade Structural Steel offers good ductility and shock resisting properties combined with resistance to wear. With these characteristics it is popular high tensile engineering steel with a tensile of 850-1000 N/mm^2. At low temperatures EN19 has reasonably good impact properties [3].

Table 2.1 Chemical Composition of EN19 Structural Steel

Material	C	Si	Mn	Cr	Mo	S	P
Base Material (%)	0.4	0.2	0.65	1.05	0.3	0.05	0.05

2.2 Selection of Suitable Welding Process

Arc welding which is the most common technique used to join structural steels. Arc welding requires striking a low-voltage, high-current arc between an electrode and the work piece (base metal). The shielded metal arc welding (SMAW) process using flux-coated electrodes (covered electrodes) was invented in 1907 [4]. This process features a simple design, easier welding procedures, and low equipment costs. SMAW is applied in welding almost all types of common metals, utilizing various types of covered electrodes. Table 2.2 gives the chemical composition of filler materials and Table 2.3 gives the welding parameters to be considered during welding to get a good quality weld.

Table 2.2 Chemical Composition of the Filler/Electrode (Weight %)

Filler wire	C	Si	Mn	Cr	Mo	S	P
E7016	0.80	0.70	0.90	0.20	0.30	0.035	0.040
E7018	0.12	0.80	0.90	0.20	0.40	0.030	0.03
E7024	0.15	0.90	1.25	0.20	0.30	0.035	0.035

Table 2.3 Welding parameters

Electrode	Diameter (mm)	Length (mm)	Welding current A	Arc voltage V
E7016	4	450	150	23
E7018	4	450	150	26
E7024	4	450	190	33

2.3 Development of Welded Structural Steel:

Three categories of welded structural steel blanks are developed by SMAW process by using three different electrodes namely E7016, E7018 and E7024, according to a particular geometry by adopting suitable weld parameters.

Five types of joints referred to by the American Welding Society are Butt, Corner, Edge, Lap and Tee [4]. The weld geometry is as shown in Fig 2.1. Here the welding is performed from both sides of the work piece called as double V joint.

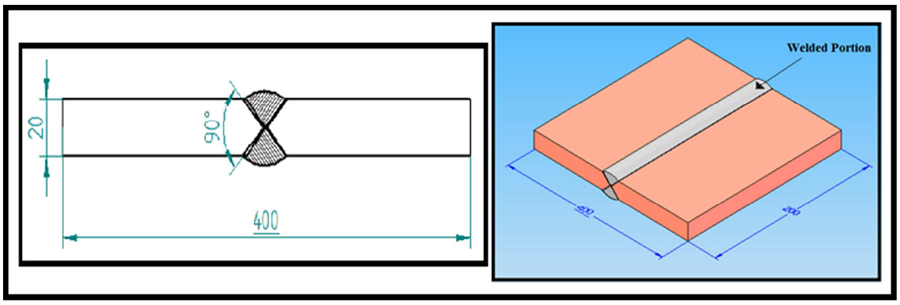


Fig 2.1 Weld geometry

2.4 Visual Test (VT)

A visual test examines bead appearance, width and thickness, welding defects such as undercut, overlap, cracks, pits and slag inclusions in the surfaces of the welds; and whether the throat is as thick as specified and the misalignment is within the allowance. This test is simple, inexpensive, and is capable of examining many weld zones at one time. Therefore, it is commonly applied to all welds. The welded specimens inspected visually are not having any defects [4].

2.5 Evaluation of Hardness for WSS Welded by E7016, E7018 and E7024 Electrodes.

The hardness test is required to confirm whether or not the weld is hard enough to resist mechanical wear or whether or not the weld is ductile enough to stresses, depending on the usage of the weldment [4]. Rockwell hardness test is selected for evaluating the hardness of the welded specimen. The dimensions of the sample used to perform Rockwell hardness test is prepared as per standard called “ASTM E18-03. The specimen is machined in to a circular disc in the welded region. For developed grade of welded structural steel blanks by using different electrodes such as E7016, E7018 and E7024, ASTM standard specimens (as shown in Fig 2.2) are prepared and tests are conducted by employing cone shaped indenter called brale with a cone angle of 120°.

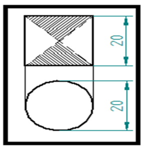


Fig 2.2 Dimensions of the specimen for Rockwell hardness test as per ASTM E18-03.

2.6 Evaluation of Impact (Charpy) Toughness for WSS Welded using E7016, E7018 and E7024 Electrodes.

The main intension of conducting impact test for welded structural steel (WSS), which is being applied in the earth moving equipments, is to measure materials ability to with stand shock load. This test uses notched bar specimen and is used to determine the tendency of a WSS material to behave in a brittle manner due to sub zero temperature in the hulls. The dimensions of the sample used for notched impact (charpy) test is prepared as per ASTM standard called “ASTM E 23: Notched Bar Impact Testing of Metallic Material” and is as shown in Fig 2.3.

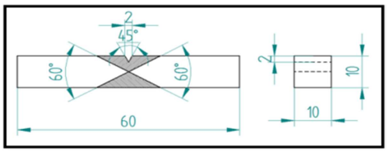


Fig 2.3 Dimension of the V notched specimen for Impact (charpy) toughness test as per ASTM E 23 standard (All dimensions are in mm)

2.7 Evaluation of Ultimate Tensile Strength (UTS) for WSS Obtained by E7016, E7018 and E7024 Electrodes.

To determine the strength and other properties such as young’s modulus, yield strength, ultimate strength and so on related to mechanical behaviour of material, tension test is conducted on a Universal Testing Machine [5]. These tests in turn support to study fracture behaviour of a material. This test makes use of a specimen prepared as per ASTM E8 and E8M standard called “Standard Test Methods for Tension Testing of Metallic Materials“. Test specimens are prepared from all the three grades of WSS welded using E7016, E7018 and E7024 electrodes. The details of the test specimen are shown in Fig 2.4. Tensile test is conducted on these specimens. The maximum stress that a test specimen can bear before fracture, based on original cross sectional area is calculated and it is referred as Ultimate Tensile Strength (UTS).

Mathematically it is given by

$$\boxed{(UTS)\sigma ult = \frac{Fmax}{Ao}} \qquad (2.1)$$

Where, F_{max} is the maximum load till specimen starts necking and

‘A_o’ is the original cross sectional area.

Also the percentage of elongation is calculated by using the following relation

$$\boxed{\%elongation = \frac{Lf - Lo}{Lo} \times 100} \qquad (2.2)$$

Where, L_f is the final gauge length measured by placing the parts together and
L_o is the original gauge length measured before test.

The results of the tension test conducted on the WSS specimen obtained by using E7016, E7018 and E7024 electrode are tabulated and compared graphically. The welded portion of the specimen is shown by inclined fill lines at the centre portion as shown in Fig 2.4.

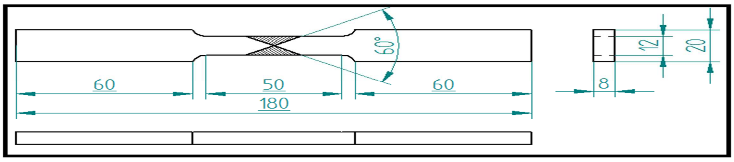


Fig 2.4 Standard tensile test specimen with rectangular cross section as per ASTM E8 and E8M standard (All dimensions are in mm)

2.8 Experimental Evaluation of Fracture Toughness (K_{IC})

Notch sensitivity impact tests are not based on rigorous analysis and it is difficult to use properly in predicting whether a crack is likely to grow under a given loading condition. In these tests, thickness of specimen is not altered based on material toughness and thus considerations of plane stress or plane strain are not accounted for. Thus a new parameter called Stress Intensity Factor (SIF) has emerged to measure the severity of stress at the vicinity of the crack tip. When this SIF reaches its critical value (crack length at fracture) then, it is termed as critical stress intensity factor or Fracture Toughness [6]. The test is conducted by involving ASTM E399-83 standard called "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials".

The fracture toughness study is made by conducting a test in servo hydraulic universal testing machine. The dimension of the CT specimen as per ASTM E399-90 standard is as shown in Fig 2.5. A cyclic loading with a maximum load of 2KN and minimum load of 0.6KN at 15 Hz frequency was maintained throughout during the application of fatigue loading. The phenomenon of introducing such crack with a plastic zone at the velocity of the notch under the application of fatigue loading is called fatigue pre-cracking. Such pre cracking is introduced with a crack length a_p=6.7mm. The number of cycles of loading taken to generate pre crack is 85,000 cycles and time is 1.57 hours. The a/W ratio for this specimen is 0.473.

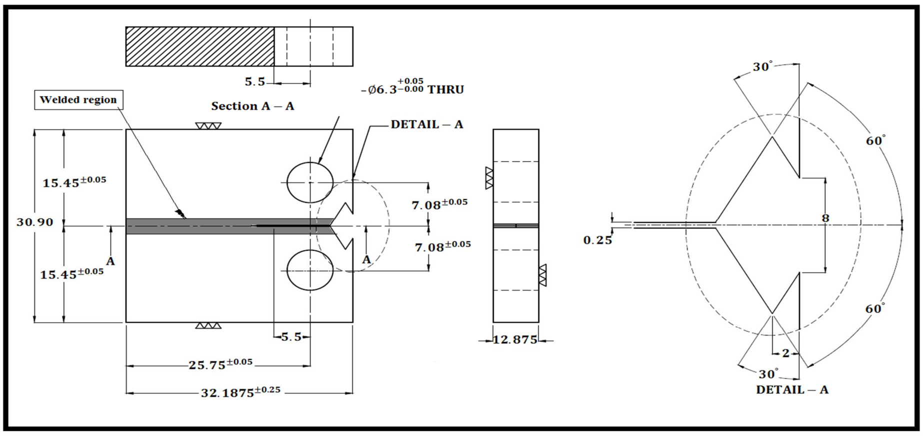


Fig 2.5 Dimensions of CT specimen as per ASTM E-399 standard used for K_{IC} test (All dimensions are in mm)

In order to obtain fracture toughness parameters, it is essential that fracture toughness test satisfies three important requirements such as 1) the specimen geometry must be such that K_{IC} can be estimated with sufficient accuracy 2) the value of the load and the crack length at the onset of cracking must be measured accurately and 3) pre-cracking must be done in order to ensure that the crack introduced is a sharp one. After recording the load V/s COD curve, draw a line through the origin at 95% of the slope. The load at which this line intersects the curve is designated P_Q unless there is a peak on the load-COD curve preceding the point of intersection. At the point P_Q a small amount of unstable crack growth occurs called as pop-in occurs before the curve deviates from linearity by 5 %. The maximum load P_{max} sustained by the cracked member can also be identified from the resultant curve. Once critical load P_Q and maximum load P_{max} is identified from the graph, it is necessary to measure the crack length.

The general expression for the plane strain fracture toughness for a CT specimen made up of WSS grade is

$$\boxed{K_Q = \left(\frac{P_Q}{B\sqrt{W}}\right) f\left(\frac{a}{W}\right)} \qquad (2.3)$$

Where, P_Q= Critical load where unstable crack growth occurs

B=Thickness of the CT specimen

W=Distance from the centre of the loading holes to the edge of the specimen.

A= Total crack length (initial plus pre crack), and

$f\left(\frac{a}{W}\right)$= Geometrical correction factor whose value can be noted down from ASTM E399 standards.

The geometrical correction factor in equation (2.3) is given by the following equation:

$$f\left(\frac{a}{W}\right) = \frac{2+\frac{a}{W}}{(1-a/W)^{3/2}}\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)2 + 14.72\left(\frac{a}{W}\right)3 - 5.60\left(\frac{a}{W}\right)^4\right] \qquad (2.4)$$

By involving ASTM E399 standards, the K_Q value obtained from eqn (2.3) can be equated to K_{IC} only if, all validity constraints which are cited in the following equations are met

$$B \geq 2.5\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 \rightarrow Plate\ thickness \qquad (2.5\ a)$$

$$a \geq 2.5\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 \rightarrow Crack\ length \qquad (2.5\ b)$$

$$W \geq 5.0\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 \rightarrow Width \qquad (2.5\ c)$$

$$Pmax \leq 1.1\ PQ \rightarrow Load \qquad (2.5\ d)$$

Where, σ_{ys}= Yield stress of graded WSS obtained from tension test.

If 'K_Q' satisfies all the requirement of STM E399 and validity conditions, then K_Q=K_{IC}. This test is carried out on selected Welded Structural Steel sample of dimensions shown in Fig 2.5. The load V/s COD plots is also drawn for the same selected specimen.

2.9 Evaluation of Stress Intensity Factor

A parameter called the stress-intensity factor (K) is used to determine the fracture toughness of most materials. A Roman numeral subscript indicates the mode of fracture and the three modes of fracture are available. Mode I fracture is the condition in which the crack plane is normal to the direction of largest tensile loading [7]. This is the most commonly encountered mode and therefore, for the remainder of the material we will consider K_I. The stress intensity factor is a function of loading, crack size, and structural geometry. The stress intensity factor may be represented by the following equation:

$$\boxed{K = \sigma Z Y \sqrt{a}} \qquad (2.6)$$

Where,

σ = The uncracked body constant stress (= Load / (Thickness x W))
a = crack length in m

$$if\ \left(\frac{a}{w}\right) < 0.701 \text{ Then } ZY = Y3\left(\frac{a}{w}\right) \qquad (2.7\,a)$$

$$if\ \left(\frac{a}{w}\right) > 0.701 \text{ Then } ZY = Y4\left(\frac{a}{w}\right) \text{ x } Y\left(\frac{a}{w}\right) \qquad (2.7\,b)$$

Where,

$$Y3\left(\frac{a}{W}\right) = 29.6 - 185.5\left(\frac{a}{W}\right) + 655.7\left(\frac{a}{W}\right)^2 - 1017\left(\frac{a}{W}\right)^3 + 638.9\left(\frac{a}{W}\right)^4 \qquad (2.7\,c)$$

$$Y4\left(\frac{a}{W}\right) = 4 - 6\left(\frac{a}{W}\right)\left[0.6366 - 0.365\left(\frac{a}{W}\right) + 0.0581\left(\frac{a}{W}\right)^2\right] \qquad (2.7\,d)$$

$$Y\left(\frac{a}{w}\right) = \frac{\sqrt{\pi}\left(1+2\left(\frac{a}{W}\right)\right)}{\left(1-\left(\frac{a}{W}\right)\right)^{3/2}} \text{ x } V \qquad (2.7\,e)$$

Where,

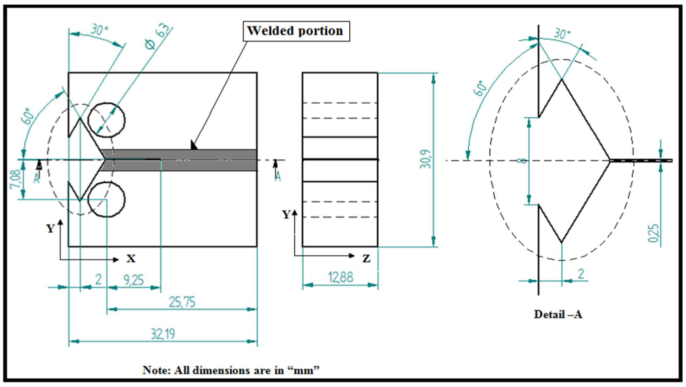
$$V = 1.12078 - 3.68220\left(\frac{a}{W}\right) + 11.95434\left(\frac{a}{W}\right)^2 - 25.85210\left(\frac{a}{W}\right)^3 + 33.09762\left(\frac{a}{W}\right)^4 - 22.4422\left(\frac{a}{W}\right)^5 + 6.17836\left(\frac{a}{W}\right)^6 \qquad (2.7\,f)$$

Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaw is not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. LEFM approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture.

2.10 Validation of Stress Intensity Factor by FEM

2.10.1 Problem Description

Compact Tensile (CT) specimen is one specimen type to measure fracture toughness of a material. In this project, we will model a crack of length a=12.2mm in a CT specimen and compute the mode I stress intensity factor (SIF) along the crack front. The material is Structural Steel welded using E7016 electrode with Elasticity Modulus = 325 GPa, σ_Y= 416 MPa, γ= 0.3. The dimensions are given in Fig 2.6 and a load of P= 6.4KN is applied on the specimen.



Note: All dimensions are in "mm"

Fig 2.6 Dimension of CT specimen as per ASTM E-399 standard

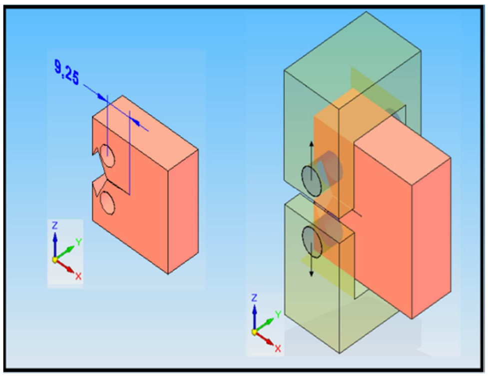


Fig 2.7 3D modelled CT Specimen

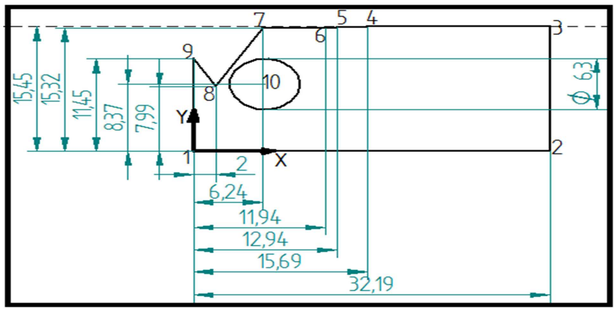
2.11 Generation of the Finite Element Model within the ANSYS Preprocessor

The specimen is model as a 3D problem using multi-layers of 3D elements in the out of plane direction.and due to the symmetry of the problem, only analysis of a half the model is done. To do this, back face of the domain meshed the with area (2D) elements and then the mesh is extruded in the third direction. PLANE82 and SOLID95 elements from the ANSYS element library are used for this.

2.11.1 Define Keypoints

10 key points are given in the following Table 2.4 are created along with their location and they are also indicated in the figure 2.8 given below.

Table 2.4 Location of Keypoints

Keypoints	LOCATIONS			
	X(m)	Y(m)	Z(m)	
1	0	0	0	 **Fig 2.8** Location of keypoints
2	0.03219	0	0	
3	0.03219	0.01545	0	
4	0.01469	0.01545	0	
5	0.01294	0.01545	0	
6	0.01194	0.01532	0	
7	0.00624	0.01532	0	
8	0.002	0.00799	0	
9	0	0.01145	0	
10	0.00644	0.00837	0	

2.11.2 Applying Boundary Conditions

Following boundary conditions are imposed on the model

1. On symmetry area (Top Area): Uy =0
2. On corner 1, constrain Ux=Uy=Uz=0
3. On corner 2, constrain Ux (to avoid the rotation about the Y axis.
Note that: we could choose the corner 3 (Uz=0), instead.)
4. Applied load is 6.4 KN

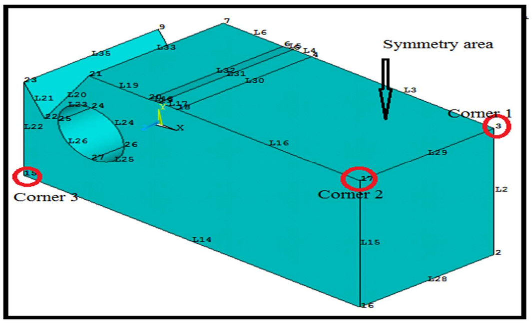


Fig 2.9 Applied Boundary Condition

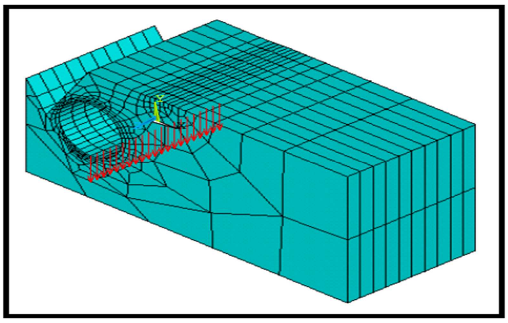


Fig 2.10 Applied Load

2.12 Static Stress Analysis of Mini Hydraulic Excavator Bucket

The static analysis is performed for the mini hydraulic excavator bucket and stress analysis is carried out based on FEA approach using ANSYS software. Von Misses stress is used as a criterion in determining the onset of failure in ductile materials, and the materials in the presented study for the bucket is ductile material, so the design of the bucket should be on the basis of Von Misses stresses acting on the parts [8]. The failure criterion states that the Von Misses stress should be less than the yield stress of the material and the factor of safety (FOS) for the excavator bucket model is calculated by using equation 2.8 below.

$$\boxed{Factor\ of\ safety\ (FOS) = \frac{\sigma_y}{\sigma_d}} \tag{2.8}$$

Static force analysis is carried out based on the digging force calculation according to SAE J1179 standards. Digging force is calculated and applied on the bucket tooth. The stress analysis is performed for bucket based on the loading conditions obtained from the static force analysis. Orthographic view of excavator bucket is as shown in Fig 2.10.

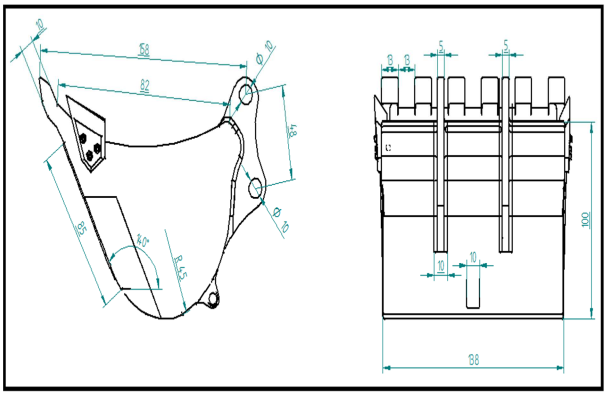


Fig 2.11 Orthographic view of Excavator Bucket

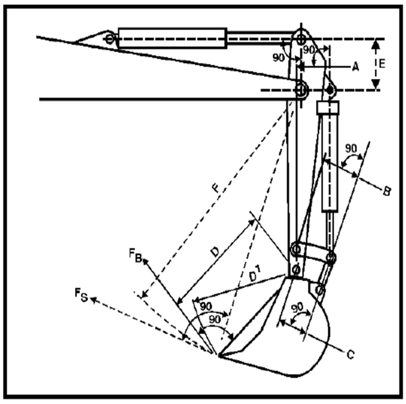


Fig 2.12 Determination of Digging Force

2.12.1 Calculation of Digging Force:

Specification of bucket:

Bucket penetration into a material is achieved by the bucket curling force (FB) and arm crowd force (FS). The rating of these digging forces is set by SAE J1179 standard “Hydraulic Excavator and Backhoe: Digging Forces”. These digging forces are the forces that can be exerted at the outermost cutting point (that is the tip of the bucket teeth) [9]. Fig 2.12 shows the forces acting on the bucket including the bucket curling force F_B and the other distance terms A, B, C, D, D^1 , E, and F.

According to SAE J1179, Maximum radial tooth force due to bucket cylinder (bucket curling force) F_B is the digging force generated by the bucket cylinder.

$$F_B = \frac{p \text{ x } (\pi/4) {D_B}^2}{D} \left(\frac{A\text{x } C}{B}\right) \qquad 2.9$$

Where,

D_B= 9 mm (Diameter of the bush).
A = 56 mm (Distance between boom nose pin and arm cylinder pin).
C = 39 mm (Distance between two bushes of the side plate stiffener).
B = 48 mm (Distance between two bushes of the ear plate stiffener).
D = 158 mm (Arm link length).
p = Working pressure and it is assumed as 5 MPa.

Therefore the digging force F_B generated by the bucket cylinder is calculated as follows. From Eqn 2.9 we get,

$$F_B = \frac{5 \text{ x } (\pi/4) 9^2}{158} \left(\frac{56\text{x } 39}{48}\right) = 92\ kN$$

This force is applied on the bucket teeth for the static stress analysis using FEM.

3. Results and Discussions

3.1 Hardness Test:

The results of the Rockwell hardness test conducted on the ASTM standard specimen (dimensions as shown in Fig 2.2) of various specimens of Structural Steel of EN19 welded using different electrodes are tabulated as shown in Table 3.1 below.

Table 3.1 Hardness Test Results for WSS welded by E7016, E7018 and E7024.

SL. No	Grades of electrode used for welding	Scale symbol	Total Load (kgf)	Indentor	HRC	Average
01	E7016	C	150	BRALE	85	86
			150	BRALE	84	
			150	BRALE	88	
02	E7018	C	150	BRALE	96	95
			150	BRALE	95	
			150	BRALE	94	
03	E7024	C	150	BRALE	90	92
			150	BRALE	93	
			150	BRALE	92	

From the above table, it is evident that RHN for specimen welded using E7016 is lesser than specimens welded using E7018 and E7024. It is observed that specimen welded with E7016 exhibits more plastic deformation under load compared to the specimens welded with E7018 and E7024. This feature is very much essential for the complex welded structure of earth moving equipments in order to withstand cyclic and dynamic loads. Hence it is concluded that ductility is more for the WSS welded with E7016 and thus the weld joint made with E7016 possesses more load bearing capability before fracture in contrast with joints made with E7018 and E7024.

Fig 3.1 Hardness test specimen after indentation

3.2 Impact (Charpy) Toughness Test.

The result of the impact (Charpy) test conducted on the ASTM standard specimens (dimensions as shown in Fig 2.3) made out of welding EN19 grade using different electrodes are tabulated in Table 3.2 below

Table 3.2 Impact (Charpy) Toughness Test result for Welded Structural Steel

SL. No	Grades of electrode used for welding	Trial No	Impact Toughness (J)	Average
01	E7016	1	53	54
		2	54	
		3	55	
02	E7018	1	50	50
		2	51	
		3	48	
03	E7024	1	50	49
		2	48	
		3	50	

From Table 3.2, it is evident that impact toughness or fracture energy obtained on WSS grade of EN19 welded with E7016 is higher than the specimen welded with E7018 and E7024. It has been observed that WSS grade of EN19 weld with E7016 obsorbs more impact energy compared with the specimen welded using E7018 and E7024. This feature is very much essential for the complex welded steel structure used in earth moving equipments which are subjected to high impact loads.

Hence it can be concluded that welded joint made with E7016 possesses more ductility and thus it can obsorb more energy under impact loads before fracture. The charpy test specimen after the breakage is as shown in Fig 3.2.

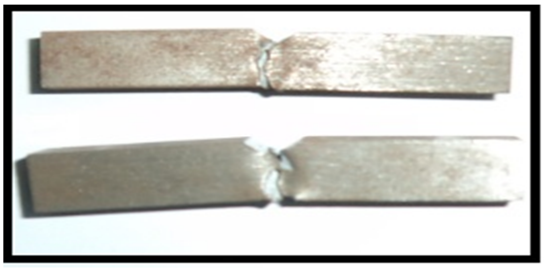


Fig 3.2 Impact Toughness (Charpy) specimen after breakage.

3.3 Ultimate Tensile Strength (UTS) Test.

The results of the UTS test conducted on the ASTM standard specimens (dimensions as shown in Fig 2.4) made out of welded structural steel (WSS) of EN19 welded using E7016, E7018 and E7024 are tabulated in Table 3.3, in order to examine the percentage of elongation or ductility existing in different specimens.

Table 3.3 UTS Test results for WSS obtained by E7016, E7018 and E7024 electrodes.

SL.No	Grades of electrode used for	Trail No	Load at yield	Yield Strength (MPa)	UTS (MPa)	Average

	welding		(KN)			
01	E7016	1	38	412	588	589
		2	39	420	590	
		3	37	416	585	
02	E7018	1	35	410	595	597
		2	33	405	597	
		3	34	406	599	
03	E7024	1	37	415	603	605
		2	38	417	606	
		3	37	412	605	

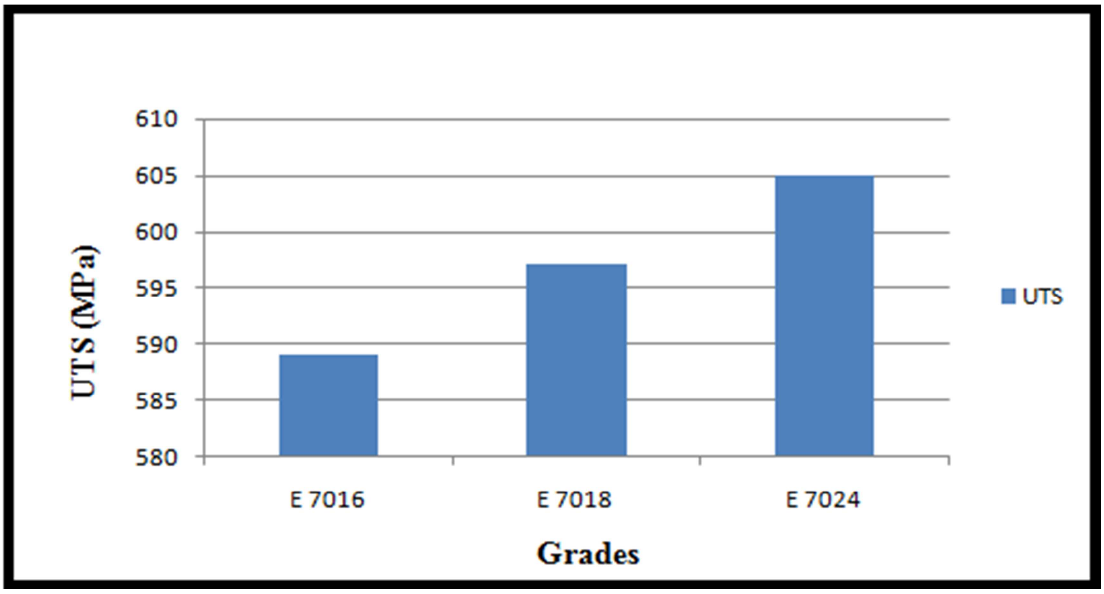


Fig 3.3 UTS for different grades of WSS

From Fig 3.3, it is evident that the UTS for specimen welded using E7016 electrode is less than the UTS of other two grades. It signifies specimen welded with E7016 will withstand relatively lesser load before fracture than specimen welded with E7018 and E7024. In case of earth moving equipments, it is generally expected to show a yielding before fracture as a sign of likely failure so that some preventive action can be initiated in order to postpone or avoid failures. Based on UTS, impact toughness and hardness tests, it is recommended to consider the percentage of elongation in to effect. Hence percentage of elongation, which is nothing but measure of ductility for all the welded joints has been evaluated and tabulated in Table 3.4.

Table 3.4 Percentage of elongation results for Welded Structural Steel.

SL.No	Grades of electrode used for welding	Trail No	Initial length (mm)	Final length (mm)	% of elongation	Average
01	E7016	1	50	61.00	22.00	23
		2	50	60.30	20.60	
		3	50	61.70	23.40	
02	E7018	1	50	59.75	19.50	20

		2	50	58.95	17.90	
		3	50	60.20	20.40	
03	E7024	1	50	60.95	21.90	21
		2	50	60.20	20.40	
		3	50	59.75	19.50	

From Fig 3.4, it can be clearly identified that percentage of elongation of specimen welded with E7016 is more compared to specimen welded using E7018 and E7024 electrodes. Therefore based on percentage of elongation, WSS of EN19 welded using E7016 electrode exhibits more elongation (or yielding) before the initiation of necking compared to other specimens welded using E7018 and E7024 electrodes. More elongation in the specimen welded using E7016 means; it shows a signs of likely failure a bit earlier than specimen welded with E7018 and E7024. Once yielding initiates, preventive measures can be taken in advance without allowing the yielding to progress and this is possible with specimen welded with E7016. Hence it can be concluded that the ductility is higher in case of specimen welded with E7016 in contrast with specimen made using E7018 and E7024 electrodes.

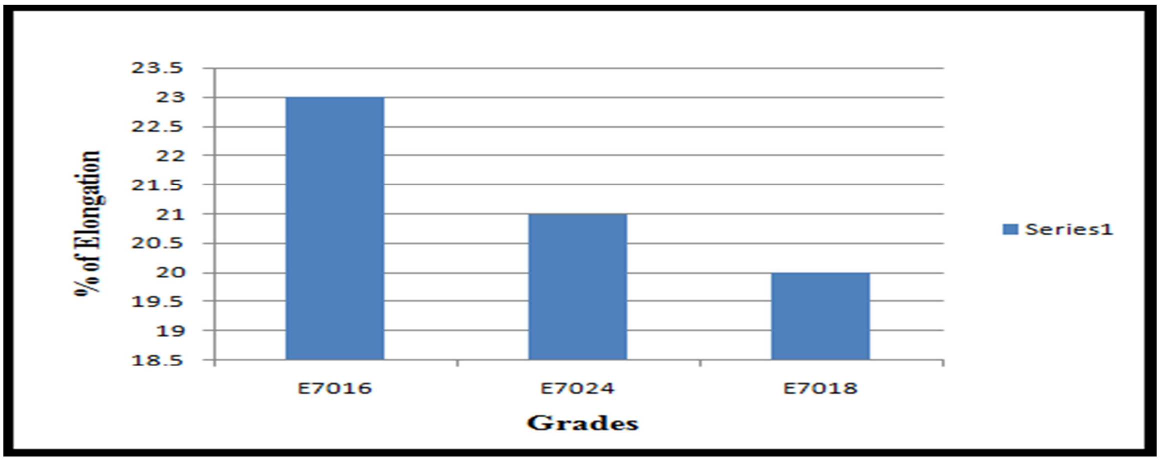


Fig 3.4 Pecentage of elongation for different grades of WSS

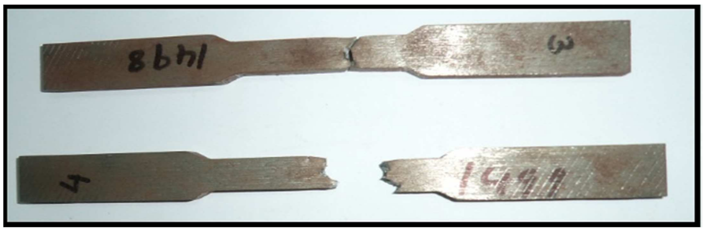


Fig 3.5 Tension test specimen after breakage

The tensile test specimen after breakage is as shown in Fig 3.5, Based on the discussions held in the previous sections, it can be concluded that structural steel welded using E7016 electrode shows better mechanical properties and hence the results for crack resisting capability or fracture toughness for joints made with E7016 electrode is calculated in the subsequent sections.

3.4 Fracture Toughness Test

The results of the fracture toughness test conducted with the aid of servo hydraulic UTM on the ASTM E399 standard CT specimen made up of welded structural steel (WSS) of EN19 grade are presented in this section. The load versus Crack Opening Displacement (COD) curve generated digitally in servo hydraulic UTM during testing of WSS blank in the form of CT specimen is as shown in Fig 3.6.

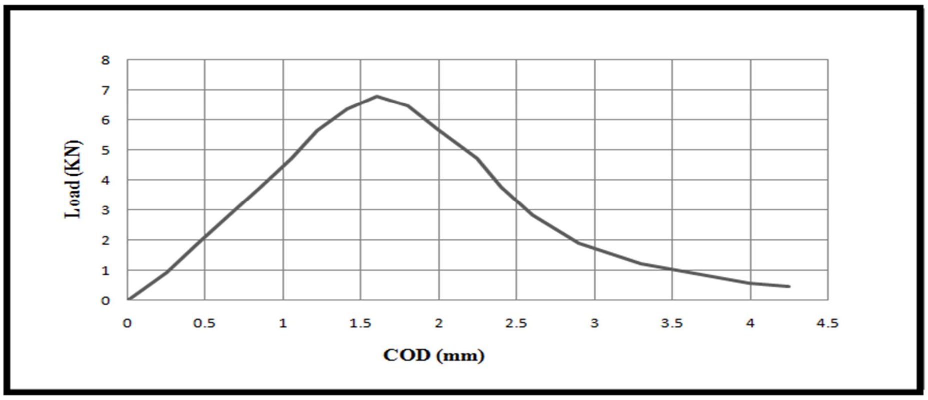


Fig 3.6 Load V/S COD curve for WSS developed by E7016.

From the Fig 3.6 the values of critical load ‘P_Q’ and maximum load ‘P_{max}’ is found to be P_Q= 6.4kN and P_{max}= 6.8kN for the non dimensional term $a/w = 0.473$ and corresponding geometrical correction factor $f(a/W)$ recommended by ASTM E399 standards table was found to be 8.96

For plain strain fracture toughness, the value of K_Q can be computed as follows by using $f(a/W) = 8.96$

$$K_Q = \frac{P_Q}{B\sqrt{W}} f\left[\frac{a}{W}\right]$$

$$K_Q = \frac{6.4 \text{ x } 10^3}{0.01287\sqrt{0.02575}} 8.96$$

$$\boxed{\boldsymbol{K_Q = 28.00\ MPa\sqrt{m}}}$$

3.4.1 Check for Validity Constraints:.

For validating the constraints B, a, W and P_{max}, it is assumed $K_{IC} = K_Q$ and these constraints are calculated as below. The yield stress value for welded structural steel (WSS) of EN19 grade is found from the tension test is given by σ_{ys} = 416 MPa.

(i) For plate thickness

$$B \geq 2.5\left[\frac{K_{IC}}{\sigma_{ys}}\right]^2$$

$$B \geq 2.5\left[\frac{28}{416}\right]^2$$

$$\boxed{\boldsymbol{B \geq 11.32\ mm}}$$

Plate thickness (B) value for the tested specimen is12.88 mm, it is greater than 11.32mm and hence it is satisfying the condition.

(ii) For crack length

$$a \geq 2.5\left[\frac{K_{IC}}{\sigma_{ys}}\right]^2$$

$$a \geq 2.5\left[\frac{28}{416}\right]^2$$

$$\boxed{\boldsymbol{a \geq 11.32\ mm}}$$

Crack length (a) value for the tested specimen is 12.20 mm, it is greater than 11.32mm and hence it is satisfying the condition.

(iii) For width

$$W \geq 5.0\left[\frac{K_{IC}}{\sigma_{ys}}\right]^2$$

$$W \geq 5.0\left[\frac{28}{416}\right]^2$$

$$\boxed{\boldsymbol{W \geq 22.65\ mm}}$$

Width (W) value for the tested specimen is25.75 mm, it is greater than 22.65mm and hence it is satisfying the condition.

(iv) For load ratio

$$P_{max} \leq 1.1 P_Q$$

$$P_{max} \leq 1.1 \text{ x } 6.4$$

$$\boxed{\boldsymbol{P_{max} \leq 7.04\ kN}}$$

Load ratio (P_{max}) value applied for the tested specimen is 6.8kN, it is lesser than 7.04kN and hence itis satisfying the condition.

Hence obtained K_Q satisfies all the validity requirements, thus computed K_Q itself K_{IC}. Therefore,

$$\boxed{K_Q = K_{IC} = 28\, MPa\sqrt{m}}$$

3.5 Stress Intensity Factor Calculation

The stress intensity factor is a function of loading, crack size, and structural geometry. The stress intensity factor may be represented by the following equation:

$$\boxed{K = \sigma Z Y \sqrt{a}}$$

Where,

$$\sigma = \left(\frac{Load}{(Thickness \text{ x } W)}\right)$$

$$\sigma = \left(\frac{6.4 \text{ x } 10^3}{(12.87 \text{ x } 25.75)}\right)$$

$$\sigma = 19.31\, MPa$$

$$a = 0.0122\, m$$

$$W = 0.02575\, mm$$

$$\left(\frac{a}{W}\right) = 0.473$$

$$if\ \left(\frac{a}{w}\right) < 0.701 \text{ Then } \quad ZY = Y3\left(\frac{a}{w}\right)$$

$$if\ \left(\frac{a}{w}\right) > 0.701 \text{ Then } \quad ZY = Y4\left(\frac{a}{w}\right) \text{ x } Y\left(\frac{a}{w}\right)$$

Here, $\left(\frac{a}{W}\right) < 0.701$ and hence,

$$ZY = Y3\left(\frac{a}{w}\right)$$

Where,

$$Y3\left(\frac{a}{W}\right) = 29.6 - 185.5\left(\frac{a}{W}\right) + 655.7\left(\frac{a}{W}\right)^2 - 1017\left(\frac{a}{W}\right)^3 + 638.9\left(\frac{a}{W}\right)^4$$

Substituting value of $\left(\frac{a}{w}\right)$ in the above equation,

$$Y3\left(\frac{a}{W}\right) = 29.6 - 185.5(0.473) + 655.7(0.473)^2 - 1017(0.473)^3 + 638.9(0.473)^4$$

$$Y3\left(\frac{a}{W}\right) = 29.6 - 87.74 + 146.69 - 107.62 + 31.97$$

$$Y3\left(\frac{a}{W}\right) = 12.90$$

Now stress intensity factor can be calculated as follows

$$K = \sigma Z Y \sqrt{a}$$

$$K = \sigma\, Y3\left(\frac{a}{W}\right)\sqrt{a}$$

$$\text{Since } ZY = Y3\left(\frac{a}{w}\right)$$

$$K = 19.31 \text{ x } 12.90\ \sqrt{0.0122}$$

$$\boxed{\mathbf{K = 27.51\, MPa\sqrt{m}}}$$

The stress intensity factor for the selected welded structural steel is calculated as $27.51\, MPa\sqrt{m}$, and this value is lesser than the fracture toughness (K_{IC}) obtained for the same welded structural steel.

3.6 Validation of Stress Intensity Factor by FEM

The Stress Intensity Factor is also evaluated by using the Finite Element Analysis for Compact Tensile (CT) specimen to know the developed Stress Intensity Factor for the known boundary and loading conditions.

As mentioned a crack length of 12.2mm in a CT specimen is modelled and mode I stress intensity factor (SIF) along the crack front is computed. The material is structural steel welded using E7016 with Elasticity modulus E=325 GPa, σ_Y= 416 MPa, P= 6.4 kN, $\nu =$ 0.3. The dimensions of the CT specimen is shown Fig 2.6. The meshing details, boundary conditions, the loading details and the SIF obtained by FEM are given in the figures listed below

Figure 3.7 shows the meshing of the Compact Tensile (CT) Specimen with 10709 nodes and 2453 elements.

Figure 3.8 depicts the boundary conditions applied for the Compact Tensile (CT) specimen.

Figure 3.9 indicate the loading conditions applied for the Compact Tensile (CT) specimen.

Figure 3.10 shows the SIF obtained for Compact Tensile (CT) specimen.

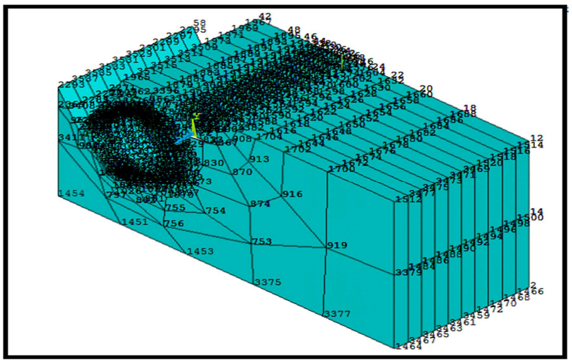


Fig 3.7 Meshing details for the compact tensile (CT) specimen

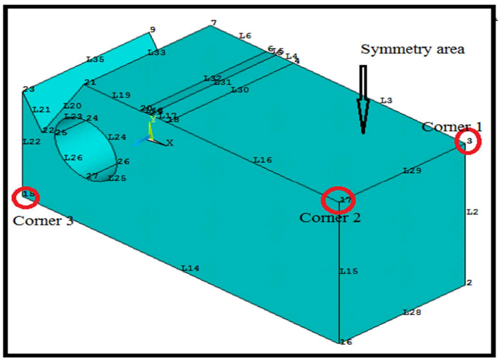


Fig 3.8 Boundary conditions applied to the compact tensile (CT) specimen

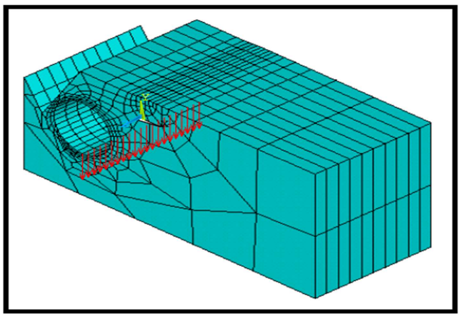
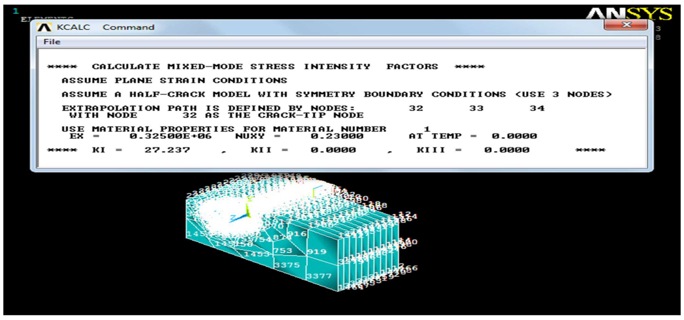


Fig 3.9 Loading condition applied for the compact tensile (CT)specimen



```
****  CALCULATE MIXED-MODE STRESS INTENSITY  FACTORS  ****
  ASSUME PLANE STRAIN CONDITIONS
  ASSUME A HALF-CRACK MODEL WITH SYMMETRY BOUNDARY CONDITIONS <USE 3 NODES>
  EXTRAPOLATION PATH IS DEFINED BY NODES:       32       33       34
   WITH NODE      32 AS THE CRACK-TIP NODE
  USE MATERIAL PROPERTIES FOR MATERIAL NUMBER     1
   EX =     0.32500E+06   NUXY =    0.23000       AT TEMP =  0.0000
****  KI =   27.237    ,   KII =   0.0000    ,   KIII =   0.0000      ****
```

Fig 3.10 Mode-I Stress Intensity Factor using KCALC command

The solution of the problem is as shown in Fig 3.10, the stress intensity factor is obtained as27.373 $MPa\sqrt{m}$. It can be conclude that the stress intensity factor (SIF) using FEM is almost equal to the theoretically calculated value.

3.7 Analysis of the Bucket

The static analysis of the excavator bucket is carried out using Finite Element Analysis to predict the developed stress for the given boundary and loading conditions. The meshing details, boundary conditions, and the stresses at various locations of the bucket are given in the figures listed below

Figure 3.11 shows the meshing of the excavator bucket with 73936 nodes and 39718 elements.

Figure 3.12 depicts the boundary and loading conditions applied for the excavator bucket.

Figure 3.13 shows the Von Misses stresses developed in the bucket and

Figure 3.14 shows the enlarged view of the same. Maximum Von Misses stress acting on the bucket is 213.95 MPa, the part of the bucket are made up of EN19 material.

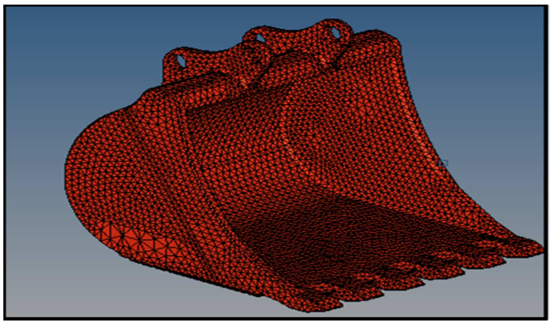


Fig 3.11 Meshing details of Excavator Bucket

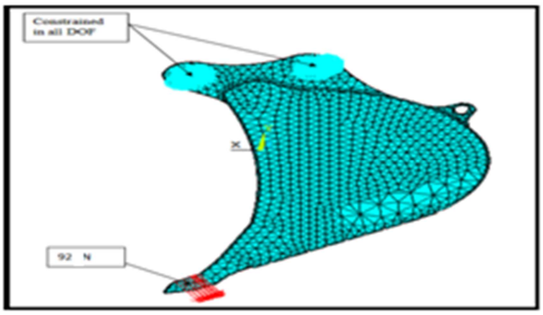


Fig 3.12 Boundary condition for Excavator Bucket

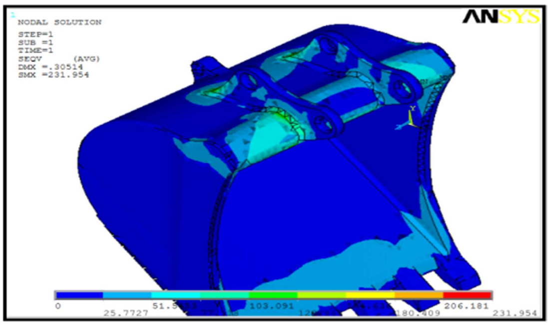


Fig 3.13 Von Misses stress of Excavator Bucket

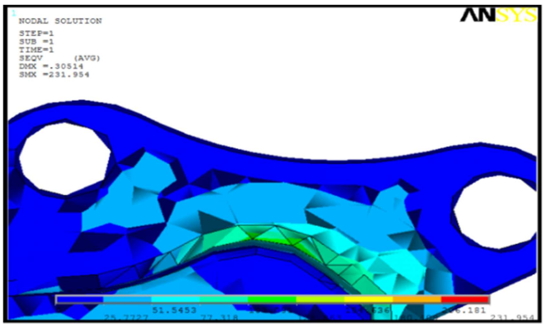


Fig 3.14 Enlarged view of stress in welded portion

The maximum Von Misses stress is acting at the welded portion of bucket as shown in Fig 3.14, which is made up of welded structural steel of EN19 material with the yield strength of 416MPa.

The maximum stress obtained for the excavator bucket model using FEM is 231.954 MPa it is very much less than yield strength of material used for the excavator bucket.

There exists a factor of safety (FOS) in the design and is calculated as follows:

$$Factot\ of\ Safety\ (FOS) = \frac{\sigma_y}{\sigma_d}$$

$$Factot\ of\ Safety\ (FOS) = \frac{416}{231.954}$$

$$Factot\ of\ Safety\ (FOS) = 1.8$$

Based on the results it can be concluded that the maximum stress produced in the welded part is very less compared to the yield stress measured on the welded portion of the excavator bucket.

4. Conclusion

In order to quantify the severity of embrittlement on Welded Structural Steel (WSS) of EN 19 grade which is being used as the main body of the earth moving equipments, an attempt was made in this work to illustrate how exactly the welding consumables are affecting to the embrittlement. After making the comparative study among the three categories of welded joints on specimens made out of WSS of EN19 by welding with different grades of electrodes such as E7016, E7018 and E7024, it becomes possible to bring the following conclusions:

1. The effect of welding consumables on the mechanical properties of structural steel of grade EN19 and joints fabricated by SMAW processes have been analysed in detail.
2. On the basis of the hardness test results, it is found that WSS of EN19 welded using E7016 exhibits less hardness value among all other grades and this shows a sign of reduced embrittlement, which is desirable in the body of complex welded steel structures.

3. From impact (charpy) toughness test carried out on all the types of welded specimens using three grades of electrodes, WSS of EN19 welded using E7016 shows more toughness and thus it is obvious that the weld can sustain more sudden loads (due to digging force) before fracture in comparison with WSS of EN19 welded by E7018 and E7024.
4. The ultimate tensile strength and percentage of elongation results indicates that WSS of EN19 welded by E7016 had lesser ultimate tensile strength and shows more percentage of elongation compared to other welded specimen prepared using other two grades of electrodes. The higher percentage of elongation shows that there exists more ductility and obviously loses its embrittlement. The lesser value of ultimate tensile strength for WSS of EN19 specimen prepared using E7016 proves loss of embrittlement.
5. Based on the above findings, it is concluded that WSS of EN19 welded using E7016 grade electrode possesses better mechanical properties in contrast with WSS of EN19 prepared by E7018 and E7024 electrodes. Hence plain strain fracture toughness test has been conducted on the specimen welded using E7016 electrode to evaluate its crack resisting capability and the value is found to be $28 MPa\sqrt{m}$
6. The Stress intensity factor is evaluated for WSS of EN19 prepared by E7016 grade electrode is $27.51\ MPa\sqrt{m}$ and the value of stress intensity factor found using finite element method is $27.237\ MPa\sqrt{m}$ for compact tensile (CT) specimen and this value is almost matching with the value obtained by analytical solution.
7. The mini hydraulic excavator bucket model is developed for the static stress analysis by FEM with the consideration of welding. The static force obtained by analytical means is used in the finite element analysis. It is concluded from the analysis that the maximum stress 231.954 MPa obtained at the welded region is very much less than the yield strength of the WSS of EN19 obtained from the test conducted on the welded specimen 416 MPa.

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