DEVELOPMENT OF A COMPUTATIONAL TOOL FOR FATIGUE ASSESSMENT OF STEEL STRUCTURES ACCORDING TO THE MASTER S-N CURVE METHOD

Guilherme Alencar[1,*], J. G. S. da Silva[2], Rui Calçada[3], Abílio de Jesus[3]

[1]*Departamento de Engenharia Civil e Ambiental*
Universidade de Brasília, Distrito Federal, Brasil
[*]*Autor para correspondência: guilherme.alencar@unb.br*
[2]*Departamento de Estruturas e Fundações, Universidade do Estado do Rio de Janeiro, Rio de Janeiro/RJ, Brasil*
[3]*Faculdade de Engenharia da Universidade do Porto, Porto, Portugal*

Abstract. In a recent publication, Alencar et al [1] demonstrated that the Master S-N curve method is equally appropriate to assess the fatigue strength of welded bridge details. The Master S-N curve method is an alternative option included in the context of the American mechanical engineer’s standard (ASME Sec VIII Div2) in the last decade, which allows the use of coarse finite elements to carry out estimates of the remaining fatigue life of welded details, despite its advantage in the use of a unique fatigue strength S-N curve. This paper presents the development of a computational tool for the Master S-N curve method. The tool was built into ANSYS Mechanical and allow to carry out fatigue life estimations of welded structures and mechanical components under constant amplitude loading.

Keywords: Fatigue of Steel Structures; Engineering software development; Master S-N curve method.

1 Introduction

Fatigue is an important degradation phenomenon in welded connections common in steel construction, when subjected to dynamic loading, affecting the service life, thus being a topic of intensive research [1].In this context, the Master S-N curve method is an alternative procedure to assess the fatigue strength of welded connections [2], which enables the use of computationally efficient coarse FE models with either hexahedron or tetrahedron solid elements and triangular or rectangular shell elements without overlooking accuracy in fatigue life estimates. Furthermore, the method also offers the possibility to use a unique fatigue strength definition, the so-called Master S-N curve. By developing the method, some researchers have proven the capability of the Master S-N curve to collapse into a narrow band several weld fatigue failures based on different loading modes, dimensions and thicknesses of offshore and marine [3], piping and pressure vessels [4] and bridge structures [5]. In the last decades, the method has been included as an alternative procedure to the standard methods in the following codes: ASME B&PV Code, Section VIII, Div2 [6] and API 579-1/ASME FFS-1 2016 Fitness-For-Service [7]. However, the use and spread of the method is limited because of the necessity of a largely available post-processor, since to manually compute the required fatigue stress parameters from the finite element solution may be highly cumbersome.This paper briefly presents the development of a computational tool which intends to be a post-processor for the Master S-N curve method. More details of the developed tool can be found in Alencar *et al.*[8].

2 The Master S-N curve method

Seeking for a consistent fatigue stress parameter, Dong *et al.*[2] proposed to compute structural stresses from nodal forces and nodal moments at a local reference level based on elementary mechanics, since in the displacement-based finite element method element forces are a primary solution and always can guarantee the local equilibrium. Structural stresses obtained in this form are often called equilibrium-equivalent structural stresses. The basic idea is to recover nodal forces and nodal moments acting in the crack plane of the weld line in a local coordinate system and convert them to forces per unit of length, *f*, and moments per unit of length, *m*. Thus, based on the imposition of equilibrium conditions for the elements in front of the weld, structural stresses can be recovered in the following form:

$$\Delta\sigma_m = \frac{f}{t} \tag{1}$$

$$\Delta\sigma_b = \frac{6}{t^2} m \tag{2}$$

$$\Delta\sigma_s = \Delta\sigma_m + \Delta\sigma_b \tag{3}$$

One interesting feature of the structural stress definition presented above is that it should minimize the mesh-size sensitivity in the structural stress calculations. Indeed, several authors have verified this feature to some extent [9–14]. Alencar [15] demonstrated with the above procedure, the computed stresses may deviate ±3% depending on the FE mesh size, which can contribute to obtain less scattered fatigue life estimations. Once the mesh-size, mesh-shape, and mesh type insensitivities are ensured, the structural stress could serve as an intrinsic stress parameter to derive a fatigue strength definition. Indeed, based on a two-stage crack growth model, an equivalent stress parameter (ΔS_S) taking into account of both plate thickness and bending ratio effect was proposed by Dong *et al.*[2] under Mode I dominated loading condition as:

$$\Delta S_S = \frac{\Delta\sigma_s}{t^{*\frac{2-m}{2m}} I(r_b)^{\frac{1}{m}}} \tag{4}$$

$$r_b = \frac{|\Delta\sigma_b|}{|\Delta\sigma_m| + |\Delta\sigma_b|} \tag{5}$$

where $\Delta\sigma_s$ is computed according to Section 2.1; *m* is the inverse slope of Paris-Law with a two-stage crack growth model in a log-log scale [2], usually taken as 3.6; t^* is a dimensionless plate thickness ratio in relation to a unit thickness ($t^* = t/\ t_{ref}$, with $t_{ref} = 1$ mm), thus handling the equivalent stress parameter with stress units (MPa); and the integral $I(r_b)$ is a dimensionless function of the bending ratio, r_b, computed as (in SI units) [6]:

$$I(r_b)^{1/m} = 0.0011 \cdot r_b^6 + 0.0767 \cdot r_b^5 - 0.0988 \cdot r_b^4 + 0.0946 \cdot r_b^3 + 0.0221 \cdot r_b^2 + 0.014 \cdot r_b + 1.2223 \tag{6}$$

for displacement-controlled conditions, which can occur under certain test conditions, and,

$$I(r_b)^{1/m} = 2.1549 \cdot r_b^6 - 5.0422 \cdot r_b^5 + 4.8002 \cdot r_b^4 - 2.0694 \cdot r_b^3 + 0.561 \cdot r_b^2 + 0.0097 \cdot r_b + 1.5426 \tag{7}$$

for load-controlled conditions. Dong *et al.*[2] have verified the usefulness of Equation (4) in the form of equivalent structural stress range parameter, ΔS_S, versus cycles to failure, *N*, for various types joints, with different thicknesses, dimensions and loading modes. The analysis demonstrated the capability to collapse several fatigue tests of welded components into a narrow band. The derived curve was then designated as Master S-N curve:

$$\Delta S_S = C \cdot N^h \tag{8}$$

where C and h are parameters determined based on a linear regression analysis. ASME Sec VIII Div2 [6]provides C and h parameters fatigue analysis of welded joints under Mode I dominated loading using the Master S-N curve method.

3 Developed tool built into FE program

The structural stress recovery procedure described by Equations (1)-(8) can be very cumbersome to be manually computed for every step of an analysis, even with the aid of MATLAB or a spreadsheet. Therefore, the application of the method can become much more efficient with the use of a post-processor tool operating on the FE results. Some proprietary post-processor are available to be used in conjunction with FE program suites [10,16]. However, this work presents a tool developed a new post-processor developed from scratch to be used in conjunction with ANSYS Mechanical (as can be seen in Figure 1). The developed post-processor takes advantage of the APDL Math, a library available in the ANSYS program for advanced computation with matrices, allowing the users to operate in the finite element results. It works with either shell or solid elements, with linear or quadratic shape functions. The details of the sub-macros of the implemented post-processor are described below:

- **SSTR.MAC:** This macro is responsible for setting all the user definitions for the analysis.
- **RUNSSTR.MAC:** This is the main macro and, once all the analysis parameters are defined by the user, it must be run to compute the equilibrium-equivalent structural stresses, the equivalent stress ranges and the estimated fatigue lives of each node lying in the selected weld lines. The results are stored in vectors in the workspace of the FE program.
- **SSTRCP.MAC:** This macro is responsible for making stress contour plots of the FE model representing each parameter computed and stored by the macro RUNSSTR.MAC.
- **PLOTLIFE.MAC:** This macro is responsible for performing fatigue life contour plots, which have a different logic from stress contour plots since the engineer usually searches for the points with the least values (lives) instead of the points with the maximum values (stresses).
- **EXPSTR.MAC:** This macro allows the user to export all the computed results to ASCII files, which is useful to save the results for further computations.

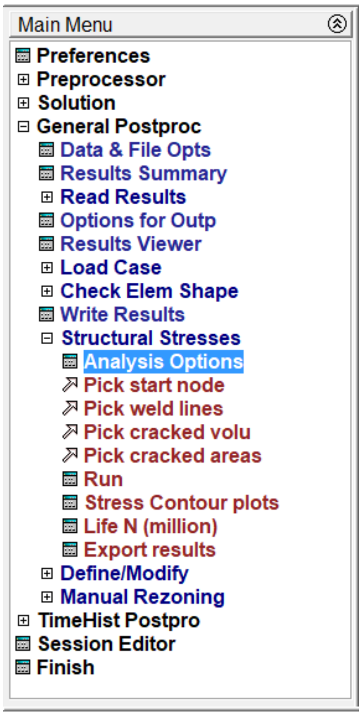
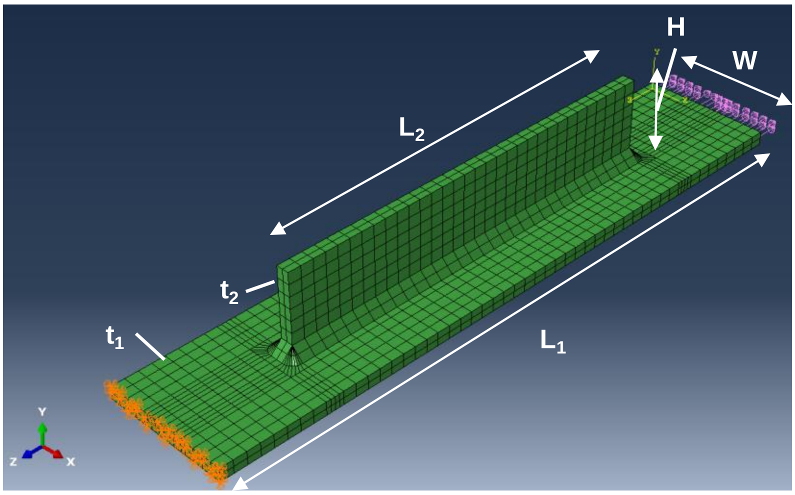


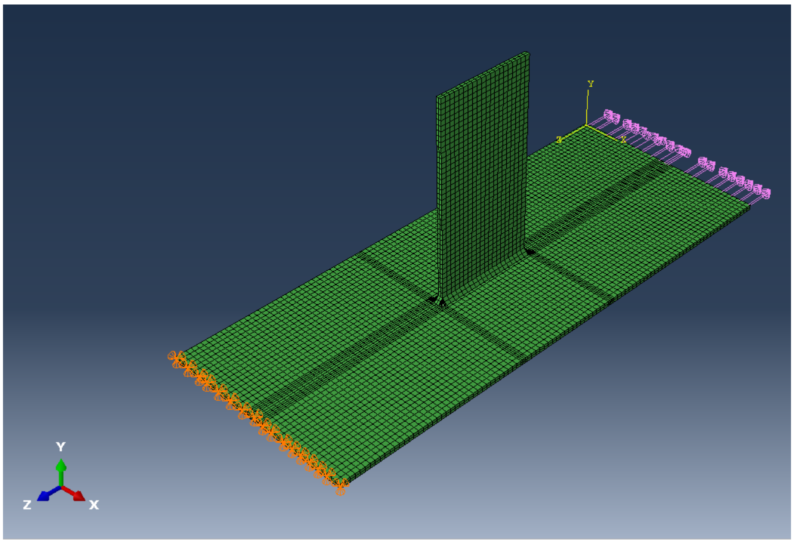
Figure 1. A short demonstration of the developed post-processor macros bult into ANSYS Mechanical.

4 Demonstration use for a longitudinal welded attachment

The developed post-processor was validated with a benchmark comparison with a proprietary post-processor developed for ABAQUS called Verity® Fe-Safe, which implemented the Battelle Structural Stress method. Four different FE models of one-side non-load carrying welded attachments were developed in ANSYS, with two different geometries using two different types of solid elements, linear 8-noded and quadratic 20-noded, respectively. The FE models were then exported to ABAQUS (Figure 2), by converting the FE mesh in an interchangeable file format between both programs. The plates are subjected to a unit nominal stress (1 N/m^2) in one-side and restricted in the three displacement directions in the other (x, y, and z). The developed post-processor based on ANSYS was applied to the four models, as the Fe-Safe post-processor was also applied to the imported FE models in ABAQUS. Comparisons of the results of both post-processors in terms of structural stresses are shown in Figure 3, showing a very good agreement for all types of elements used.



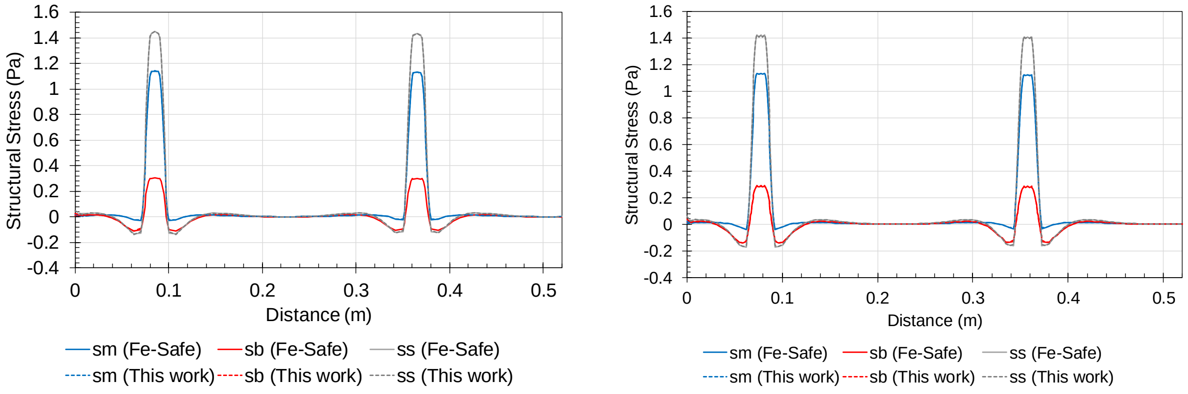
(a)



(b)

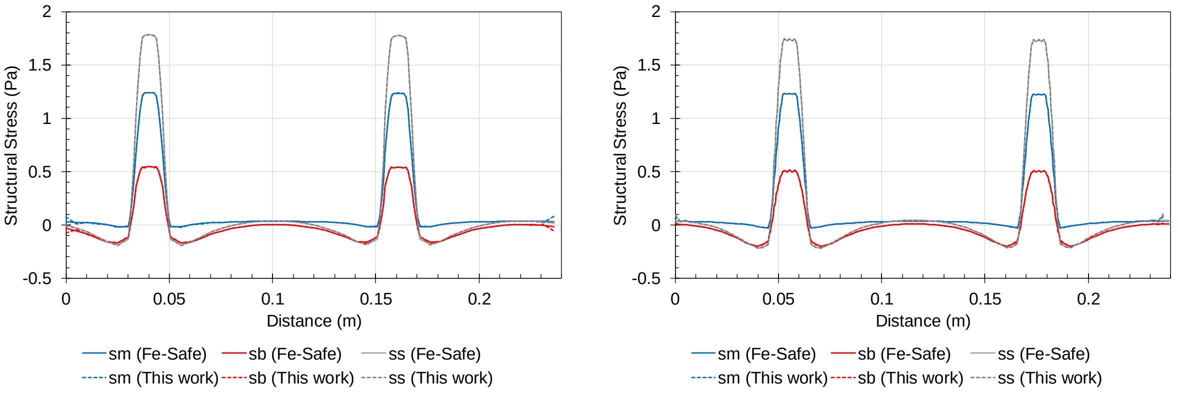
Figure 2. FE models exported to ABAQUS (E = 210 GPa, n = 0.3): (a) Detail 1 and (b) Detail 2.

Detail 1: L_2 = 250 mm; L_1 = 400 mm; W = 80 mm; H = 50 mm; $t_1 = t_2$ = 8 mm; Weld leg = 7 mm; mesh-size = 8 mm



(a) (b)

Detail 2: L_2 = 100 mm; L_1 = 500 mm; W = 200 mm; H = 200 mm; $t_1 = t_2$ = 5 mm; a_w = 5 mm; mesh-size = 5 mm



(c) (d)

Figure 3. Benchmark analysis of the developed post-processor. One side non-load carrying welded attachment: (a) and (c) 8-node linear solid; (b) and (d) 20-node quadratic solid.

5 Conclusions

The following conclusions can be taken from the presented study:

- The proposed tool was validated with another proprietary tool used in industry;
- The use of this tool can accelerate fatigue design of mechanical components, and help engineers design for fatigue limit-state with more confidence;
- The Master S-N curve method can offer some advantages over traditional method for welded connections, such as the use of a single S-N curve and coarse FE models.

Acknowledgments. The first author acknowledges the financial support provided by CNPq, grant number 203662/2014-8. The authors acknowledge the financial support provided by CNPq, CAPES, FAPERJ and FCT.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship)of the authors or has the permission of the owners to be included here.

References

[1] Alencar G, de Jesus A, da Silva JGS, Calçada R. Fatigue cracking of welded railway bridges: A review. Eng Fail Anal 2019:154–76.

[2] Dong P, Hong JK, Osage DA, Prager M. Master S-N curve method for fatigue evaluation of welded components 2002.

[3] Dong P, Hong JK. The master S-N curve approach to fatigue evaluation of offshore and marine structures. Proceeding OMAE04 - 23rd Int. Conf. Offshore Mech. Arct. Eng., Vancouver, British Columbia, Canada: 2004, p. 1–9.

[4] Dong P, Hong JK. The master SN curve approach to fatigue of piping and vessel welds. Weld World 2004;48:28–36.

[5] Alencar G. Structural stress-based methodologies for fatigue assessment of welded railway bridges (PhD Thesis). Faculty of Engineering of University of Porto, 2021.

[6] ASME VIII Div2. Secion VIII-Division 2: Rules for Construction of Pressure Vessels. ASME Boil Press Vessel Code 2013.

[7] API 579-1/ASME FFS-1. API 579-1/ASME FFS-1 Fitness-For-Service 2016.

[8] Alencar G, De Jesus A, Silva JGS, Calçada R. A finite element post-processor for fatigue assessment of welded structures based on the Master S-N curve method. Int J Fatigue (in Press 2021.

[9] Ghahremani K, Walbridge S, Topper T. High cycle fatigue behaviour of impact treated welds under variable amplitude loading conditions. Int J Fatigue 2015;81:128–42. https://doi.org/10.1016/j.ijfatigue.2015.07.022.

[10] Yaghoubshahi M, Alinia MM, Milani AS. Master S-N curve approach to fatigue prediction of breathing web panels. J Constr Steel Res 2017;128:789–99. https://doi.org/10.1016/j.jcsr.2016.10.015.

[11] Ye XW, Su YH, Jin T, Chen B, Han JP. Master S-N Curve-Based Fatigue Life Assessment of Steel Bridges Using Finite Element Model and Field Monitoring Data. Int J Struct Stab Dyn 2018:1940013. https://doi.org/10.1142/S0219455419400133.

[12] Dong P, Hong JK, De Jesus AMP. Analysis of Recent Fatigue Data Using the Structural Stress Procedure in ASME Div 2 Rewrite. J Press Vessel Technol 2007;129:355. https://doi.org/10.1115/1.2748818.

[13] Niemi E, Fricke W, Maddox SJ. Structural Hot-Spot Stress Approach to Fatigue Analysis of Welded Components. Singapore: IIW Collection. Springer Singapore; 2018. https://doi.org/10.1007/978-981-10-5568-3.

[14] Nussbaumer A, Grigoriou V. Round Robin on local stress evaluation for fatigue by various FEM software. IIW-Doc XIII-2650-16 2016:1–15.

[15] Alencar G. Source code of a finite element post-processor implementation of the Master S-N curve approach 2021. https://doi.org/10.17632/9sh2njddvn.1.

[16] Dong P. VerityTM Weld Fatigue Method in Fe-SafeTM Using ANSYS. Int. ANSYS Conf. A world Simul., Pittsburgh, Pennsylvania: 2006.