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## Fatigue Crack Growth Studies on Rail Steel

S.R. Shamili<sup>1</sup>, P. Gandhi<sup>2</sup>, S. Vishnuvardhan<sup>3</sup>, P. Gajalakshmi<sup>4</sup>

M.Tech.Project Student, Department of Civil Engineering, B.S.AbdurRahman University, Vandalur, Chennai, India<sup>1</sup>

Senior Principal Scientist, CSIR - Structural Engineering Research Centre, Council of Scientific and Industrial  
Research, Taramani, Chennai, India<sup>2</sup>

Scientist, CSIR – Structural Engineering Research Centre, Council of Scientific and Industrial Research, Taramani,  
Chennai, India<sup>3</sup>

Associate Professor, Department of Civil Engineering, B.S.AbdurRahman University, Vandalur, Chennai, India<sup>4</sup>

**ABSTRACT:** Long welded rails are being introduced for railway tracks extensively in India for increasing the speed of the rolling stock and for better travel comfort. Thermit welding and flash butt welding are being used for welding of rails in many countries. A number of firms are using these two techniques for welding of rails in India. Fatigue fracture of rails is a possible occurrence in railway tracks due to the fluctuating stresses caused by the varying traffic conditions including impact forces and also due to the low fracture toughness of the rail steels. Hence, a fatigue crack growth study of rail steel is paramount importance for ensuring the safe usage of the same in the railway tracks. In this background, experimental investigations have been carried out on rail steel to study the fatigue crack initiation and crack growth behaviour of base and weld metals. The fatigue crack growth studies were carried out on compact tension, C(T), specimens. The test specimens were fabricated from the base and weld metals of a typical rail section used in Indian Railways following ASTM E647 standard. The experiments were carried out as per the ASTM E1820 standard. The fatigue crack growth studies were carried out under constant amplitude sinusoidal loading using computer controlled servo - hydraulic fatigue rated universal testing machine. The test frequency was 5 Hz and the load ratio was 0.1. During the experimental studies, crack growth was monitored at regular intervals of fatigue loading cycles using Image Processing Technique. This paper discusses the experimental investigations carried out on rail steel and the results.

**KEYWORDS:** Long welded rails, Thermit welding, Flash butt welding, Base metal, Weld metal, Fatigue, Crack initiation, Crack growth, Fracture toughness, Paris constants

### I. INTRODUCTION

Long welded rails are used extensively in railway tracks in India for increasing the speed of rolling stock and better comfort. Fatigue fracture of rails is a possible occurrence in railway tracks because of the fluctuating stresses due to the varying traffic conditions and low fracture toughness of rail steels. Most rails are made from the plain carbon steel to keep their cost low. Due to the heat affected zone adjacent to the weld, fatigue becomes critical in welded joints. The fatigue cracks forming on the rail surface grow according to load and lubricating conditions and may end up breaking the rail. Therefore, the crack growth rate needs to be estimated precisely according to the conditions of the track and load to develop a mechanism of crack initiation and growth on a rail due to repetitive loading.

Evans et al.[1] studied the effects of mean stress on fatigue crack growth and failure in a rail. The study was on the fatigue crack propagation and critical fatigue crack size associated with sudden fracture in centre-notched plate specimens of rail steel under pulsating loading. The specimens used for the study were cut from a rail. All the tests were carried out under constant load to fracture at a frequency of 8-19 cycles/min. in a 600kN capacity universal hydraulic testing machine. The number of cycles to crack initiation was determined. The transition from the fatigue to final failure mode of fracture was abrupt with brittle fracture occurring totally by cleavage. Feddersen and David Broek [2] developed a rail fracture model to enable the determination of safe inspection intervals, through prediction of fatigue crack propagation in rail steels. The study comprised of the generation and analysis of fatigue crack growth data on 66 rail samples of various ages, producers and weights. The baseline crack growth tests with compact specimens were

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performed under constant amplitude cyclic loading with maximum load of 11.1kN and a stress ratio of zero. The cyclic frequency was 40 Hz through most of the test; however, as the crack growth accelerated in approaching the terminal fracture condition, the frequency was reduced to 4 Hz to obtain a more accurate visual recording of the critical crack length. The final crack size at failure showed a wide quite variation which reflected in the toughness number. Jung Won Seo et al. [3] conducted experiments on fatigue crack growth and fracture behaviour of rail steels. Contact fatigue tests and finite element analysis using small specimens were conducted in order to assess the crack growth behaviour occurring on a rail. The applied contact pressure and slip ratio at contact surface were 1100MPa and -1% respectively. The test velocity was kept at 500RPM. Under the condition of lubrication, cracks occurred on most contact surfaces, the cracks continuously grew due to the contact pressures. Crack growth rate was obtained by the FEA. Crack growth rate accelerated by the effect of hydrostatic pressure. Surface crack growth rate increased as the crack length increased. However, the crack growth rate decreased when the crack length exceeded a certain level. Lennart Josefson and Jonas Ringsberg [4] studied the risk for initiation of fatigue cracks in the rail head and web in the weld zone of a rail. The interaction between the welding residual stress field and the stress field caused by service loads was simulated in a nonlinear finite element analysis where the welding residual stress distribution and magnitude, the service load magnitude and the material parameters are varied. The propagation of fatigue cracks in the rail web was carried out using Paris crack growth law. The presence of welding residual stresses increases the risk for fatigue crack initiation and larger the risk for fatigue failure.

In the present study, fatigue crack growth experiment was carried out on rail steel by applying constant amplitude cyclic loading using a  $\pm 250$  kN capacity fatigue rated Universal Testing Machine (UTM). The test frequency was 5 Hz and the load ratio was 0.1. Details of the experimental study carried out and the fatigue crack growth data obtained during the experiment has been discussed. Based on this study, fatigue crack growth constants  $C$  and  $m$  were obtained.

## II. MATERIAL PROPERTIES

Table I gives the chemical composition of rail steel used in the investigations. The table also gives the specified values as per IRS - T - 12 - 96 [5]. Mechanical properties of the material were determined by carrying out tension tests as per ASTM E8/E8M [6]. Three tension test specimens were tested. The tests were carried out by using a  $\pm 250$  kN capacity UTM. An extensometer of 25 mm gauge length was used to measure the elongation during testing. Table II shows the mechanical properties of the steel, average values based on the three tests, and the specified values as per IRS - T - 12 - 96. The average yield and ultimate tensile strengths of the material were found to be 880MPa and 560MPa respectively. The Young's Modulus of the material was 205GPa.

TABLE I. CHEMICAL COMPOSITION OF THE STEEL

Element	Tested (per cent)	Specified (per cent) IRS-T-12-96
Carbon	0.675	0.6 – 0.8
Silicon	0.272	0.19 – 0.5
Manganese	1.120	0.8 – 1.3
Phosphorous	0.013	0.035 max
Sulphur	0.002	0.035 max
Chromium	0.004	-
Molybdenum	0.010	-
Nickel	0.002	-
Copper	0.004	-
Neobium	0.003	-
Titanium	0.006	-
Vanadium	0.003	-

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TABLE II. MECHANICAL PROPERTIES OF THE STEEL

Properties	Tested	Specified IRS-T-12-96 (min)
Yield strength, $\sigma_y$ (MPa)	880	260
Ultimate tensile strength, $\sigma_u$ (MPa)	560	880
Modulus of Elasticity, $E$ (GPa)	205	-
Elongation (%)	15.3	10

### III. EXPERIMENTAL STUDIES

#### A. Specimen Details

ASTM E647 [7] recommends three types of specimens namely compact specimen C(T), middle tension specimen M(T) and eccentrically loaded single edge notch tension specimen ESE(T). The C(T) specimen is chosen for the present study. The C(T) is a single edge-notch specimen loaded in tension. It advantages over many other specimen types in that it requires the least amount of material to evaluate crack growth behaviour. Figure 1 shows the typical C(T) specimen configuration as per ASTM E647. It is recommended that the C(T) specimen thickness be in the range  $W/20 \leq B \leq W/4$ , where  $W$  is the width of the specimen and  $B$  is the thickness of the specimen.

The C(T) specimen was fabricated from the flange of the rail steel having length 360 mm, thickness 12.7 mm. Totally three specimens were fabricated. 'V' notch of length 32.4 mm at the mid height of the specimen was made by wire cutting.

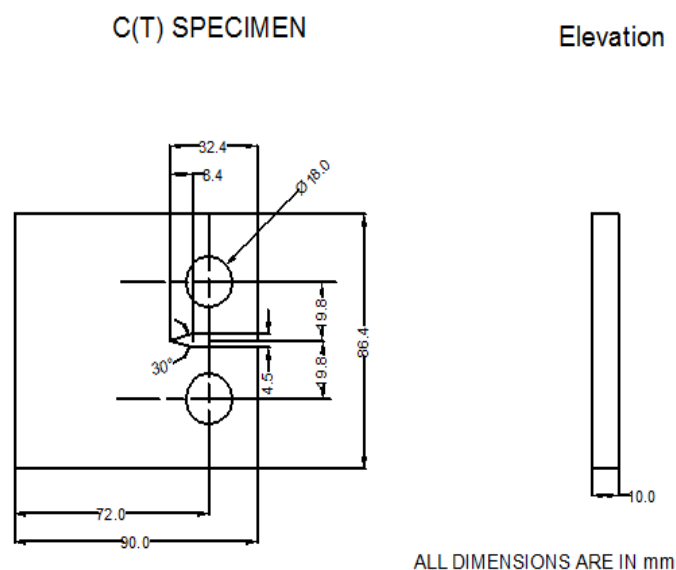


Fig. 1.C (T) specimen dimensions

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## B. Test Details

The Fatigue Crack Growth (FCG) test was carried out on C(T) specimen by using a servo-hydraulic fatigue rated UTM of capacity  $\pm 250$  kN. The load applied during the FCG tests was decided based on the  $P_m$  value, recommended in ASTM E 1820 [8] and it is given as follows:

$$P_m = \frac{0.4B b_0^2 \sigma_y}{2W + a_0} \tag{1}$$

Where

- $B$  = thickness of the specimen, mm
- $W$  = width of the specimen, mm
- $a_0$  = initial notch length, mm
- $b_0$  = uncracked ligament =  $W - a_0$ , mm
- $\sigma_y$  = yield strength of the material, MPa

As per ASTM E647, in order for results to be valid, it is required that the specimen be predominantly elastic at all values of applied force. To satisfy the above condition, the following is required:

$$(W - a) \geq \left( \frac{4}{\Pi} \right) \left( \frac{K_{max}}{\sigma_y} \right)^2 \tag{2}$$

Where

- $W - a$  = uncracked ligament, mm
- $\sigma_{ys}$  = yield strength, MPa
- $K_{max}$  = maximum SIF,  $\text{MPa}\sqrt{\text{m}}$

The tests were conducted at a frequency of 5 Hz and load ratio of 0.1. Maximum and minimum loads for the specimens R1/FCG10-1/FBT, R1/FCG10-3/FBL, R1/FCG10-2/FWT were 12 and 1.2 kN, 18 and 1.8 kN, 15 and 1.5 kN respectively. Table III shows the details of the FCG tests. Figure 2 shows a view of experimental set-up. Number of cycles for crack initiation was recorded. Crack growth was continuously monitored using image processing technique and images were recorded at regular intervals of fatigue cycles. The experiment was continued till crack growth in the specimen became unstable. Figure 3 shows view of the specimens after failure.

TABLE III. Details of FCG Tests

Specimen ID	Load(kN)		Test frequency, $f$ (Hz)
	Max.	Min.	
R1/FCG10-1/FBT	12	1.2	5
R1/FCG10-3/FBL	15	1.5	5
R1/FCG10-2/FWT	18	1.8	5
FBT: Foot Base metal Transverse FBL: Foot Base metal Longitudinal FWT: Foot Weld metal Transverse			

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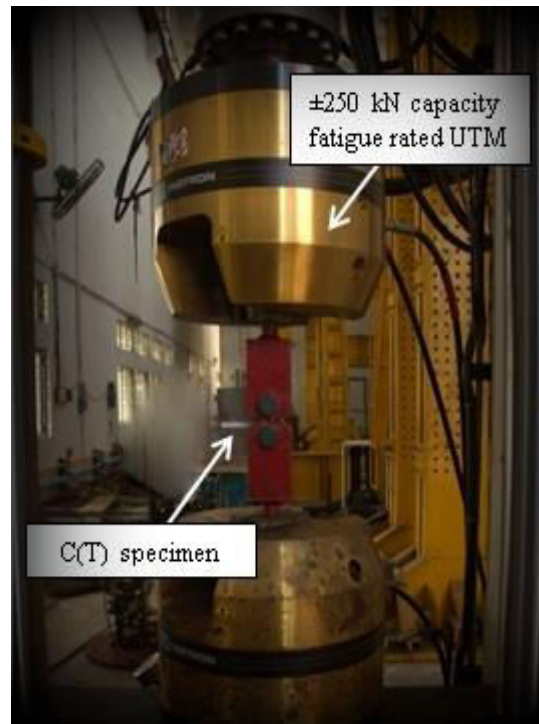


Fig. 2 Experimental set-up

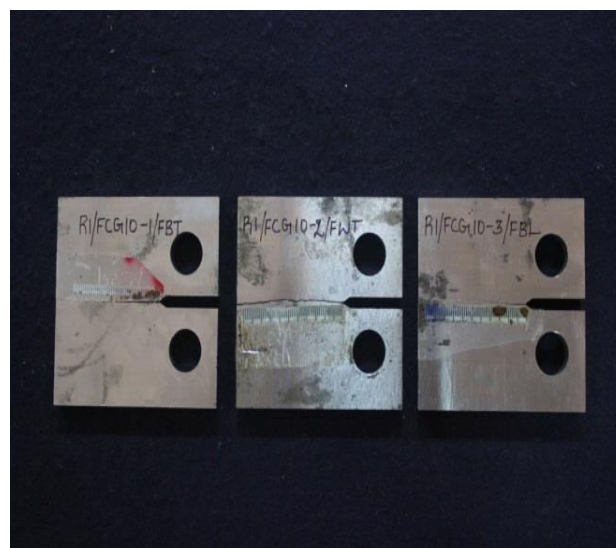


Fig. 3 View of the specimens after failure

## IV. RESULTS AND DISCUSSION

Table IV gives number of cycles to crack initiation, end of experiment, and the corresponding crack length including initial notch length. The tests were terminated when the crack growth in the specimens became unstable and the uncracked ligament was insufficient to take further load. Figure 4 shows number of cycles versus crack length for the three specimens.

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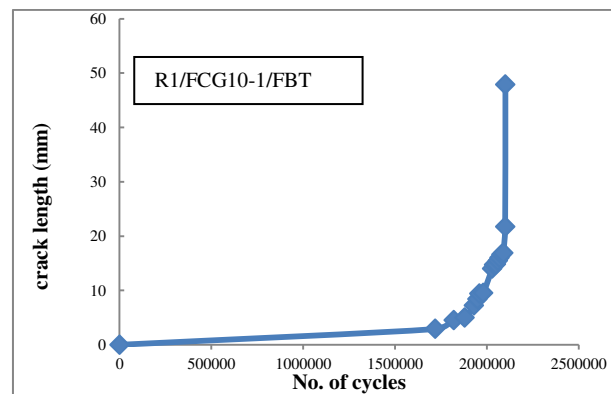
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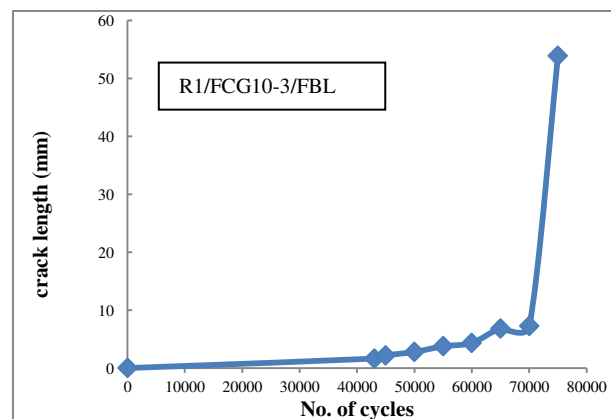
TABLE IV. RESULTS OF FCG TESTS

Specimen ID	Crack initiation		End of experiment	
	Number of cycles	Crack length (mm)	Number of cycles	Crack length (mm)
R1/FCG10-1/FBT	1720000	2.90	2101464	47.89
R1/FCG10-3/FBL	43000	1.64	75000	53.89
R1/FCG10-2/FWT	145000	1.32	216000	53.90

\* Excluding initial notch length of 32.4mm



(a)

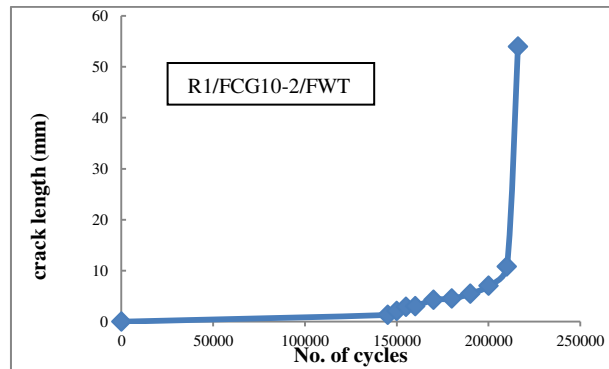


(b)

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(c)

Fig. 4 Number of cycles vs. Crack length curves for the three C (T) specimens

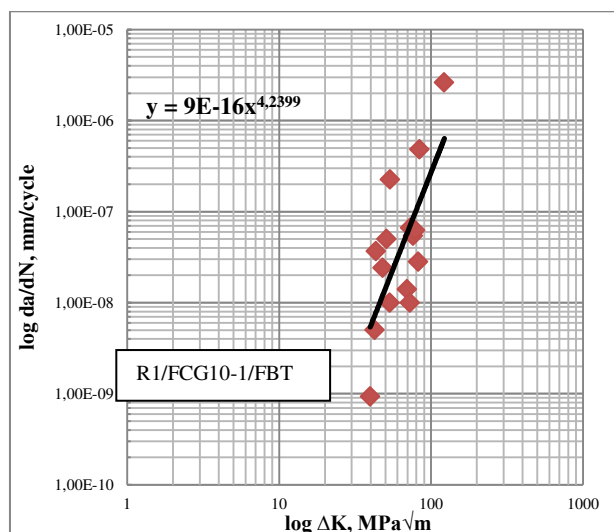
Stress intensity factor range ( $\Delta K$ ) for different crack length values was obtained using the expression given in ASTM E647-13a:

$$\Delta K = \frac{\Delta P(2+\alpha)}{B\sqrt{W(1-\alpha)^{3/2}(0.886+4.64\alpha-13.32\alpha^2+14.72\alpha^3-5.6\alpha^4)}} \quad (3)$$

Where

- $\Delta P$  = force range, N
- $B$  = thickness of the specimen, mm
- $W$  = width of the specimen, mm
- $A$  =  $a/W$  for  $0 < \alpha < 1$

Using the crack growth data, fatigue crack growth rate ( $da/dN$ ) was evaluated for different crack length values. Plot between  $da/dN$  and  $\Delta K$  was obtained for the specimen as shown in Fig.5. The  $da/dN$  vs.  $\Delta K$  curve was fitted using the Paris' law and FCG constants  $C$  and  $m$  were obtained. Table V gives value of the FCG constants. Table VI gives SIF values for various crack lengths.

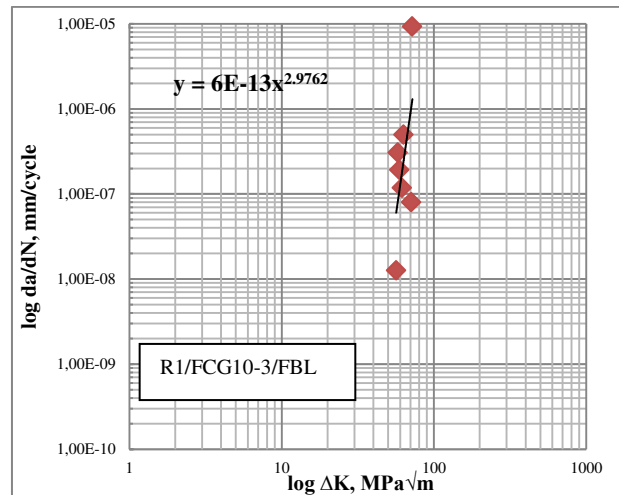


(a)

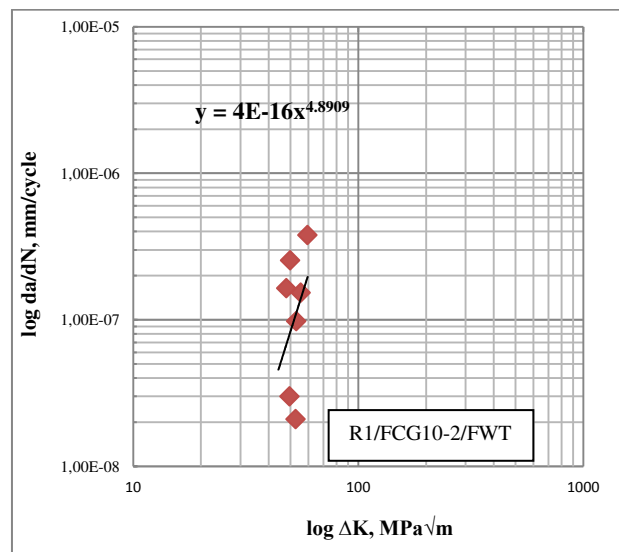
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(b)



(c)

Fig 5  $da/dN$  vs  $\Delta K$  curves for the three C (T) specimens

TABLE V. FCG CONSTANTS

Specimen ID	FCG constants	
	$C$	$m$
R1/FCG10-1/FBT	$9 \times 10^{-16}$	4.2
R1/FCG10-3/FBL	$6 \times 10^{-13}$	2.9
R1/FCG10-2/FWT	$4 \times 10^{-16}$	4.8



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TABLE VI. STRESS INTENSITY FACTOR RANGE VALUES

R1/FCG10-1/FBT		R1/FCG10-3/FBL		R1/FCG10-2/FWT	
Crack length (mm)	$\Delta K$ (from ASTM)	Crack length (mm)	$\Delta K$ (from ASTM)	Crack length (mm)	$\Delta K$ (from ASTM)
32.4	35.33	32.4	53.00	32.4	44.16
35.3	39.71	34.0	56.56	33.7	46.53
36.9	42.51	34.5	57.81	34.4	47.92
37.4	43.46	35.1	59.29	35.2	49.57
40.8	50.95	36.1	61.74	35.4	49.88
41.8	53.59	36.7	63.33	36.6	52.66
41.9	53.86	39.2	70.86	36.9	53.14
39.6	48.07	39.6	72.21	37.8	55.50
41.9	53.86	86.2	-	39.4	59.55
46.4	69.37			43.2	72.11
47.1	72.47			86.3	-
47.2	72.93				
47.8	72.93				
48.4	78.87				
49.0	82.26				
49.3	83.88				
54.1	122.30				

## V. CONCLUSIONS

Fatigue crack growth studies were carried out on rail steel as ASTM standards. The crack growth studies were carried out on C(T) specimens. The C(T) specimens were fabricated from base and weld metal of a typical rail section used in Indian Railway tracks. Based on the fatigue crack growth studies, Paris crack growth constants were obtained.

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