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FATIGUE STRENGTH EVALUATION OF RIVETED SHEAR SPLICES

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Abstract

Fatigue damages occur in historical steel riveted bridges, necessitating the assessment of their remaining life and fatigue strength. However, no coded recommendation exists for evaluating the fatigue strength of riveted structural details. The current literature provides some references, but they are still being researched through experimental and numerical studies to demonstrate their suitability. This work presents the results of numerical simulations that evaluate the fatigue strength of double-shear riveted connections. Experimental fatigue test results are collected from the literature, and some of them are used to develop a finite element model in ABAQUS and Fe-Safe. The adopted modelling fatigue approach is successively used to investigate the fatigue behaviour of double-shear riveted connections with different geometrical properties. The numerical results are compared with all collected data showing the procedure's effectiveness in predicting the fatigue strength of double-shear riveted connections. The numerical and experimental results are also compared with the S-N curves currently recommended to compute the fatigue strength of riveted details.

Keywords: Steel Bridges, Riveted Connection, Fatigue Strength, S-N Curve, Finite Element Model.

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1 INTRODUCTION

Rivets are the oldest type of fasteners used to assemble metal pieces and, since the 19th century, contributed to manufacturing steel civil constructions, mainly railway and highway bridges. Although welding and bolting have progressively replaced the riveting process, many old steel riveted bridges still exist and are in operation. Due to the high number of cyclic stresses such structures have sustained over the years, they are prone to fatigue damage [1]. Fatigue cracks occur mainly in the connections [2] and, if not controlled, can reduce the structural members' bearing capacity. Therefore, to determine possible repairs able to guarantee their safety, the evaluation of the fatigue behaviour of riveted details is required.

Current codes [3]-[4] use the fatigue curves (i.e., S-N curves), formerly conceptualised by Wöhler, for fatigue verification and design of steel structural details. S-N curves are expressed both in terms of normal and tangential stresses. Besides, specific structural details are identified based on the potential fatigue crack location (e.g., the gross or net section in a double-covered symmetrical joint) and associated with S-N curves to be used for their fatigue assessment. However, construction standards do not include riveted details, and some recommendations have been proposed over time to compensate for the absence of specific requirements. In particular, detail category 71 is recommended to verify the fatigue behaviour of any riveted structural details according to the JRC-ECCS technical report [5], as the 95% lower bound of experimental data of full-scale fatigue tests. Moreover, conforming to AASHTO guidelines [4], detail D, characterised by a slope of 3 until a stress threshold value of 48.3 MPa (similarly to detail category 71 of Eurocode), can be used.

Although using the coded structural details allows for safe-sided fatigue assessment of riveted assemblies, several studies highlighted the excessive conservative estimation obtained mainly in the long-life fatigue regime [6],[7]. Besides, more recent studies relying on the assessment of the remaining capacity and life of existing steel bridges demonstrated the importance of using suitable fatigue details to properly design maintenance or retrofit operations (e.g., [8]-[11]). Additionally, the influence of joint details on the overall behaviour of steel structures is widely recognized in literature [12]-[31].

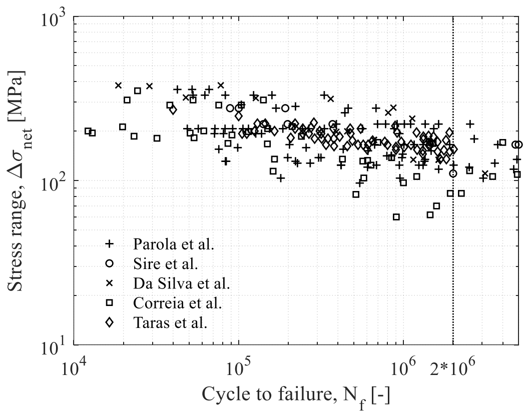
Recently, Taras and Greiner [32] discussed the inappropriate assumption that all riveted structural details behave similarly and developed a fatigue class catalogue distinguishing five riveted constructional details. The catalogue has been created as a result of the categorisation and statistical evaluation of prior fatigue test results [33]. However, the proper assessment of the detail category to predict the fatigue behaviour of riveted connections is still an open issue in the research community.

This work presents a numerical study concerning the fatigue behaviour of riveted double-shear splices. Fatigue literature data on riveted shear splices have been collected and used to calibrate a numerical procedure to predict their fatigue strength. Numerical models have been built in ABAQUS [34], used in conjunction with Fe-Safe [35] to perform fatigue calculations. The fatigue strength of the modelled connections is computed by determining the number of cycles to crack initiation as the lower bound of the number of cycles to fatigue failure and relevant phase in the case of riveted and bolted connections [36]. The numerical approach is successively used to implement a numerical study on the fatigue behaviour of double-shear splices with different geometrical properties (e.g., riveted and hole diameters, pitch, width and thickness of the plates). Numerical and experimental data are compared, showing the reliability of the adopted procedure.

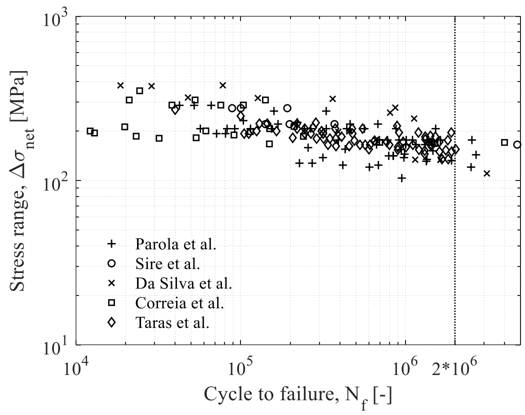
2 FATIGUE LITERATURE DATA

Experimental results of fatigue tests on riveted shear splices have been collected from [36]-[38],[39]-[43]. Figure 1(a) reports the collected data. All the tests refer to riveted splices subjected to shear fatigue tests at constant stress amplitude characterized by different geometrical properties, number of rivets and shear planes, steel type, bearing ratio, test frequency and stress ratio ($R = \sigma_{min}/\sigma_{max}$, in which σ_{min} and σ_{max} represent the maximum and minimum normal stresses applied to the specimen, respectively). In particular, R values ranging from -1 up to 1 are applied. It is noteworthy that a negative R value means the application of both tension and compressive stresses.

To reduce the scatter of the data and provide more reliable comparisons, unsymmetrical connections (one shear plane) and tests with no failure conditions are excluded. Besides, according to Eurocode, the beneficial effect of compressive stresses on fatigue behaviour is considered by correcting data with negative R values [3]. Figure 1(b) depicts the filtered data.



a)



b)

Figure 1: Literature experimental data. a) row and b) filtered and normalized data used in the comparisons.

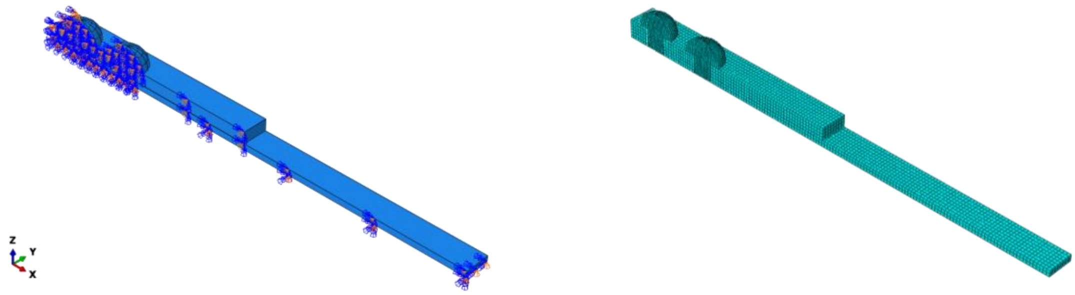
Among others, the results of the experimental tests carried out by Da Silva [36] are used to calibrate the fatigue calculation presented in the following section. In particular, the experimental campaign includes fatigue tests on two series of double-shear riveted splices: with a single row and two rows of rivets (four and eight rivets, respectively). All specimens in each series have the same geometrical properties and are subjected to cyclic stresses with R equal to 0.01. In this work, only the experimental results related to double-shear riveted splices with four rivets arranged in a single row are considered (Section **3**).

3 FINITE ELEMENT MODELLING

3D finite element models (FEM) are built in ABAQUS [34], aiming to numerically investigate the fatigue behaviour of riveted shear splices. Using two symmetry planes (i.e., XY and XZ planes), only ¼ of the geometry is modelled, and the displacement/rotation of the nodes at such planes is constrained according to the symmetry conditions. Figure 2(a) and (b) depict an overview of the adopted boundaries and meshing approach, respectively. Null clearance between the rivet shanks and the holes is adopted, as characteristic property resulting from the riveting process ([44],[45]), whereas a '*Bolt load*' is used to introduce the rivet clamping. The material of both rivets and plates is modelled as linear elastic and isotropic, considering a young modulus equal to 210 GPa and a Poisson ratio of 0.27. The '*surface-to-surface*' interaction property defines the contact behaviour among steel surfaces. In particular, the '*Hard contact*' option describes the interaction in the normal direction. In contrast, the tangential one is modelled with a '*Penalty*' friction formulation with friction coefficients equal to 0.30.

The adopted fatigue analysis procedure comprises two main steps (Figure 3(a)): linear-elastic FEM analysis to compute the initial stress distribution within the connection and fatigue evaluation of the number of cycles to crack initiation (assumed in this work as the lower bound of the fatigue strength). The elastic analysis is performed in ABAQUS [34]. A single stress range is applied at the left gross section end as '*pressure*', and the corresponding elastic stress distribution is obtained using the static solver. Fe-Safe software [35] successively read the obtained datasets as an ODB file for fatigue assessment. The fatigue calculation is performed by scaling the stress distribution according to a sinusoidal signal and applying the strain-life approach with the Coffin-Manson cyclic constitutive relation [46]-[47]. Specifically, the material constants are obtained from experimental fatigue tests published in [36] and statistically evaluated considering a 95% tolerance interval, as shown in Figure 3(b).

Figure 4 illustrates the numerical results obtained by applying the adopted procedure. In particular, Figure 4(a) and (b) depict the contour stresses at the end of the static analysis in ABAQUS and Fe-Safe fatigue results for a single riveted shear splice investigated, respectively. A maximum stress value in the net section of the central plate characterises the elastic stress field obtained by applying uniform tensile stress (Figure 4(a)), and the corresponding predicted fatigue life reports the same critical position. It is noteworthy that the distribution of the fatigue life is obtained in a logarithmic scale (i.e., log(N)), and the most critical value for the crack initiation is the lowest log(N), depicted in red in Figure 4(b). For the sake of brevity, the results related to the other connections investigated are not reported. However, all the riveted shear splices studied exhibit net-area tensile failure of the plates, in agreement with the experimental results [36].



a) b)

Figure 2: ABAQUS modelling. a) overview and b) meshing approach of the FE models.

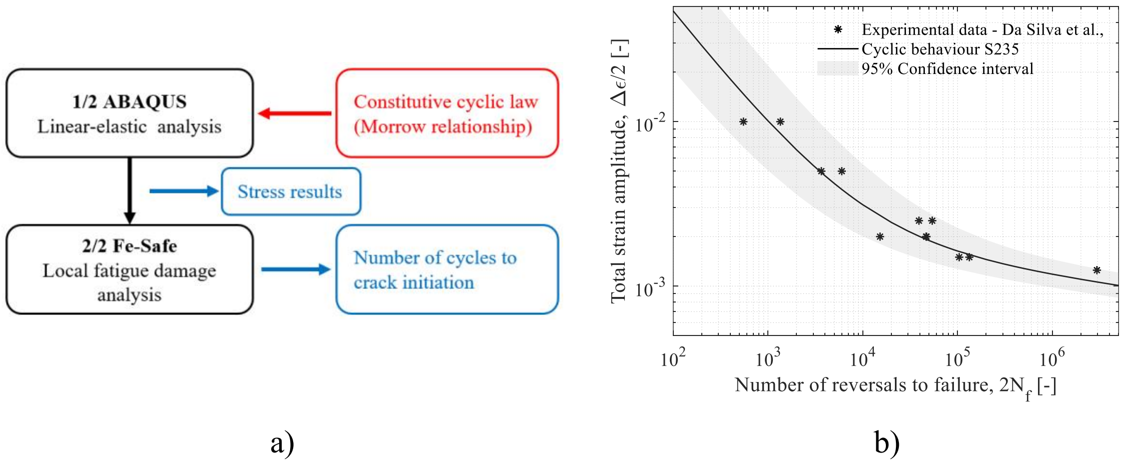


Figure 3: Fatigue modelling. a) workflow adopted in this study; b) cyclic behaviour of the constituent material.

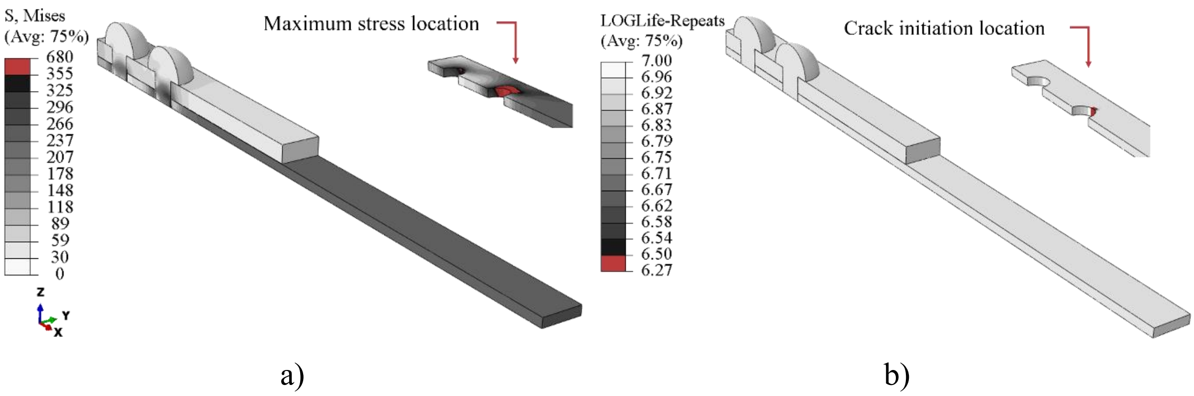


Figure 4: Fatigue calculation. a) linear-elastic static analysis in ABAQUS; b) fatigue calculation in Fe-Safe.

Figure 5 shows the comparison between the numerical and experimental data. In particular, the experimental fatigue results are depicted with black markers and described through the mean linear regression (black line) and the 99% tolerance interval (filled grey area). The numerical results are obtained by adopting the mean, the lower and the upper properties of the confidence interval of the material's cyclic constitutive law, previously reported in Figure 3(b). It can be observed that the curves have the same slope, but different intercepts, and the fatigue strength is generally underestimated. It is important to highlight that the adopted modelling approach computes only the fatigue crack initiation. Additionally, the preload provided by the riveting process and its influence on fatigue behaviour is challenging to quantify rigorously [36]. The best prediction is obtained when the upper fatigue material constants are used. Nevertheless, for the numerical study presented in Section **4**, the lower fatigue material constants are used for safe-sided predictions.

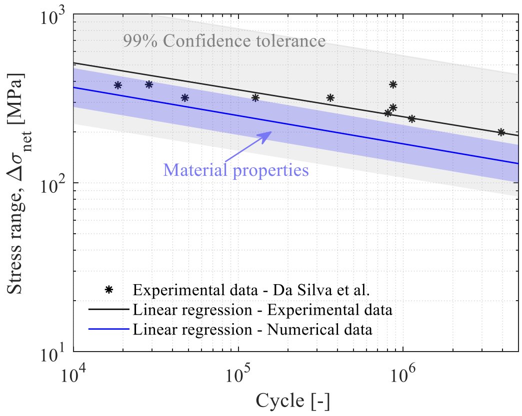


Figure 5: Comparison of the numerical and experimental results.

4 FATIGUE LIFE PREDICTION OF RIVETED SPLICES

A numerical study has been conducted to evaluate the fatigue behaviour of double-shear splices with different geometrical properties. The fatigue modelling follows the approach described in Section **3**. Table 1 lists all analysed cases that differ in rivet and hole diameters, width and thickness of the plates, and pitch. The geometrical properties are chosen to contain typical values of riveted connections in steel bridges.

In the present study, each connection is subjected to ten cyclic loadings to build their S-N curves. In particular, five maximum stresses ranging from 100 MPa to 225 MPa are selected, and two R values are adopted (i.e., 0 and 0.5), keeping the maximum stress unchanged.

Identifier	Diameter Φ, (mm)	Width w, (mm)	Thickness t, (mm)	Edge distance a, (mm)	Pitch p, (mm)	p/Φ ratio
R2-13-8-2.95	13	34.22	8	17.11	38.30	2.95
R2-13-8-3.50	13	34.22	8	17.11	45.50	3.50
R2-13-8-4.50	13	34.22	8	17.11	58.50	4.50
R2-13-12-2.95	13	34.22	12	17.11	38.30	2.95
R2-13-12-3.50	13	34.22	12	17.11	45.50	3.50
R2-13-12-4.50	13	34.22	12	17.11	58.50	4.50
R2-19-8-3.50	19	50.00	8	30.00	66.50	3.50
R2-19-8-4.50	19	50.00	8	30.00	85.50	4.50
R2-19-12-2.95	19	50.00	12	30.00	56.00	2.95
R2-19-12-3.50	19	50.00	12	30.00	66.50	3.50
R2-19-12-4.50	19	50.00	12	30.00	85.50	4.50
R2-25-8-2.95	25	65.80	8	39.50	73.70	2.95
R2-25-8-3.50	25	65.80	8	39.50	87.50	3.50
R2-25-8-4.50	25	65.80	8	39.50	112.50	4.50
R2-25-12-2.95	25	65.80	12	39.48	73.70	2.95
R2-25-12-3.50	25	65.80	12	39.48	87.50	3.50
R2-25-12-4.50	25	65.80	12	39.48	112.50	4.50

Table 1: Geometrical properties of the investigated double shear riveted splices.

Figure 6 shows the comparison between the numerical results, their statistical evaluation carried out according to [48], and the experimental filtered data (previously shown in Figure

1(b)). The numerical results are described by a mean curve (blue line) with a slope equal to 6.64 and a fatigue resistance of 124 MPa at 2 x 10^6 cycles. In addition, 95% and 99% tolerance intervals are represented by filled areas. Since the above intervals include almost all the experimental data, the modelling approach adopted in this work can be considered a good tool for estimating the fatigue strength of the considered double-shear riveted splices.

In Figure 7(a) and (b) fatigue numerical results are compared to the detail category 71 and Taras' proposal, respectively. In the first case (Figure 7(a)), the detail 71 overestimates the fatigue resistance for the riveted splices investigated subjected to a stress range over 125 MPa. Therefore, it does not represent the lower boundary of the investigated connections. Conversely, the comparison in Figure 7(b), shows that the S-N curves proposed by Taras to characterise the fatigue resistance of double-shear splices are close to the 95 % lower tolerance limit of the numerical results, hence providing a better estimation of their fatigue behaviour.

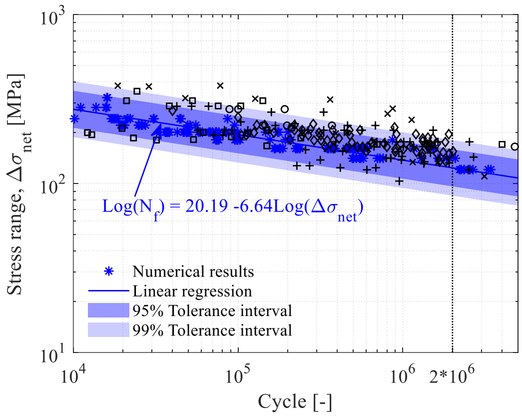


Figure 6: Comparison between the numerical and filtered experimental literature data.

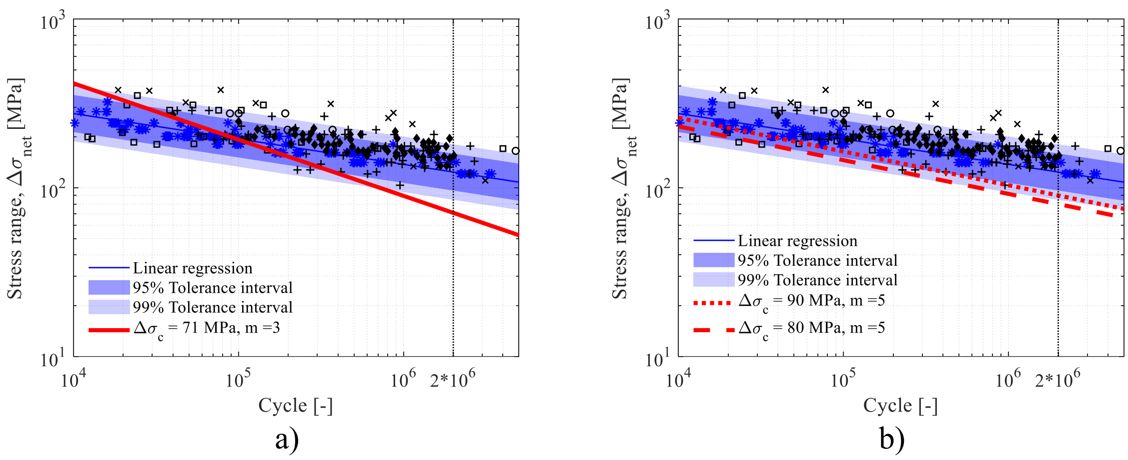


Figure 7: Comparison a) Fatigue numerical data; b) comparison with filtered experimental literature data.

Figure 8 finally shows the S-N curve that best fits all the considered results. In particular, the curve is characterized by a slope equal to 7 (higher than the aforementioned recommended details) and a fatigue strength of 90 MPa for 2 x 10^6 cycles.

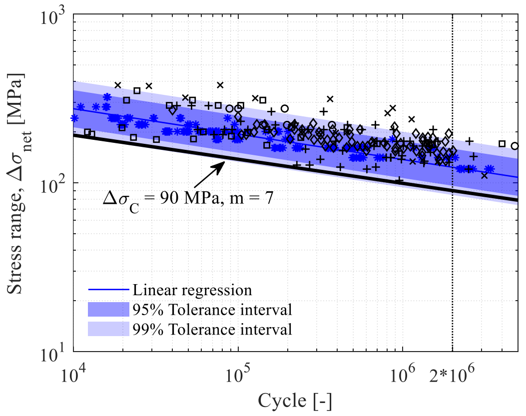


Figure 8: Fatigue curve proposed to describe the strength of the investigated case-studies.

5 CONCLUSIONS

This work performs a numerical study to investigate the fatigue behaviour of double-shear riveted splices. Finite Element Models are built in ABAQUS and Fe-Safe to perform fatigue calculations. The fatigue modelling approach is calibrated against fatigue results collected from the literature and successively used to conduct a numerical study to predict the fatigue strength of double-shear riveted splices with different geometrical properties. The following outcomes can be made: i) the number of cycles to crack initiation can be assumed as a reasonable lower bound to fatigue estimation of riveted double-shear splices; ii) the adopted numerical fatigue calculation can be considered a good tool to estimate the fatigue strength of riveted double-shear splices. It is noteworthy that the procedure requires the cyclic properties of the constituent materials.

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