

(An ISO 3297: 2007 Certified Organization) Vol. 4, Special Issue 6, May 2015

Fatigue Life Evaluation of Fillet Welds Subjected to Shear

C. Neeladharan¹, S. Vishnuvardhan², M. Saravanan², R. Regupathi³

P.G. Student, Department of Structural Engineering, Vel Tech High Tech Engineering College, Avadi, Chennai, India¹

Scientist, Fatigue & Fracture Laboratory, CSIR- Structural Engineering Research Center, Taramani, Chennai, India²

Assistant Professor, Department of Civil Engineering, Vel Tech High Tech Engineering College, Avadi, Chennai,

India³

ABSTRACT: This paper presents the analytical results of fatigue life offillet weld transmitting shear conforming to Constructional Detail 39 of IS 800:2007. The Analytical studies were based on the principles of linear elastic fracturemechanics (LFEM). Finite Element Analysis was conducted by initiating cracks at the weld root and toes. These studies were carried out at the various values of maximum stress which were decided as a percentage of yield strength of the material. The maximum value of stress intensity factor was observed for a case with crack at weld toe. The *S-N* data obtained for these connections are compared with the characteristic *S-N* curve recommended in IS 800. It is observed that the fatigue life obtained analytically for fillet welded specimens which were subjected to maximum stress value of 70% of the yield strength of the material (stress range = 193 MPa) and above was lower than the fatigue life specified by IS 800: 2007. Fatigue design provisions for constructional details given in EC 3 – Part 1.9 and IS 800 are also discussed.

KEYWORDS: Fillet weld, fatigue life, LEFM, S-N data, S-N curve

I INTRODUCTION

Fracture due to fatigue and consequent failure is very common in steel structures. Such failures occur predominantly at component connections. Connections refer to those locations in a structure where elements are joined to accommodate changes in geometry and/or fabrication or service requirements. Fatigue cracking in bridges, ships, offshore structures, pressure vessels, and building occurs, almost without exception, at the welded or bolted connections and attachments. Classification method or *S-N* curve approach is the basic method for fatigue strength evaluation of structural connections recommended in most of the current fatigue design specifications. Indian Standard Code of practice IS 800:2007, includes a section on 'fatigue' where *S-N* curves have been given for different non-welded and welded constructional details. The *S-N* curves adopted in IS 800 are similar to those given in Euro code 3: Part 1-9 for different constructional details.

Takeshi Mori et al. studied the effect of crack initiation points at fillet welded joints. Experimental and numerical models of fillet welded joints were investigated. The cracks were located at weld roots and toes, where high stress concentration occurs. The fatigue crack originated from the weld root when the stress range was large and from the weld toe when the stress range was small. A. M. Al-Mukhtar et al. stated that all the cracks were found to be initiated at the weld toe and at the weld root. The stress intensity factors were calculated by using the finite element method based on the principles of fracture mechanics. The stress intensity factor at weld toe is more than the crack at weld root. Nabil Mahmoud et al. studied the effects of variation of crack position and crack increment on stress intensity factor for load carrying fillet welded joints. The maximum value of stress intensity factor was observed at toe crack. The values of stress intensity factor for the weld root and the weld toe cracks increased with the increase in the crack size. C.L TSAI et al. carried out the fatigue crack propagation studies on fillet welded T- joint. The studies were conducted on notched and unnotched specimens. The fatigue crack propagation rate of notched specimen is more than the unnotched specimen.



(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

II MATERIAL PROPERTIES

The steel used in the present studies is regular structural steel used in India, conforming to IS 2062: 2011. Tension tests were carried out on samples of the steel to evaluate mechanical properties.

Mechanical Properties

Mechanical properties of the material were determined by carried out tension tests as per ASTM E 8M. Three specimens were tested. The tests were carried out using a \pm 500 kN capacity Universal Testing Machine. An extensometer of 50 mm gauge length was used to measure the elongation during the test. Table 1 gives the mechanical properties of the steel, average values based on the three tests, and the specified values as per IS 2062. The average yield and ultimate tensile strengths of the material were found to be 306 MPa and 455 MPa respectively. The Young's modulus and % elongation of the material were 200 GPa and 25.6 respectively. The steel used in the present studies satisfies the requirements of Grade E 300 of IS 2062.

Properties	Tested	Specified, Min. (IS 2062 : 2011)
Yield strength (σ_y) , MPa	306	300
Ultimate strength (σ_u), MPa	455	440
Modulus of elasticity (E), GPa	200	-
Elongation, %	25.6	22

TABLE 1 MECHANICAL PROPERTIES OF THE STEEL

III FATIGUE DESIGN PROVISIONS

The fatigue design provisions given in EC 3 and IS 800 for constructional details are discussed. The detail category in EC 3 is designated by a number which represents the fatigue strength of the constructional detail at 2 x 10^6 cycles in N/mm². Figure 1 shows the standard *S-N* curves for each detail category for shear stress range given EC 3. The fatigue strength of the standard detail category for shear fatigue stress is given by Equation 1,

$$\Delta \tau_R^m N_R = \Delta \tau_C^m \ 2 \ge 10^6 \tag{1}$$

With m=5 for N $\leq 10^8$

Where,

 $\Delta \tau_c$ =reference value of the fatigue strength at N_c =2million cycles. $\Delta \tau_R$ = shear stress range in N/mm²

 N_R = design life time expressed as number of cycles.

IS 800:2007 includes a section on 'Fatigue' where *S*-*N* curve has been given for different constructional details. Detail category designation is given to a particular constructional detail which represents the fatigue strength at 5 x 10^6 cycles in N/mm². Figure 2 shows the standard *S*-*N* curves for each detail category for shear stress range given in IS 800.



(An ISO 3297: 2007 Certified Organization) Vol. 4, Special Issue 6, May 2015



Fig. 1 EC 3 Part 1-9 fatigue strength curves forshear stress rangesFig. 2 IS 800: 2007 fatigue strength curves forshear stress rangesThe uncorrected fatigue strength of the standard detail category for the normal fatigue stress is given by Equation 2.

(2)

$$\tau_f = \tau_{fn} \sqrt[5]{5 * 10^6 / N_{sc}}$$

Where,

 τ_f = design shear fatigue stress range of the detail for life cycle of N_{sc} .

 τ_{fn} = shear fatigue strength of the detail for 5 x 10⁶ cycles for the detail category.

In the present studies, fatigue life evaluation of fillet weld transmitting shear conforming to Constructional Detail 39 of IS 800 has been carried out. The explanation for this constructional detail as per IS 800: 2007 is given in Table 2. Table 2 also gives the comparison of detain category as per EC 3 and IS 800 for the constructional detail under consideration. Table 3 gives fatigue strength values determined as per EC 3 and IS 800 for the constructional detail under consideration for 2×10^6 , 5×10^6 and 10×10^6 cycles. It is observed that the predicted fatigue strength at different fatigue cycles using the two codes is almost the same.

	Compton 4 and Data: 1 and 10 800-2007	Detail category			
Detail Number	Constructional Detail as per 18 800:2007	EC3 part 1-9	IS 800:2007		
39	Welds loaded in shear: Stress range should be calculated on welded throat area	80	67		

Constructional Detail as per	Number of cycles to failure	Fatigue strength (MPa) as per			
IS 800:2007	runnber of cycles to fundre	EC: Part 1-9	IS 800 : 2007		
	2×10^{6}	80.00	80.48		
39	5 x 10 ⁶	66.60	67.00		
	$10 \ge 10^6$	57.98	58.33		

IV ANALYTICAL STUDIES

Finite Element Analysis (FEA) is a numerical method which provides solutions to problems that would otherwise be difficult to obtain. In the present studies, analysis was carried out by using FE software ABAQUS 6.12 to predict number of cycles.Every complete FEA consists of 3 separate stages:



(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

- Pre-processing or modelling: This stage involves creating an input file which contains an engineer's design for a finite-element analyzer (also called "solver").
- Processing or finite element analysis: This stage produces an output visual file.
- Post-processing or generating report, image, animation, etc. from the output file: This stage is a visual rendering stage.

Specimen Modelling

Finite element analysis was carried out on fillet welded joints. Figure 3 shows the configuration and dimensions of specimens. Size of the flange plate was $200 \times 300 \times 10$ mm, size of the web plate was $250 \times 300 \times 10$ mm and size of the weld was 10mm leg and 7mm throat. The fatigue crack propagation life was calculated using the modified Paris law:

$$\frac{da}{dN} = C(\Delta K^m - \Delta K_{th}^m)$$

Where da/dN is the fatigue crack propagation rate, ΔK_{th} is the threshold value of the SIF range, and *C* and *m* are material constants. The fatigue crack propagation life required for an initial crack of size a_i to propagate to a final crack of size a_f was determined using Equation 3.

$$N_p = \int_{a_i}^{a_f} \frac{da}{C(\Delta K^m - \Delta K_{th}^m)}$$
(3)

In the analysis, *C*, *m* and ΔK_{th} were taken as 1.5×10^{-11} , 2.75 and 2.9 respectively. The units of da/dN and ΔK were m/cycle and MPa \sqrt{m} , respectively. The stress intensity factor (SIF) range, ΔK was obtained from the finite element analysis for each crack increment of 10 mm for the given stress range. The number of cycles predicted using finite element analysis for different shear stress ranges are compared with the codal values.

Procedures for Finite Element Analysis

The fillet welded specimen was first created as a part using 3D deformable solid element. The 'V' notch has been created at three points in weld element like weld root, ground toe and upper toe along the effective length of the weld. It has a flank angle of 45° . Initial crack length has been taken has 10mm along the effective length of weld. Figure 4 shows the solid model of fillet welded specimen and Figs. 5, 6 & 7 show the crack tips at weld upper toe, ground and root respectively.



Fig. 3 Geometry of specimen

Fig. 4 Solid model of fillet weld specimen



(An ISO 3297: 2007 Certified Organization) Vol. 4, Special Issue 6, May 2015



Fig.5 Crack tip at weld upper toe



Fig.6 Crack tip at weld ground toe



Fig.7 Crack tip at weld root

Assumption

The isotropic parameters were assigned as μ =0.3 and E=200x10³ MPa, where μ defines poisson's ratio and E defines young's modulus. The entire specimen was defined as a solid homogeneous section. The crack was defined at the tip of the 'V' notch. The q-vector option was used to specify the direction of crack propagation with the notch tip point as the starting point and the point lying in the same line on the opposite edge of the specimen as the end point of the crack.



(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

Loading and Boundary conditions

The load was applied as pressure on the web plate along Z direction. The applied pressure intensity interms of stress ranges were decided as the percentage of the yield strength (306 MPa) of the material. The flange plate was fixed by boundary condition. Figure 8 shows the loading and boundary conditions.

Mesh Description

The specimen was first seeded using the seed by edge option. The notch edges were seeded to a size of 0.5 mm and the partitioned portions were seeded to a size of 2 mm. All other edges were seeded to a size of 5 mm. The mesh was generated with hexahedron elements and sweep meshing technique. The element type was given as quadratic for plates and linear for welded portion. Thus C3D20R (Continuum three dimensional 20 noded quadratic brick reduced integration) element and C3D8R (Continuum three dimensional 8 noded quadratic brick reduced integration) were used. Figure 9 shows the mesh modelling on fillet welded joints.



Fig. 8 Loading and boundary conditionsFig. 9 A typical mesh modelling on specimen

V RESULTS

The stress intensity factors were obtained for three modes (opening mode, Shearing mode & Tearing mode). The value of stress intensity factor for second mode was taken because of shear mode. Figure 10 shows typical deformation contours obtained for fillet welded joint for a stress range of 138 MPa. Tables 4, 5 & 6 give the values of stress intensity factor obtained for fillet welded joints at weld root, ground toe and upper toe respectively for different stress ranges. It is observed that the value of stress intensity factor increased with increase in stress range for all cases. The maximum stress intensity factor was observed at weld upper toe compared to the other two cases (weld ground toe and weld root).



(An ISO 3297: 2007 Certified Organization) Vol. 4, Special Issue 6, May 2015



Fig. 10 Typical deformation contours obtained for fillet welded joints

Stress range	Stress intensity factor for different crack lengths(MPa√m)									
(MPa)	10mm	20mm	30mm	40mm	50mm	60mm	70mm	80mm	90mm	100mm
138	106.03	150.51	165.94	182.24	224.06	232.90	249.24	303.90	358.56	435.58
151	116.02	164.69	181.57	199.41	245.17	254.85	272.71	332.53	392.34	476.62
166	170.06	241.40	266.14	292.29	359.36	373.55	399.74	487.41	575.09	698.62
180	230.50	327.20	360.74	396.18	487.08	506.31	541.82	660.65	779.49	946.93
193	296.57	420.99	464.15	509.75	626.71	651.45	697.14	850.04	1002.94	1218.39
207	371.10	526.79	580.79	637.85	784.21	815.15	872.32	1063.65	1254.97	1524.57
220	450.75	639.85	705.44	774.75	952.52	990.10	1059.55	1291.94	1524.33	1851.81
234	539.37	765.64	844.12	927.06	1139.78	1184.73	1267.85	1545.92	1823.99	2215.87
247	632.59	897.98	990.02	1087.29	1336.77	1389.49	1486.98	1813.55	2139.25	2598.88
262	738.11	1047.76	1155.16	1268.66	1559.75	1621.25	1735.02	2115.55	2496.08	3032.40

TABLE 5Stress intensity factors at weld ground toe

Stress range	Stress intensity factor for different crack lengths(MPa\mathcal{m})									
(MPa)	10mm	20mm	30mm	40mm	50mm	60mm	70mm	80mm	90mm	100mm
138	115.94	165.35	178.54	198.32	237.16	252.29	291.36	323.87	379.47	459.82
151	140.78	208.53	228.46	257.61	291.36	308.97	345.66	394.97	472.09	579.69
166	181.23	251.71	284.12	316.61	379.26	388.09	422.02	510.83	600.07	727.23
180	248.43	346.50	379.12	410.64	511.62	536.69	564.32	690.77	810.58	996.48
193	324.05	447.60	494.13	553.12	675.83	704.82	739.06	892.66	1049.14	1271.88
207	396.06	559.24	621.56	684.63	834.94	875.52	925.44	1127.90	1332.06	1615.51
220	480.07	679.30	748.24	834.47	1020.31	1059.72	1148.58	1372.81	1622.83	1964.68
234	588.08	820.43	898.71	997.06	1200.58	1235.56	1321.11	1622.99	1948.41	2452.17
247	679.09	947.87	1043.50	1139.72	1425.38	1476.94	1548.98	1922.34	2263.32	2749.08
262	792.11	1130.07	1224.65	1354.91	1672.06	1779.01	1887.16	2242.76	2645.85	3226.11



(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015

Stress range	Stress intensity factor for different crack lengths(MPa\mu)										
(MPa)	10mm	20mm	30mm	40mm	50mm	60mm	70mm	80mm	90mm	100mm	
138	126.17	183.11	206.47	228.87	266.63	296.59	308.59	361.64	426.69	518.34	
151	153.06	195.98	216.07	237.30	291.75	309.27	324.53	395.71	466.89	567.17	
166	187.36	235.21	293.71	347.83	427.64	444.52	475.69	580.02	684.35	731.35	
180	257.07	359.31	407.27	441.42	569.63	592.51	644.76	786.17	927.59	1026.85	
193	332.92	470.97	512.33	556.60	645.78	775.22	829.59	1011.55	1193.50	1349.89	
207	441.61	626.87	691.13	759.04	933.20	1070.03	1238.07	1465.74	1693.41	1714.12	
220	536.39	761.42	799.47	921.96	1133.50	1178.22	1392.31	1637.40	1964.93	2103.73	
234	641.85	911.11	1004.51	1103.20	1356.34	1409.83	1508.74	1839.65	2170.55	2536.01	
247	752.79	1068.59	1178.12	1293.88	1590.76	1653.49	1769.51	2158.13	2545.71	3092.67	
262	823.45	1146.39	1274.64	1509.71	1856.10	1929.29	2264.67	2517.51	3270.34	3408.26	

TABLE 6Stress intensity factors at weld upper toe

The maximum stress intensity factor occurred at crack tips. The computed SIF range for each stress range for fillet welded joints for different crack lengths is shown in Figs 11, 12 & 13.





Fig. 12 Stress intensity factor range vs. crack length for crack at weld ground toe



(An ISO 3297: 2007 Certified Organization)

Vol. 4, Special Issue 6, May 2015



Fig. 13 Stress intensity factor range vs. crack length for crack at weld upper toe

The fatigue life of fillet welded joints was determined by using the obtained stress intensity factors. The number of cycles was calculated by using Paris law. The SIF range increased with the increase of stress range and hence the fatigue life reduced. Table 7 gives comparison of number of cycles predicted using finite element analysis and codal values.

	Number of Cycles to Failure								
Stress Range (MPa)		Analytical							
	as per IS 800: 2007	Crack at weld root	Crack at weld ground toe	Crack at weld upper toe					
138	134880	421358	332343	248185					
151	85992	328950	184634	181907					
166	53555	114929	97823	89180					
180	35725	49799	42243	36089					
193	25209	24899	20226	18314					
207	17762	13442	11249	8015					
220	13098	7875	6600	4894					
234	9621	4807	3942	2982					
247	7342	3101	2623	1921					
262	5468	2029	1671	1436					

TABLE 7 Fatigue life evaluation of fillet welded joints transmitting shear

As can be observed from Table 7, the fatigue life decreased with increase in stress range. Out of the three locations, presence of crack at the weld upper toe has lesser fatigue life compared to other cases. Figure 14 shows the comparison of analytical results with the *S*-*N* curve given in IS 800: 2007. The fatigue life for stress ranges up to 65% of yield strength of the material satisfies the codal provisions and above failed to satisfy the codal provisions. The results show obtained stress intensity factor increased with the increment of crack length. The fatigue life decreased with increment of crack length.



(An ISO 3297: 2007 Certified Organization) Vol. 4, Special Issue 6, May 2015



VI. CONCLUSION

Fatigue life evaluation of fillet weld transmitting shear conforming to Constructional Detail 39 of IS 800: 2007 was carried out using Euro code and Indian code of practice. The analytical studies were carried out using the principles of LEFM. The maximum stress intensity factor was observed when the crack was located at weld upper toe compared to other locations. Out of three locations of crack, crack at the weld upper toe has lesser fatigue life compared to other two cases. The fatigue life obtained from finite element analysis was compared with the S-N curve given in IS 800: 2007 for fillet weld transmitting shear. It is observed that the fatigue life obtained analytically for fillet welded specimens which were subjected to maximum stress value of 70% of the yield strength of the material (stress range = 193 MPa) and above was lower than the fatigue life specified by IS 800: 2007.

ACKNOWLEDGEMENT

The first author thanks the Director, CSIR-SERC, Chennai for permitting him to carry out his M.E. project work at CSIR-SERC based on which this paper has been prepared. The authors from CSIR-SERC thank the Director and Advisor (Management), CSIR-SERC for the constant support and encouragement extended to them in their R&Dactivities. This paper is published with the kind permission of the Director, CSIR-SERC- Chennai.

REFERENCES

- [1] IS 800:2007, "Code of Practice for General Construction in Steel", Bureau of Indian Standards, New Delhi.
- [2] Euro code 3, "Design of steel structures", Part 1-9: Fatigue, European Committee for Standardisation, 2005.
- [3] IS 2062: 2011, "Hot Rolled Medium and High Tensile Structural Steel Specification', Bureau of Indian Standards, New Delhi.
- [4] Takeshi Mori and ShigenobuKainuma, "A study on fatigue crack initiation point of load-carrying fillet welded cruciform joints", 2007, International Journal of Fatigue, Vol.30, pp. 1669- 1677.
- [5] A. M. Al-Mukhtar, S. Henkel, H. Biermann and P.Hubner, "A Finite Element Calculation of Stress Intensity Factors of Cruciform and ButtWelded Joints for Some Geometrical Parameters", 2009, Jordan Journal of Mechanical and Industrial Engineering, Vol.3, pp. 236-245.
- [6] Nabil Mahmoud, Ahmed Badr, Fikry Salim and AmroElhossainy, "Analysis and Determination of the Stress Intensity Factor of Loadcarrying Cruciform Fillet welded joints", 2014, Journal of American Science, Vol.10, pp. 30- 36.
- [7] C. L. Tsai, D. S. Kim and J. C. Parpritan, "Analysis of fatigue crack propagation Behaviour in Fillet welded T- joints", 1991, Welding Research Supplement, Vol.64, pp.150s-155s.