Prediction of Crack Propagation Rate and Stress Intensity Factor of Fatigue and Welded Specimen with a Two-Dimensional Finite Element Method

Y. O. Busari1,3, A. Ariri1,2, Y. H. P. Manurung*,1, D. Sebayang2, M. Leitner4, W. S. B. W. Zaini1, M. A. B. M. Kamilzukairi1, E. Celik1,5
1Advanced Manufacturing Technology Excellence Center (AMTEx), Faculty of Mechanical Engineering Universiti Teknologi MARA (UiTM), Shah Alam, Malaysia.
2Faculty of Mechanical Engineering, Mercubuana University, Jakarta Indonesia.
3Materials & Metallurgical Engineering Department, University of Ilorin, Ilorin, Nigeria.
4Montanuniversität Leoben, Chair of Mechanical Engineering, 8700 Leoben, Austria.
5Faculty of Mechanical and Bioprocess Engineering, Hochschule Hannover, 30459, Hannover, Germany.

*yupiter.manurung@uitm.edu.my

Abstract. This paper presents the fundamental investigation on crack propagation rate (CPR) and Stress Intensity Factor (SIF) for a typical fatigue and welded specimens which are Compact Tension (CT) and Single Edge Notch Tension (SENT) as well as Butt and longitudinal T-joint. The material data of austenitic stainless steel SS316L was used to observe crack propagation rate with different initial crack length and different tensile load was used for the fracture mechanics investigation. The geometry of the specimens was modelled by using open source software CASCA while Franc 2D was used for post processing based on Paris Erdogan Law with different crack increment steps. The analysis of crack propagation using fracture mechanics technique requires an accurate calculation of the stress intensity factor SIF and comparison of the critical strength of the material (KIC) was used to determine the critical crack length of the specimens. It can be concluded that open source finite element method software can be used for predicting of fatigue life on simplified geometry.

1. Introduction
The weldment of structural steel under load can fracture not only due to imperfection, but the process can be strongly influenced by the presence of certain components such as voids and other defects of different size which possibly evolve into crack are likely to be present in a welded joint, under increasing load the cracks begin to propagate depending on the tip of the crack.

Corrosion resistance stainless steel is used to improve the strength of a components because of its lightweight in design. Components subjected to variety of loads can be found in many applications. Over the time, a small crack will appear due to the tensile stresses that can lead the propagation of crack up to the point where the crack cannot be controlled, this is classified as failure or sudden fracture [1].

The weld material is more brittle than the parent material making it more susceptible to failure from repeated loadings, because welding process induce voids, high tensile residual stress, local stress concentration at the weld geometry, that encourage the initiation and growth of cracks in the welded

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structures. However, predicting the fatigue life of welded structures can be a challenge, despite the amount of research that has been carried out in this field even when the weld stress calculation is obtained and the S-N fatigue curve is plotted in its logarithms.

Access to fatigue life information early in the design phase results in shorter time to market, improve the product reliability, and customer confidence. Recently, many experimental approaches were used to investigate the crack propagation in welded structure but most of these experimental procedures are destructive, expensive and require a lot of time to reach a significant solution. However, researchers developed various analytical and numerical approach to reach results quickly [2-6].

Since the manufacturing cost is increasing day by day, the real systems become impractical. It is involving prototyping and testing cost. Trial and error method to get the best parameters is becoming irrelevant, because it demands extreme cost and has reliability issues. Thus, the investigation on fatigue crack growth and critical crack length by using a two-dimensional finite element method (FEM) such as freeware Franc 2D with CASCA. The issue is now what sample specimen best represent the real crack propagation. The existing fracture mechanic sample specimen of CT and SENB was simulated using CASCA and FRANC2D as finite element analysis (FEA) method compared with the SENT sample specimen. However, the study on crack growth and evaluation of the critical position for the specimen to fracture based on critical stress intensity factor and the remaining life of a certain structural component, rigorous numerical analyses were performed to evaluate SIFs [4]. The fatigue crack will begin on the point of the notch and extend through the sample, the fatigue crack is a good representation of real life inconsistencies which are introduced to a material due to processing techniques or welding [5].

Since no crack propagation takes place at the SIF range near to a lower threshold values $\Delta K_{th}$ [7]. The linear portion of the Paris law provides a good approximation to the extant experimental data, the law relates the crack growth and SIF range and the $K_{max}$ tends to the critical SIF, $K_{IC}$ where the crack propagation becomes more rapid and the crack becomes more unstable. Therefore, the crack propagation software Franc 2D can give a good representation to establish the best specimen for crack propagation.

The purpose of the crack propagation measurements is to understand the crack behaviour of such materials and set load cycles limit at a particular crack depth $a$. The measurements of displacement to cycles points are normally evaluated in the form of a crack growth rate $(da/dN)$ versus Stress Intensity Factor ($\Delta K$) curve. It is not always the case that the crack propagation can be described by the range of stress-intensity factor $\Delta K$. If it cannot be so described, other laws can be applied, e.g. crack growth rate as a function of $K_{max}$.

However, the crack growth behaviour depends on a number of parameters (such as temperature and environment, residual stress and load spectrum). The framework within which the test is to be carried out needs to be precisely defined in order to avoid undesired effects on the results. The crack-growth measurements are generally used for investigating the influence of fatigue-crack growth on the predicted life of a component, or for evaluating the crack-growth resistance of a material or heat-treat condition, defining the requirements of NDT testing and macroscopic quantitative determination of various factors (e.g. load, microstructure, manufacture, etc.).

Few different methods to get the stress intensity factor calculation that has been implemented in FRANC2D that can produce accurate results [8]. The methods are the displacement correlation technique [9][10] and the modified crack closure integral [11] and the equivalent domain version of the elastic J-integral [12]. FRANC2D is finite element based two-dimensional crack propagation simulator and is specifically employed for predicting the crack propagation assuming material having isotropic nature are following the manual guide from Cornell University [13]. Application of FRANC2D proved useful and time saving for predicting the edge crack propagation behaviour of stainless steel 316L. The availability and applicability of such innovative simulation tools encourage research and development of applied fracture mechanics to address crack growth problems in a variety of engineering alloys [14]. Single Edge Notch Tension (SENT) specimen has been tested by [15].

A.M. Al-Mukhtar et al in 2009 investigated the calculation of stress intensity factor (SIF) of cruciform and butt joint from some geometrical parameters since he agreed, that stress concentrations occur at the weld toe and at the weld root, which make these regions the points from which fatigue cracks may initiate. To calculate the fatigue life of welded structures and to analyse the progress of these
cracks using fracture mechanics technique requires an accurate calculation of the stress intensity factor SIF.

[16] said that the requirements of endurable light-weight structures are challenging tasks for engineers. His research was on comparison of crack gauge and optical measurement for a specimen made of S355 and S960 at constant amplitude loading using SENT sample specimen. [17] modelled the fatigue process in welded joints for example butt welded joint. A fracture mechanics model has been proposed to describe the entire fatigue process. The model is calibrated to fit the crack growth measurements carried out on fillet welded joints. The objective is to establish a unified approach, which is consistent with rules and regulation both based on the S-N approach and applied fracture mechanics. High-cycle fatigue tests were conducted to investigate the effects of temperature, stress ratio (R), specimen orientation, welding and specimen size on the fatigue behaviour of type SS316L stainless steel. The high-cycle fatigue test results indicated that the fatigue limits significantly decreased, when the stress ratio (R) decreased [18].

The stress intensity factors during the crack propagation phase were calculated by using the software FRANC2D, which is shown to be highly accurate, with the direction of crack propagation being predicted by using the maximum normal stress criterion. The SIF results from FRANC2D were compared with those from the International Institute of Welding-IIW, and literature. A good correlation was obtained and the work results have bench marked, which made it possible to use FRANC2D to simulate different weld geometries.

Al-Mukhtar et al used Franc 2D FE Based to show that no difference between the quarter and complete model. The different in mesh size has no or negligible effect on the SIF calculations by Franc 2D [19]. This study aims at applying different 2D FEM fatigue sample model to evaluate the practicability of these concept in order to assess the critical displacement crack growth in each case for butt weld and longitudinal T-joint in a stainless steel 316.

2. FEM modelling & simulation for fatigue crack propagation

Stress intensity factor of a material is used to predict the stress state near the tip of a crack caused by a loads or residual stresses. It describes the stress on crack tip and it is related with the crack growth. Stress intensity factor can also locate the critical displacement of crack distance on specimen. It is the most fundamental and useful parameters in all of fracture mechanics. Hence, lot of information was gathered from the previous researchers to justify the value of critical displacement crack growth using CASCA and Franc2D.

The parameters involved are thickness of the work piece, the loads, the initial crack condition, yield strength, and critical stress intensity factor.

2.1 Geometry Modelling

The geometry was two-dimensionally design and modelled using CASCA then imported into FRANC2D software. The model of specimens for Compact Tension (CT), Single Edge Notch Tension (SENT), Longitudinal T-joint and Butt-Welded Joint were designed with dimension based on the standard of ASTM and ISO [2,3]. The thickness is 10mm. Figure 1 to 4 show the dimension used for Compact Tension (CT), Single Edge Notch Tension (SENT) and Butt Welded Joint. For the Butt-welded Joint specimen, the weld bead is 10mm while the weld height is 2mm. In this simulation, X-groove weld bead was used. Stress Intensity Factor is being considered.

The longitudinal T-joint weld had a web plate dimension of length, breadth and thickness of (147x55x10) mm and the base plate of (20.5x54x10) mm respectively. The reason is the variety of parameter selection can be determined according to several standards. In this stage CASCA was used as pre-processor software to create specimen geometrical layout according to its dimension and a mesh pattern was generated as shown below.
Figure 1. Dimension of Compact Tension (CT) Specimen ASTM E647-00[2] and developed CASCA model.

Figure 2. a) Dimension of Single Edge Notch Tension (SENT) Specimen (b) Dimension of SENT Notching.

Figure 3. a) Dimension of Butt Welded Joint and CASCA Model

Figure 4. Welded T-joint specimen geometry and Longitudinal T-Joint mesh geometry
2.2 Material Modelling
The materials that represent the specimens are stainless steel SS316L. The properties are listed in the table 1 below:

| Property       | Value       |
|----------------|-------------|
| Young’s Modulus (GPa) | 205         |
| Poisson Ratio    | 0.275       |
| K<sub>IC</sub> (MPa√m) | 112         |
| Density (g/m<sup>3</sup>) | 8.07        |

2.3 Simulation Procedure for Fatigue Crack Growth
The material properties of stainless steel S316L, specimen fixity point, load, pre-crack and crack increment was embedded in the FRANC2D software to start the propagation of crack.
Pre-crack or initial crack value was inserted in FRANC2D before the propagation of crack. The crack will start propagate at the tip of pre-crack as a starting point. As shown in the figure 6 below:

![Schematic Flowchart of the Simulation](image)

**Figure 5. Schematic Flowchart of the Simulation**
2.3.1 Crack Propagation
After the value of pre-crack was defined such as 0.1mm, 0.2mm and 0.5mm in FRANC2D and the load with 3MPa, 5MPa and 10MPa started to propagate the crack according to the number of steps. If the number of crack propagation step exceeds the specimen boundary, the crack will stop to propagate automatically [8]. The result in terms of stress intensity factor and crack length was calculated in the
software. The same processes sequence was conducted for all sample specimens as shown in figure 7 and 8 below.

![Figure 7](image1.png)

**Figure 7.** Propagation of crack in SENT and CT specimen to determine the critical crack length.

![Figure 8](image2.png)

**Figure 8.** Propagation of crack in Butt weld joint and longitudinal T-joint to determine the critical crack length.

### 3. Results and Discussion

The simulation in FRANC2D created an initial crack, crack propagation with a certain load. The SIF results is then used to determine the critical displacement of crack growth. The simulations for Compact Tension (CT), Single Edge Notch Tension (SENT), Butt Welded Joint and longitudinal T-joint weld joint specimens was conducted on CASCA and FRANC2D and the effect of loads, initial crack and crack growth on the critical displacement crack length. Tensile loads of 3MPa, 5MPa and 10MPa with an initial crack of 0.1mm, 0.2mm and 0.5mm along with crack propagation of 0.5mm, 0.6mm and 0.7mm with 10mm thickness was used. Blue, red and green indicator indicates the 3MPa, 5MPa and 10MPa respectively.
3.1. Comparison of SENT specimen with CT specimen

The simulation for Single Edge Notch Tension (SENT) specimen was conducted on FRANC2D and the effect of loads, initial crack and crack growth on the critical displacement crack length was observed. Loads of 3MPa, 5MPa and 10MPa with an initial crack of 0.1mm, 0.2mm and 0.5mm along with crack propagation of 0.5mm, 0.6mm and 0.7mm with 10mm thickness compared to the same conditions of the compact tension CT specimen. The result of SENT specimen show more conservative critical crack length compared to that of the CT specimen because with 0.1mm initial crack, 0.5mm pre-crack and 3MPa load for the same SS316L steel model in Franc2D, the SENT specimen has 14.7mm critical crack length while CT specimen is 17.9mm. Other critical crack length were examined as shown in the figure 9 and 10 below.

![Crack Propagation](image1)

**Figure 9.** a) 0.1 mm initial crack (b) 0.2 mm initial crack (c) 0.5 mm initial crack for CT Specimen
Figure 10. a) 0.1 mm initial crack (b) 0.2 mm initial crack (c) 0.5 mm initial crack for SENT Specimen

However, the critical crack length was obtained from the extrapolated value between the upper and lower limit value of the SIF range (K_I) derived from the simulation, given that the yield strength (K_{IC}) of the material is 112 MPa√m in the case of S316L and its equivalent crack length was obtained and tabularised in table 2 below:

The value of the SENT specimen is more conservative because of the level reliability in fatigue and fracture analysis of component because of the return of investment or life that may be involved.

Table 2. Value of Critical Displacement Crack Growth of Compact Tension and SENT

| Pre-Crack (mm) | Crack Propagation (mm) | Load (MPa) | Critical Length (mm) (CT specimen) | Critical Length (mm) (SENT specimen) |
|---------------|------------------------|------------|------------------------------------|--------------------------------------|
| 0.1           | 0.5                    | 3          | 17.9                               | 14.7                                 |
|               |                        | 5          | 7.8                                | 10.4                                 |
|               |                        | 10         | 3.9                                | 3.0                                  |
| 0.6           | 0.5                    | 3          | 17.8                               | 15.2                                 |
|               |                        | 5          | 7.7                                | 10.1                                 |
|               |                        | 10         | 4.0                                | 3.0                                  |
3.2. SENT specimen with Butt weld and longitudinal T-joint weld specimen

The approach of linear elastic fracture mechanics as a fatigue assessment tool such as Franc2D, gives more in-depth method resulting in the evaluation of both the crack growth direction and the crack propagation. The advantages of this method can be combined with the implementation of the initial crack which represents the weld toe in this case to evaluated the critical crack length of weld such as butt and longitudinal T-Joint welds.

Since cracks occur because of the stress concentration in the weld toe region, the initial crack and plays an important role in the fatigue life of these joints [4, 9]. Therefore, the weld model has an initial crack size at the weld toe and the effects of varying size of pre-crack was used to determine critical crack length with different loads and varying crack increment as shown in figure below 11 for butt weld joint and figure 12 for Longitudinal T-joint weld below.
Figure 11. a) 0.1 mm initial crack (b) 0.2 mm initial crack (c) 0.5 mm initial crack for Butt weld Specimen

Figure 12. a) 0.1 mm initial crack (b) 0.2 mm initial crack (c) 0.5 mm initial crack for Longitudinal T-joint weld Specimen
Moreover, the weld metal is more brittle than the base metal therefore the critical crack length obtained in the butt and T-joint welds with varying parameters and conditions shows a more reduced length as shown in the table 3 below

**Table 3.** Value of Critical Displacement Crack Growth of Butt Welded Joint and Longitudinal T-Joint weld specimen

| Pre-Crack (mm) | Crack Propagation (mm) | Load (MPa) | Critical Length(mm) (Butt Weld Joint) | Critical Length(mm) (Longitudinal T-Joint Weld) |
|----------------|------------------------|------------|----------------------------------------|-----------------------------------------------|
| 0.1            | 0.5                    | 3          | 7.696                                  | 7.56                                          |
|                |                        | 5          | 6.797                                  | 6.71                                          |
|                |                        | 10         | 4.679                                  | 5.20                                          |
|                | 0.6                    | 3          | 7.671                                  | 7.53                                          |
|                |                        | 5          | 6.781                                  | 6.71                                          |
|                |                        | 10         | 4.709                                  | 5.20                                          |
|                | 0.7                    | 3          | 7.678                                  | 7.54                                          |
|                |                        | 5          | 6.838                                  | 6.68                                          |
|                |                        | 10         | 4.677                                  | 5.21                                          |
| 0.2            | 0.5                    | 3          | 7.650                                  | 7.66                                          |
|                |                        | 5          | 6.815                                  | 6.80                                          |
|                |                        | 10         | 4.681                                  | 5.32                                          |
|                | 0.6                    | 3          | 7.640                                  | 7.64                                          |
|                |                        | 5          | 6.776                                  | 6.82                                          |
|                |                        | 10         | 4.686                                  | 5.31                                          |
|                | 0.7                    | 3          | 7.632                                  | 7.66                                          |
|                |                        | 5          | 6.745                                  | 6.79                                          |
|                |                        | 10         | 4.696                                  | 5.31                                          |
| 0.5            | 0.5                    | 3          | 7.591                                  | 8.00                                          |
|                |                        | 5          | 6.750                                  | 7.10                                          |
|                |                        | 10         | 4.711                                  | 5.62                                          |
|                | 0.6                    | 3          | 7.612                                  | 7.98                                          |
|                |                        | 5          | 6.760                                  | 7.13                                          |
|                |                        | 10         | 4.674                                  | 5.61                                          |
|                | 0.7                    | 3          | 7.595                                  | 8.01                                          |
|                |                        | 5          | 6.703                                  | 7.01                                          |
|                |                        | 10         | 4.693                                  | 5.56                                          |

4. **Conclusion**

Accurate predictions of critical crack length and fatigue life require accurate SIF estimates because of the nature of the Paris crack growth law. However, the Single Edge Notched tension (SENT) specimen model shows a more cautiously moderate representation of fracture mechanic crack growth with respect to loading thus it is more reliable compare to the Compact Tension (CT) specimen in S316L steel.

Since Fatigue limit increased with decreasing the grain size and the lower crack growth rate also yielded an increase critical crack length for all the specimen samples this further confirms Finite element analysis solution for calculation of SIF for the initial crack steps by A. Al-Mukhtar et al., [9] which
agrees with Frank and Fisher, BS.7910 and IIW recommendations. However, it can be concluded that open source finite element method software can be used for predicting of fatigue life on simplified geometry.

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