Fracture toughness of railway for higher speed rail corridors in Malaysia

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Abstract. When Keretapi Tanah Melayu Berhad (KTMB) introduced the High Speed Electrical Train System (ETS) in 2013, the fracture toughness of the railway rail remains relatively unknown. The aim of this study was to evaluate the fracture toughness of rail steel. The rail steel specimen was prepared according to ASTM E1820 and cut using electrical discharge machining (EDM) wire cut process. The specimen was pre-cracked using Biss Fatigue Machine to obtain a relatively accurate results followed by three point bend testing under Universal Testing Machine (UTM), in accordance to the standard of ASTM E1820. The fractured crack tip was then observed using an optical microscope. From the three point bend test, the fracture toughness was calculated and the behaviour of the steel failing was then studied and compared to previous studies. The fracture toughness of the steel was found to be 44.009 MPa√m, which is within the range of the various rail steels used around the world.

1. Introduction
In this study, the fracture toughness of the railway used by the ETS service is to be determined. Specifically, the subject of interest is the railway steel grade 900A International Union of Railways (UIC 54), which is used in the ETS railway. Fracture toughness is a material constant that is independent of the size and geometry of the cracked body. Fracture poses a danger in railways as fracture of the railway rail will lead to derailment. In general, fatigue and fracture are caused by loadings. In railway applications, rails are subjected to primary and secondary loading components. From the loading applied to the rail by the wheel, the rail is subjected to bending stress, axial stresses and Hertzian pressure during rolling contact. The failure of the rail steel has caused various incidents that was followed by detrimental outcomes, namely serious injuries and deaths aside from impact towards the economy and the various. Although, derailments due to rail failure are rare in Malaysia, low maintenance of the rail will eventually results in derailments. Hence, the purpose of this study is to evaluate the fracture toughness of UIC 54 rail profile according to ASTM E1820 standard as well as to study the crack surface of the fractured specimen of UIC 54 profile obtained from KTMB. The fracture toughness of UIC 54 rail steel will be compared with the other rail steels used in other countries.

2. Methodology

2.1 Material and Specimen Preparation
In this study, the material of interest is the rail steel used in Malaysia railways, which is of grade 900A, meeting the requirements of Codex UIC 54 standard. The weight of the 900A UIC 54 is noted to be 54 kg/m. The chemical composition of the rail profile is provided in Table 1.
The Single Edge Notched Bend (SENB) specimen was used in the evaluation of the fracture toughness of the UIC 54 rail profile. The specimens were prepared in accordance to the ASTM E1820 standard [2]. From the UIC 54 rail profile, the web region of the rail was used to fabricate the SENB specimens. From the rail profile obtained the desirable thickness of the specimen was 13 mm as the thickness of the web of the rail profile was 16 mm. Hence, the specimen thickness cannot exceed the thickness of the rail profile. The 13 mm was used as the base parameter in preparing the specimen. In accordance to ASTM E1820, the height of the specimen was 26 mm with a width of 117 mm. A notch was designed onto the specimen and below the minimum crack length so that the specimen can be pre-cracked to obtain a pre-cracked notch, which will enable the acquisition of more accurate results. Figure 1 shows a technical drawing of said specimen.

| Quality          | Chemical Composition | Tensile Strength (MPa) | Elongation after Fracture |
|------------------|----------------------|------------------------|---------------------------|
| Grade 900 A (UIC 54) | C: 0.6, Si: 0.1, Mn: 0.8, P (max): 0.04, S (max): 0.04, Cr: -, Ni: - | 880 – 1030             | ≥ 10                      |

Figure 1: Full dimension of the SENB Specimen.

2.2 Mechanical Testing
A pre-cracking procedure was carried out using the fatigue testing machine (BISS) using a three point bend jig as shown in Figure 2. The pre-cracking was done using a determined cyclic load. The pre-cracking length of the SENB specimen was carried out in accordance to the ASTM E1820 [20]. For the load used during pre-cracking, the maximum calculated load was 5.6 kN. Therefore, the load used should not be more than 5.6 kN. The pre-cracking procedure was carried out with a maximum load of 4.5 kN and stress ratio, \( R = 0.1 \), where the minimum load was 0.45 kN. The frequency of load was set to 20 Hz.

The specimen was then tested for fracture toughness using UTM (Shimadzu AG-IS MS) which has a maximum load capacity of 250 kN. A three point bend jig was used to carry out the test as shown in Figure 3. For the load, a load rate of 5 mm/min was used to pre-crack the experiment. After the specimen was successfully cracked, the raw data were recorded and saved in .csv format.

3. Results and Discussion

3.1 Findings from Pre—cracking Process
As required, an additional 2 mm crack length was created through pre-cracking, with increasing the initial crack length from 11 mm to 13 mm. From the pre-cracking process, various findings were obtained. Figure 4 shows a graph of the crack length against the number of cycles. From the graph, it can be observed that significant crack propagation starts at the 1000th number of cycle. The trend of the propagation can be observed as increasing exponentially, where a sharp increase of the crack length can be observed near the end of the process.
Similarly, Figure 5 shows a graph of compliance against the number of cycles. Compliance is required to calculate the correction factor used in calculating the fracture toughness value of the specimen and is given by:

$$C_i = \frac{\Delta u_m}{\Delta P}$$

where $\Delta u_m$ is crack opening displacement at notched edge and $\Delta P$ is the force acting on the specimen.

However, as observed from Figure 5, the values differ as the number of cycle increases. The compliance increases exponentially with the number of cycles. In other words, the crack size increases as the value of the compliance increases significantly, resulting in the unreliable application of the compliance value. Hence, the initial value of the compliance is used in the calculation of the fracture toughness as it retains the original property of the specimen before external forces are applied to it.

Log-log plots of $da/dN$ against $\Delta K$ was also obtained from the process for each specimen, as shown in Figure 6 for specimen 1. From the graph, it can be observed that the pre-crack process happened at stage 1 of the fatigue crack growth behavior. The tangent line shows the beginning of the
stage 2 of a metal’s crack propagation behavior. By using the points on the line, the constant $m$ can be calculated as the log-log gradient of the graphs, and thus later can be used to calculate $C$. Table 2 shows the comparison between the current study and a previous study done by Gurubaran [3].

![Graph showing log-log plots of $da/dN$ against $\Delta K$ for specimen 1.](image)

**Figure 6:** Log-log plots of $da/dN$ against $\Delta K$ for specimen 1.

**Table 2:** Material constant value comparison for UIC 54 profile.

| Specimen | $P_{\text{max}}$ (kN) | $R$ | $C$ | $m$ |
|----------|------------------|----|----|----|
| Gurubaran [3] | | | | |
| 1 | 16 | 0.1 | 2.567E-13 | 3.455 |
| 2 | 13 | 0.3 | 4.482E-13 | 3.270 |
| 3 | 13 | 0.1 | 5.928E-13 | 3.223 |
| Current Study | | | | |
| 1 | 4.5 | 0.1 | 1.2894E-12 | 3.344 |
| 2 | 1.817E-12 | 3.180 |
| 3 | 1.432E-12 | 3.205 |
| 4 | 7.388E-13 | 3.401 |

### 3.2 Fracture Toughness Test of UIC54 Specimen

After the pre-cracking of the specimen was done, the specimen is then tested using the UTM with a three point bend jig. The test was done with a stroke speed of 5 mm/min. From the data obtained from the test as well as the pre-cracking process, the fracture toughness, $K_{IC}$, can be calculated using Eq. (2). Table 3 shows the results of the calculations.

$$K_{IC} = \left[ \frac{P \cdot S}{B \cdot B_{0}} \right] \frac{1}{\sqrt{W}}$$

(2)

where,

$$f\left(\frac{a}{W}\right) = \frac{3}{2} \left(\frac{a}{W}\right)^{3} \left[ 1.99 - \left(\frac{a}{W}\right) \left(1 - \frac{a}{W}\right) \right] \left[ 2.15 - 3.95 \left(\frac{a}{W}\right) + 2.7 \left(\frac{a}{W}\right)^{3} \right] \frac{1}{2 \left(1 + 2 \left(\frac{a}{W}\right) \right) \left(1 - \frac{a}{W}\right)^{2}}$$

(3)

### 3.3 Comparison between Experimental and Simulation Results

Results from other researches are then collected from the literature to compare with the current study. It should be noted that the compared results are of different rail steel materials. Table 5 shows the results of the different rail steels where the fracture toughness study was conducted.
Table 3: Comparison between Rail Steel Studies.

| Steel Grade           | Tensile Strength (MPa) | Fracture Toughness, $K_{IC}$ (MPa√m)          |
|-----------------------|------------------------|-----------------------------------------------|
| R260 [4]              | 951                    | 38.56 (Rail Head to Web)                      |
|                       |                        | 39.40 (Rail Flange)                           |
| R370CrHT [4]          | 1373                   | 40.44 (Rail Head to Web)                      |
|                       |                        | 39.60 (Rail Flange)                           |
| R350 HT [5]           | 1194 (Head)            | 42.2 (Head)                                   |
|                       | 999 (Web)              | 68.1 (Web)                                    |
| R260 (UIC 60) [5]     | 940 (Head)             | 34.1 (Head)                                   |
|                       | 907 (Web)              | 46.6 (Web)                                    |
| R900a (UIC 860) [6]   | 924 (Head)             | 32.49 (Head)                                  |
| R900a (UIC 54)        | 880-1030               | 44.01 (Web)                                   |

4. Conclusion

From this study, the behaviour of the crack size can be observed as increasing exponentially against the number of cycles. The compliance was also found to differ at different stage of the crack propagation as the compliance increases exponentially as well. The constant $m$ was found to be similar to the study done by Gurubaran [3]. From the three point bend test done using UTM, the behaviour of the specimen was observed. The trend of the graph shows a brittle behaviour of the steel, showing minimal elastic behaviour. By using data obtained from the graph, the fracture toughness of the steel was found to be 44.009 MPa√m, which is acceptable as it is within the range of the various rail steels used around the world.

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