American Journal of Mechanical and Industrial Engineering
2016; 1(3): 91-95
http://www.sciencepublishinggroup.com/j/ajmie
doi: 10.11648/j.ajmie.20160103.19

Prediction of Fatigue Life of Welded Structures

Assad Anis

Deprtment of Automotive Engineering, NED University of Engineering & Technology, Karachi, Pakistan

Email address:
soi_assad@hotmail.com (A. Anis)

To cite this article:
Assad Anis. Prediction of Fatigue Life of Welded Structures. *American Journal of Mechanical and Industrial Engineering.* Vol. 1, No. 3, 2016, pp. 91-95. doi: 10.11648/j.ajmie.20160103.19

Received: September 17, 2016; **Accepted**: October 13, 2016; **Published**: November 3, 2016

Abstract: This paper describes the fatigue life computation and comparisons of welded structures made up of high strength steels. Fatigue life of a T-joint two side fillet welded component is computed with four different methods. The methods used for investigation are nominal stress method, effective notch method, structural stress method and simple fracture mechanics method. To investigate the problem using structural stress and effective notch method, a fillet welded plate is modeled in ANSYS software and two-dimensional linear elastic analysis is performed. The fatigue lives obtained with these methods are reported and compared with the results obtained from nominal stress and simple fracture mechanics approach.

Keywords: Fatigue Life, Fillet Welded T-joint, Nominal Stress Method, Structural Stress Method, Effective Notch Method, Simple Elastic Fracture Mechanics

1. Introduction

For several years there is a trend towards application of higher strength steels in welded structures both in mechanical engineering and steel constructions. Fatigue is potentially a failure mode in all such components made up of high strengh steels. Fatigue process originates at stress concentration points such as the weld toe in weldements [1]. The assessment of fatigue welded structures may be based on several methods. IIW- recommendations allow for the nominal stress approach, the structural stress of hot spot stress approach, effective notch stress approach, and fracture mechanics based approach. In the early 1990s, Petershagen [2] derived a generalized hot-spot stress approach for plate structures using Radaj's effective notch stress approach [3] and applied it to complex welded structures [4]. Detailed recommendations concerning stress determination for fatigue analysis of welded components were given by Niemi [5], Huther [6] and Fricke [7], among others. A comprehensive guidance by the International Institute of Welding (IIW) is presently under preparation [8, 9], where the relevant stress is termed 'structural hot-spot stress' to avoid confusion created by the different terms used previously (structural stress; hot-spot stress; geometric stress). In the recent years, further variants of the structural stress approach were developed. From these, particularly the approaches by Dong et al. [10, 11] and Xiao and Yamada [12] are remarkable. Subsequently, the approaches will be applied to three typical structural details, where fatigue test results are available so that not only stresses, but also predicted fatigue lives can be compared. Teppei Okawa [19] determined fatigue life of welded structures by taking into account the effects of the residual stress and the load sequences by the crack opening and closure simulation. Mustafa Aygül [20] presented comparison of experimental work and finite element analysis work by applying hot stress methods on orthotropic bridge deck. The research work presented in this paper is unique in a way that it provides comparisons of all methods discussed.

2. Modeling Strategy

A fillet welded plate which is analyzed is shown in figure 1. Due to the symmetry, half of the plate is modeled in ANSYS software and symmetry boundary conditions are defined. The dimensions of the plate are listed in table I.

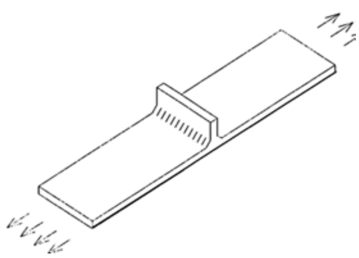

Fig. 1. *Loaded Fillet Welded Plate.*

Table 1. *Plate Dimensions.*

Length, mm	Width, mm	Height, mm	Thickness, mm	Throat Length, mm
500	100	50	10	5

3. Methods

3.1. Nominal Stress Approach

The nominal stress approach is the simplest and the most common applied method for estimating the fatigue life of steel structures [13]. This method is mainly based on the average stress in the studied cross section considering the overall linear elastic beam behavior. The nominal stress method gives satisfactory results with minimum calculation efforts. The fatigue classes based on the nominal stress are available in most design codes and guidelines. It uses the following equation [14] to compute the fatigue life of the material using a IIW recommended FAT class.

$$N(\Delta\sigma)^m = C \tag{1}$$

N = Number of cycles to failure
C = Constant (fatigue capacity)
$\Delta\sigma$ = Nominal Stress
m = slope of the S-N curve

FAT 100 class is recommeded from IIW [15] for the non-load carrying transverse fillet welded structures. Nominal stress of 150 MPa is used for analysis. The slope of the curve as recommended by IIW is 3. Equation (1) is first used to compute the constant C w.r.t recommended FAT class then it gives fatigue life of the material on the basis of nominal stress.

3.2. Hot Spot Method

The basic conept of hot spot or structural stress method belongs to Haibach [16]. The structural hot spot stresses are computed by extrapolating the surface stresses around critical weld toe (fig. 2). Finite element simulations are used to calculate these stresses. The actual method is given by Niemi [5, 8]. Plane strain approach with Plane 42 solid element is used for modeling the component and linear elastic FE simulation is performed. The extrapolation points are located at a distance of 0.4t and 1.0t from the weld toe. The extrapolation to the structural hot spot stress σ_{hs} is performed by the following equation [7].

$$\sigma_{hs} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} \tag{2}$$

The hot spot stress obtained from above equation is used to find the stress concentration factor and ultimately fatigue life of the welded componet is obtained using following equations.

$$\sigma_{hs} = K_S \Delta\sigma \tag{3}$$

$$N = \frac{C_d}{(\Delta\sigma_{hs})^m} \tag{4}$$

$$C_d = \frac{C}{\gamma_M} \tag{5}$$

C_d = Design value for fatigue capacity,

γ_M = Partial safety coefficient = 1 as recommended by SFS-ENV 1993-1-1 [18].

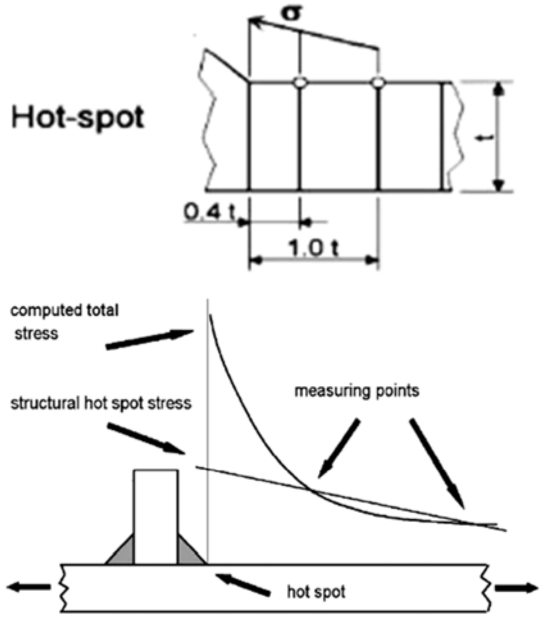

Fig. 2. *Extrapolation of Hot Spot Stress.*

3.3. Notch Stress or Effective Notch Method

The method based on notch stress predicts the amount of service life that will pass for the cracks to nucleate. Finite element analysis is a very helpful tool in determination of fatigue life of the welded joint using this method. To perform the analysis, the welded plate is modeled in ANSYS with Plane 42 solid element. An imperfection (weld reinforcement) is created near the weld toe to obtain the notch stress (fig. 3). Equation (1) is again employed to get fatigue life of the component.

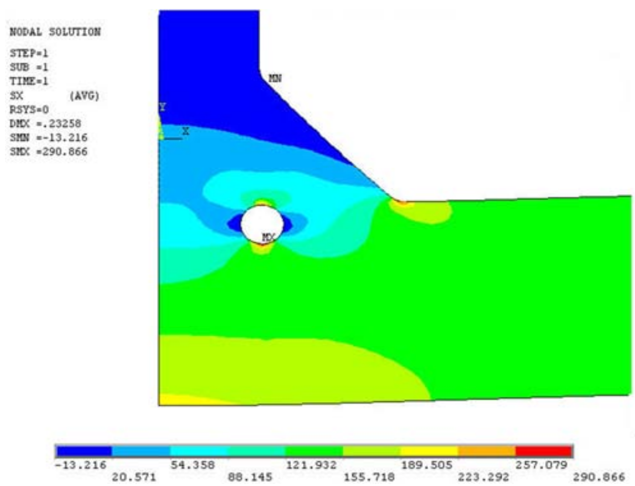

Fig. 3. *Imperfection in Welded Plate.*

3.4. Linear Elastic Fracture Mechanics (LEFM)

Linear elastic fracture mechanics is a very effective method of obtaining fatigue life of welded structures. It involves calculations of a crack growth initially present with some crack length in the component. The stress intensity range is given by [10],

$$\Delta K = \Delta\sigma\sqrt{\pi a}\,Y(a)M_K(a) \tag{6}$$

Where,

ΔK = Stress Intensity Factor (MPa $\sqrt{mm}$)

$Y(a)$ = Geometrical Factor

$M_K(a)$ = It considers the non-linear stress peak and the special geometrical conditions of the different structural details and joint types.

Here, the IIW recommendations give formula to find M_K *(a)*

$$M_K(a) = \frac{1+s_1}{s_2 + s_3\left(\frac{2a}{T}\right)^{s_4}} \tag{7}$$

s_1 = 0.59, s_2 = 0.018, s_3 = 1.6, s_4 = 0.35, *Y (a)* = 1.12, C= 3 x 10^{13}, m =3 for the welded plate shown in fig. 1. The crack growth behavior is well described by the relationship between cyclic crack growth rate *da/dN* and stress intensity range ΔK . A relationship may be represented as by the equation indentified by Paul Paris [17].

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{8}$$

The welded component is assumed to have initial crack length of 0.05 mm. Equation (8) is used to obtain fatigue life of the welded component using LEFM appoach. The table 2 shows the magnitudes of fatigue life based on the parameters used in equations (6), (7) and (8).

Table 2. *Fatigue Life based on LEFM.*

No.	a, mm	$\Delta K, Nmm^{-3/2}$	M_K	d_a/d_N, mm/cycle	N, Cycles
0	0.05	313.6102	4.71	9.2532e-6	5403
1	0.15	376.5763	3.26	1.6021 e-5	11645
2	0.25	409.0497	2.74	2.0533 e-5	16515
3	0.35	431.7086	2.45	2.4138 e-5	20658
4	0.45	449.3414	2.24	2.7218 e-5	24332
5	0.55	463.8835	2.10	2.9947 e-5	27671
6	0.65	476.3022	1.98	3.2417 e-5	30756
7	0.75	487.1580	1.88	3.4684 e-5	33639
8	0.85	496.8488	1.80	3.6795 e-5	36357
9	0.95	505.6140	1.74	3.8777 e-5	38936
10	1.05	513.5877	1.68	4.0641 e-5	41396
11	1.15	520.9790	1.63	4.2421 e-5	43754
12	1.25	527.8106	1.58	4.4112 e-5	46021
13	1.35	534.1933	1.54	4.5732 e-5	48207
14	1.45	540.1786	1.50	4.7286 e-5	50322
15	1.55	545.8161	1.47	4.8782 e-5	52372
16	1.65	551.1758	1.44	5.0233 e-5	54363
17	1.75	556.2483	1.41	5.1633 e-5	56300
18	1.85	561.0660	1.38	5.2986 e-5	58187
19	1.95	565.6765	1.36	5.4300 e-5	60028
20	2.05	570.0659	1.33	5.5500 e-5	61830
21	2.15	574.3297	1.31	5.6800 e-5	63591
22	2.25	578.3779	1.29	5.8043 e-5	65314
23	2.35	582.2811	1.27	5.9226 e-5	67002
24	2.45	586.0582	1.25	6.0387 e-5	68658
25	2.55	589.7202	1.24	6.1526 e-5	70283
26	2.65	593.2225	1.22	6.2628 e-5	71880
27	2.75	596.6578	1.20	6.3723 e-5	73449
28	2.85	599.9694	1.19	6.4790 e-5	74993
29	2.95	603.1419	1.17	6.5823 e-5	76512
30	3.05	606.2590	1.16	6.6849 e-5	78008
31	3.15	609.2999	1.15	6.7860 e-5	79482
32	3.25	612.2393	1.14	6.8846 e-5	80934
33	3.35	615.1558	1.12	6.9835 e-5	82366
34	3.45	617.9646	1.11	7.0796 e-5	83779
35	3.55	620.6851	1.10	7.1735 e-5	85173
36	3.65	623.3361	1.09	7.2658 e-5	86549
37	3.75	625.9356	1.08	7.3571 e-5	87908
38	3.85	628.5007	1.07	7.4479 e-5	89251
39	3.95	630.9885	1.06	7.5367 e-5	90578
40	4.05	633.4126	1.05	7.6239 e-5	91889

4. Results & Discussions

4.1. Fatigue Life using Nominal Stress Method

The fatigue life based on nominal stress method is simple from calculation point of view. A well defined stress is obtained without any macro-geometric effect. The details are free of any significant imperfections. The magnitude of the fatigue life came out from equation (1) is reported in table 3.

Table 3. *FAT Life based on Nominal Stress Method.*

FAT Class	C	$\Delta\sigma$, MPa	m	N, Cycles
100	2×10^{12}	150	3	592592

4.2. Fatigue Life using Hot Spot Method

In order to obtain hot spot stresses, two points P_1 and P_2 were defined near weld toe in ANSYS post-processing section fig. 4). The stresses at these points were extrapolated to get hot spot stress near weld toe. Table 4 shows the fatigue life obtained after computing the stress concentration factor for the welded plate.

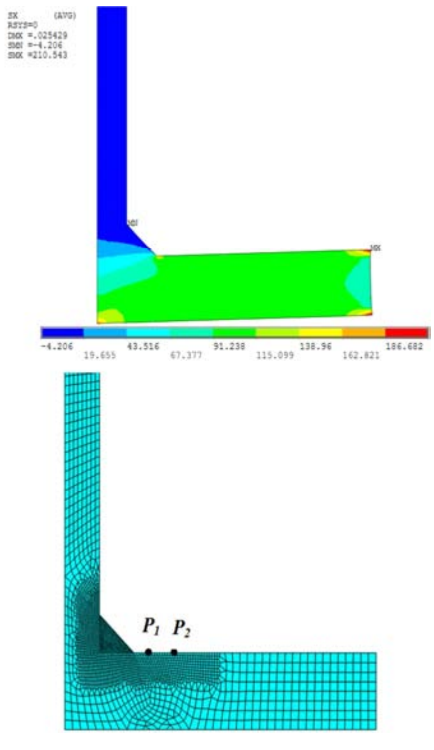

Fig. 4. *Extrapolated Stress Points.*

Table 4. *Fatigue Life based on Hot Spot Method.*

FAT Class	$\Delta\sigma_{P_1}$ MPa	$\Delta\sigma_{P_2}$ MPa	Ks	C = Cd	$\Delta\sigma_{hs}$ MPa	N, Cycles
100	150.41	149.72	3	2×10^{12}	150.8	583211

4.3. Fatigue Life Using Notch Stress Method

The calculations involved in notch stress method are the same as nominal stress method with exception of an imperfection near weld toe. This method is considered as a suitable choice for the long life (high cycle) regime, in which the crack initiation and early growth phases are dominant. The fatigue life obtained with this method is listed in table 5.

Table 5. *Fatigue Life based on Notch Stress Method.*

FAT Class	C	$\Delta\sigma$ MPa	N, Cycles
225	2.27×10^{13}	290.886	922459

4.4. Fatigue Life Using LEFM

Analysis based on fracture mechanics allows the variations in crack length and strength to be estimated so that safety factor can be evaluated. The welded component geomtery is employed in analytical method using equations (6), (7) and (8) so that a wide range of crack growth rates are obtained. Growth rates are then and plotted versus ΔK to obtain *da/dN* versus ΔK curve (fig. 5). This curve is very useful in engineering applications, with ΔK values being calculated as appropriate for the particular geometry of interest. In addition, crack length versus cycles curve (fig. 6) for a specific crack length can be predicted from a plot for the analyzed component from which estimation of life and factor of safety may be evaluated.

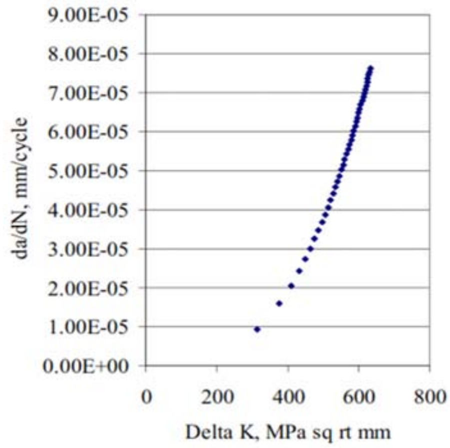

Fig. 5. *da/dN vs. ΔK curve.*

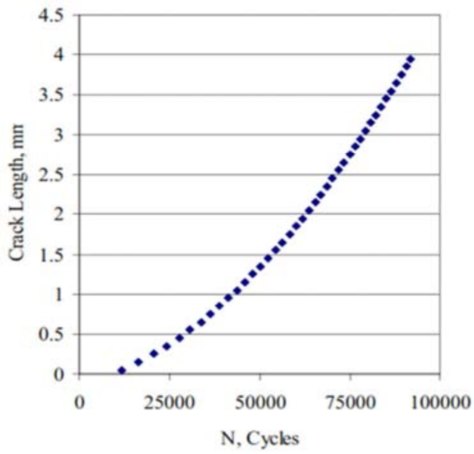

Fig. 6. *Crack length (a) vs Number of Cycles to Failure (N).*

4.5. Comparison of Results

The strategy adopted in obtaining welding stress near weld toe using nominal stress and hot spot or structural stress method is the similar in a way that the welded part does not carry any crack. The fatigue lives of the component computed with these methods are in good agreement. However, fatigue life of the component is enhanced due to the addition of imperfection in effective notch method. The welded component yields a lower fatigue due to the presence of crack already in it.

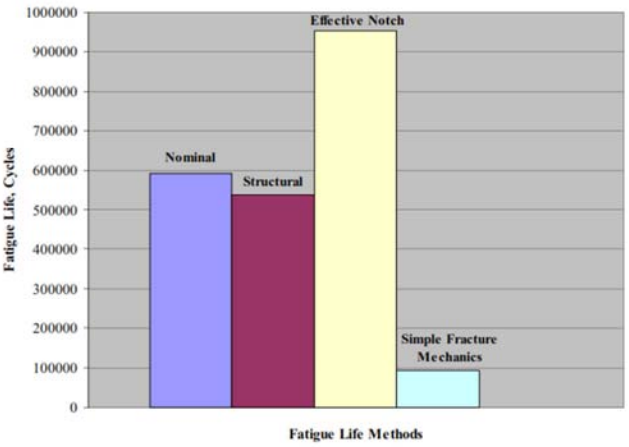

Fig. 7. *Comparison of Fatigue Life obtained with different methods.*

5. Conclusion

The fatigue life of fillet welded non-load carrying welded plate is computed using four IIW recommended methods. Few assumptions were taken due to the unavailability of experimental results. However, an experimental investigation of this plate is required to make an experimental and computational comparison. The results obtained with the methods used in this project is reported and compared.

Acknowledgment

The author would like to acknowledge Prof. Gary B. Marquis, Dean Aalto University of science and Technology for his valuable support and supervision in this research work.

References

[1] R. Schliebner, M. Vormwald, "Fatigue of welded Hybrid Joints" Mat.-wiss u. Werkstofftech, 36, vol. 11, pp. 706-714, 2005.

[2] Petershagen H, Fricke W, Massel T. Application of the local approach to the fatigue strength assessment ofwelded structures in ships. IIW Doc. XIII-1409-91, International Institute of Welding, 1991.

[3] Radaj D. Design and analysis of fatigue-resistant welded structures. Cambridge: Abington Publ; 1990.

[4] Fricke W, Petershagen H. Detail design of welded ship structures based on hot spot stresses. In: Caldwell JB, Ward G, editors. Practical design of ships and mobile units. Amsterdam: Elsevier Science; 1992.

[5] E. Niemi, ''Stress Determination for Fatigue Analysis of Welded Components'', Abington Publishing, Cambridge, 1995.

[6] Huther I, Gorski S, Lieurade HP, Laborde S, Recho N. Longitudinal non loaded welded joints-geometrical stress approach. Welding in the World 1999; 43(3):20–6.

[7] Fricke W. Recommended hot spot analysis procedure for structural details of ships and FPSOs based on round-robin FE analyses. Int J Offshore Polar Eng 2002; 12(1):40–7.

[8] E. Neimi, ''Structural stress approach to fatigue analysis of welded components'', Document XIII-1819-00/XV-1090-01/XIII-WG-3-06-99. Cambridge England, International Institute of Welding, Abington Publishing, 2001.

[9] Hobbacher A., editor. Recommendations for fatigue design of welded joints and components. IIW-Doc. XIII-1965-03/XV-1127-03, International Institute of Welding, Final draft 2005.

[10] Dong P. A structural stress definition and numerical implementation for fatigue analyses. Int J Fatigue 2001;23(10):865–76.

[11] Dong P, Hong JK, Cao Z. Structural stress based master S–N curve for welded joints, IIW Doc XIII-1930-02/XV-1119-02, International Institute of Welding, 2002.

[12] Xiao Z-G, Yamada K. A method of determining geometric stress for fatigue strength evaluation of steel welded joints. Int J Fatigue 2004; 26:1277–93.

[13] Gary B. Marquis, E. Niemi, ''Design of Plate Structures'', @ 2005, Lappeenranta University of Technology- Finland.

[14] A. Hobbacher, Fatigue design of welded joints and components. IIW Doc. XIII-1539-96/XV-845-96 Abington Hall, UK,1996.

[15] A. F. Hobbacher, ''The new IIW recommendations for fatigue assessment of welded joints and components- A comprehensive code recently updated'', International journal of fatigue, 31 (2009) 50-58.

[16] E. Haibach, ''Die Schwingfestigkeit von scheibverbindungen aus der sicht einer ortlichen Beanssprunchungsmessung'', Fraunhofer- Institure fur Betriebsfestigkeit (LFB), Bericht Nr. FB-77/1968, Dramstdat.

[17] Norman E. Dowling, Mechanical Behavior of Materials, Engineering methods for deformation, fracture and fatigue, 3rd Edition.

[18] EuroCode 3, Design of Steel Structures, Finland SFS, SFS-ENV-1993-1-1.

[19] Teppei Okawa, Hiroshi Shimanuki, Tetsuro Nose, Tamaki Suzuki, Fatigue Life Prediction of Welded Structures Based on Crack Growth Analysis, Technical Report, Nippon Steel Technical Report No. 102, January 2013.

[20] Mustafa Aygül, Mohammad Al-Emrani, Shota Urushadze, Modeling and fatigue life assessment of orthotropic bridge deck details using FEM, International Journal of Fatigue, Volume 40, July 2012, Pages 129-142.