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Practical methodology to evaluate the fatigue life of seam welded joints

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ABSTRACT

Purpose: of this paper is to present a practical and robust methodology developed to evaluate the fatigue life of seam welded joints under combined cyclic loading.
Design/methodology/approach: Fatigue analysis was conducted in virtual environment. The finite element stress results from each loading were imported to fatigue code FE-Fatigue and combined to perform the fatigue life prediction using the S x N (stress x life) method. A tube-to-plate specimen was submitted to a combined cyclic loading (bending and torsion) with constant amplitude. The virtual durability analysis result was calibrated based on these laboratory tests and design codes such as BS7608 and Eurocode 3. The feasibility and application of the proposed numerical-experimental methodology and contributions for the technical development are discussed. Major challenges associated with this modelling and improvement proposals are finally presented.
Findings: The finite element model was validated due to laboratory results. The analytical stress result presented upper value due to the approach used that considered the fillet weld supported all work. The model presented a good representation of failure and load correlation.
Research limitations/implications: The measurement or modelling of the residual stresses resulting from the welding process was not included in this work. However, the thermal and metallurgical effects, such as distortions and residual stresses, were considered indirectly with regard to the corrections performed in the fatigue curves obtained from the investigated samples.
Practical implications: Integrating fatigue analysis and finite elements, it is possible to analyse several welded joint configurations in the design phase, providing development time and cost reduction, increasing the project reliability.
Originality/value: This methodology will permit, in further studies, the modelling of both stresses, in-service and residual stresses, acting together, which seem like an advantage to engineers and researchers who work in design and evaluation of structural components against fatigue failures.
Keywords: Fatigue; Combined loading; Finite element analysis; Welding

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1. Introduction

Welding of metals is applied on a very wide scale, especially for building up structures by connecting plates and girders of different cross sections. Welded joints are unavoidable in many modern structural and mechanical components, providing different design options for the structures which cannot by simply obtained with other manufacturing techniques. For this reason, the economic advantages of welded joints have been known for over 50 years.Residual stresses may be defined as those stresses present in a material or structure without external loading, i.e. self-equilibrating stresses, a secondary loading. They arise when portion of a material or structural component undergo non-uniform plastic deformation associated with the manufacturing process, loading during the structure assemblage or in-service and heat treatments [1].

Considerable attention has been given to the residual stresses due to welding. Normally, welded joints have their final state of residual stresses brought about by the interaction of different sources [2-3]. Relatively simple residual stress distribution can be expected in a single pass weld if only shrinkage is considered. However, variations from this basic pattern occur when phase transformations are associated with shrinkage. In such cases, material's volume increases as a result of the austenite transformation. Sometimes, a surface quenching due to inhomogeneous cooling also contributes to an increase in volume. Taking into account the interaction of these different sources, a complex residual stress state can appear.

The influence of residual stresses on the structural integrity of mechanical components is largely studied. Tensile residual stresses in regions near crack tip may promote brittle fracture, fatigue failure and stress corrosion [4-7]. Compressive residual stresses, on the other hand, can reduce the buckling in welded joints [8] and improve fatigue resistance, by reducing the effective tensile stress, increasing the crack closure and, consequently, retarding the crack growth [9].

Fatigue codes or recommendations exist in almost every industrialized country. Structural design approaches are related to the lay-out of the structure, design of critical notches, type of joints, material selection, surface treatments, manufacturing parameters and load spectra in-service. Most recent fatigue design rules for steel welded structures [10-11] are based on stress range regardless of applied mean stress in order to take into account tensile residual stresses, which actual effect depends on their magnitude. In this context, most laboratory test specimens adopted to generate the fatigue design *S-N* curves are too small to contain very high residual stresses [12]. However, for design and fitness purposes of real structures a conservative assumption must be done that is tensile residual stresses will be at their highest level, that is, of the yield stress magnitude.

Although the stress range approach to design and fitness-for-purpose has theoretical basis, few test data have been obtained to justify in-service conditions, based on the fact that laboratory specimens contain residual stresses whose levels are presented in real structures. In this sense, this work presents a practical methodology developed to evaluate the fatigue life of seam welded joints under combined cyclic loading. This methodology will permit, in further studies, the modelling of both stresses, in-service and residual stresses, acting together, which seem like an advantage to engineers and researchers who work in design and evaluation of structural components against fatigue failures.

1.1. Hot spot approach

According to Fricke [13], there are six welded joint fatigue analysis approaches: nominal stress, structural or hot spot stress, notch stress, notch intensity, notch strain and crack propagation.

Hot spot is a term used to refer to the critical point in a structure [14]. In this approach, the fatigue strength, expressed as an S-N curve, is generally based on strains measured in the specimen near the point of crack initiation [15].

The structural or hot spot stress is a fictitious value but, for plate or shell structures, it corresponds to the sum of membrane and bending stress at the weld toe [16], which can be determined either by surface extrapolation or inner linearization of the stress [13]. Figure 1 presents the model of hot spot adopted in this work.

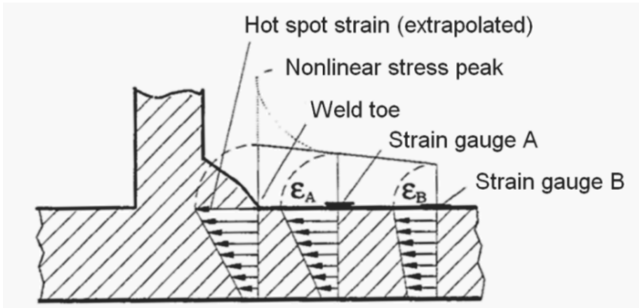


Fig. 1. Measurement of the hot spot strain range using the linear extrapolation method [15]

Recently, Bäckström [14], Gustafsson [17] and Sonsino [18] analysed fatigue life in tube to plate samples under multiaxial load, comparing results obtained in laboratory with design codes, such as BS and Eurocode3 [10-11].

2. Methodology

2.1. Materials and specimens

The sample geometry selected for the investigation is shown in Figure 2.

The samples were manufactured adopting a tube (545 mm × 116.4 mm × 9.5 mm), portion of an automotive differential axle, which was welded to a plate (250 mm x 250 mm) by means of GMAW adopting a heat input of 40.9 kJ/m. Both materials were similar to the SAE 1022 steel. Their chemical composition and mechanical properties are given in Tables 1 and 2, respectively. In Table 2, E, ν, S_y and S_{ut} mean the Young modulus, Poisson ratio, yielding stress and ultimate tensile strength, respectively.

Table 1.
Chemical composition of the material

Element	C	Mn	Si	P	S	Al	Nb	Ti	N	Ca	Fe	CE
wt %	0.17	1.39	0.21	0.023	0.002	0.042	0.031	0.017	0.007	0.003	balance	0.41

Table 2.
Mechanical properties of the material

E, GPa	ν	S_y, MPa	S_{ut}, MPa
210	0.33	350	530

In the table above, CE means the carbon-equivalent of the material.

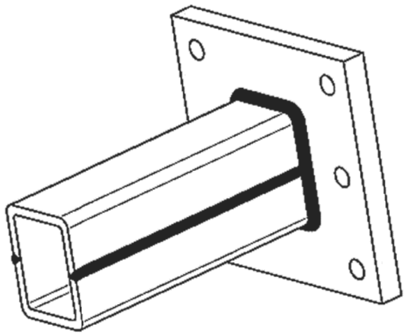


Fig. 2. Tube-to-plate sample

Figure 3 and Table 3 present the seam weld geometry and dimensional, respectively.

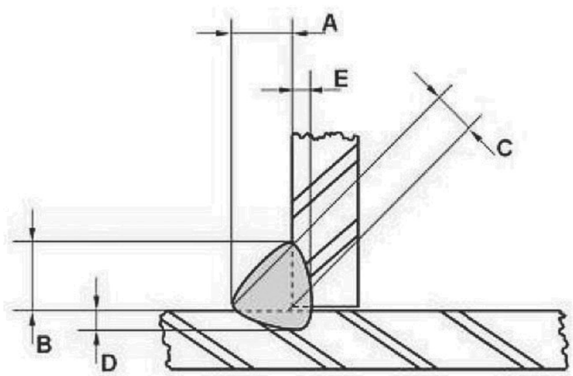


Fig. 3. Seam weld geometry

Table 3.
Seam weld dimensional, mm

Position	Sample 1	Sample 2
A	12.1	10.8
B	11.3	10.1
C	7.7	8.6
D	3.3	2.0
E	1.2	1.0

2.2. Finite element analysis (FEA)

A solid model was built using the program Pro / Engineer Wild Fire 2 and imported through the ANSYS Workbench program, creating the finite element mesh. The region of interest (weld toe) has been refined based on the work of Goes and co-authors [19]. The quadratic tetrahedral element (Solid187 ANSYS) was adopted in the analysis.

The boundary conditions were established to represent the fatigue tests carried out in the laboratory. The holes in the plate were fixed by eliminating all degrees of freedom and the remote loading of ANSYS Workbench was applied.

Figure 4 shows the load position on the face of the rectangular section. The model was constructed with 545 mm, according to the tube dimension, generating a concentrated load at 45 mm from the mouth of the tube. A linear elastic analysis was performed adopting a load of 18 kN.

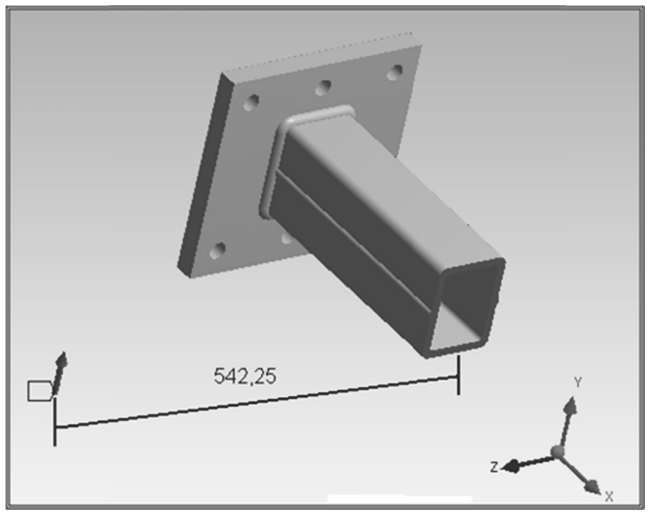


Fig. 4. 3D model loading

2.3. Fatigue life prediction

The hot spot stress approach was adopted to assess the fatigue life of the seam welded joints by means of FEA. The tube-to-plate joint was refined to better capture the stress concentration distribution at the weld toe location. Two rectangular strain gage rosettes were attached in the hot spot localization to calibrate the FE model and to obtain the experimental hot spot stress. The localization of the strain gages is presented in Figure 5.

FE-Fatigue software was used to predict the fatigue life, by importing the finite element results from Ansys software. It was necessary to define the proper fatigue life curve from FE-Fatigue database or input a specific curve. The present investigation adopted the specific curve of the material proposed by Goes and co-authors [20]. The curve of the material was fitted from the database FAP7 (Fatigue Analysis Program - a program developed by ArvinMeritor) and calibrated by testing in fatigue the differential axle, in order to obtain a representative curve regarding the welded joint under study. For this purpose, the deformation x fatigue life curve (ε x N) was selected based on the possibility to estimate low and high cycle fatigue. Figure 6 presents the specific curve of the tube concerning the tube-to-plate sample obtained by fatigue test (correct curve) in comparison with the tube (base metal).

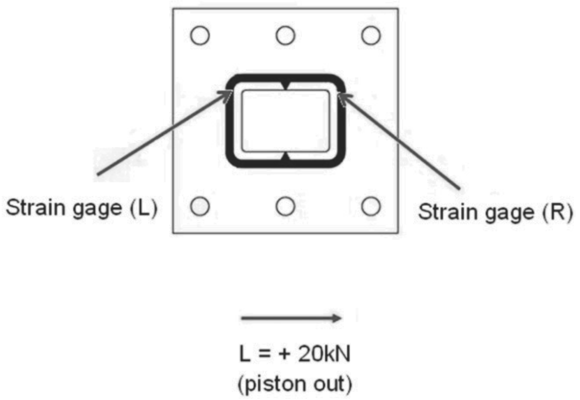


Fig. 5. Location of strain gages on the tube-to-plate sample

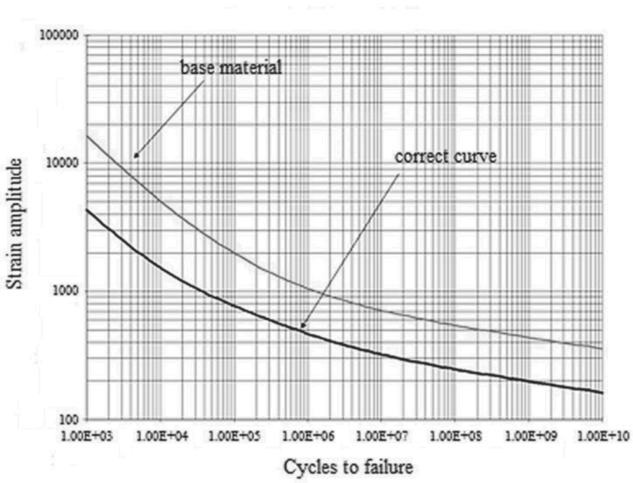
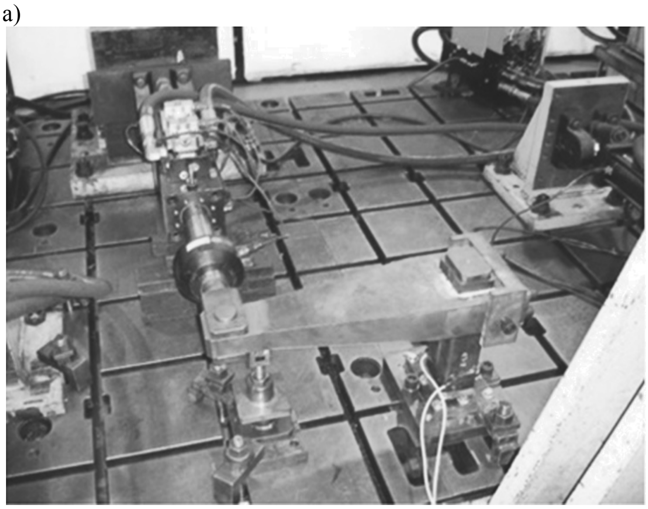


Fig. 6. ε x N curves obtained according to FAP7 database (base material) and fatigue test (correct curve)

2.4. Fatigue tests

Fatigue tests were performed to validate the virtual analysis. The tubes-to-plate samples were subjected to torsion and bending combined load of 18 kN. The specimens were unloaded after crack initiation detected by liquid penetrant testing. Figure 7 shows the fatigue tests conducted by Goes [21]. The test equipment consisted of a linear hydraulic actuator (± 100 kN) with a device applying the complete reverse load (R = -1) and a frequency of 2.0 Hz, both controlled by the MTS control system 407.

a)



b)

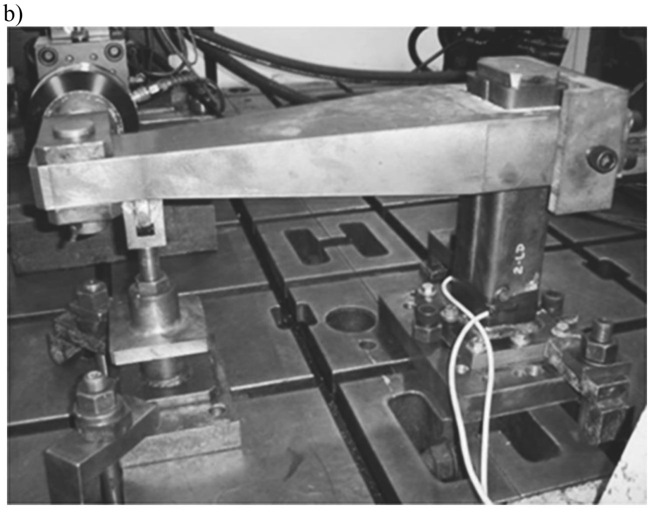


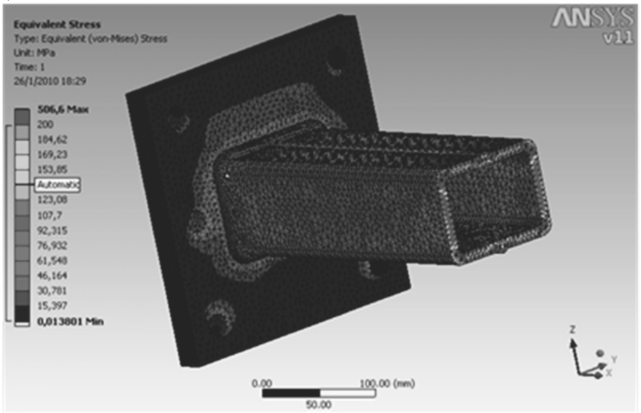
Fig. 7. Fatigue test (a) and detail of the test equipment (b)

3. Results and discussion

3.1. FEA

The equivalent stress is widely adopted for stress calculation in welded joints, on the basis that considers the effects of torsion, bending and shear to which the joint is subjected. The equivalent stress distribution for the loading of 18 kN is shown in Figure 8.

a)



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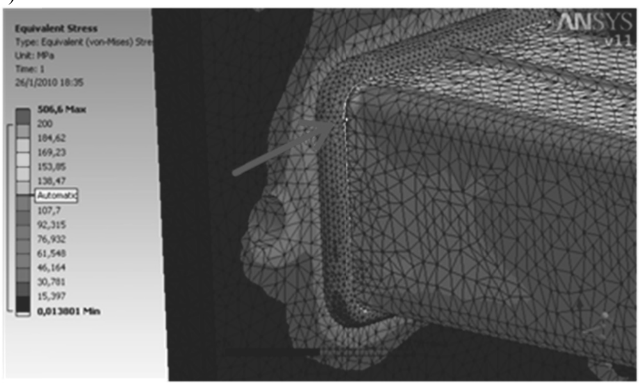

Fig. 8. Equivalent stress distribution predicted by FEA (a) and detailed in the critical region (b)

The values of the equivalent stresses calculated by FEA at the hot spot (located 4 mm from the weld toe) are given in Table 4, according to Figure 5.

Table 4.
Calculated equivalent stresses at the weld hot spot

Position	Stresses, MPa
L	154
D	144

3.2. Experimental stresses

Experimental strains were obtained in the positions 0.45 and 90º of the two rectangular strain gage rosettes attached in the hot spot region, as presented in Figure 5. Table 5 presents the results of equivalent stress for each rosette.

Table 5.
Experimental equivalent stresses at the weld hot spot

Position	Stresses, MPa
L	143
D	141

3.3. Stress comparison

The equivalent stresses obtained by both methodologies were compared and presented in Table 6.

Table 6.
Equivalent stresses at the weld hot spot

Position	Calculated, MPa	Experimental, MPa
L	154	143
D	144	141

The results presented in Table 6 show a good correlation between the predicted and experimental stresses. In this sense, the FEA model was validated by the fatigue tests performed in laboratory.

3.4. Fatigue life prediction

The stresses and strains calculated by ANSYS were adopted in the FE-Fatigue program, together with the S x N curve corrected by Goes and co-authors [20], in order to obtain the fatigue life of the welded joint concerning the equivalent stresses. Figure 9 shows the fatigue life distribution by FE-Fatigue software.

The fatigue life of the welded joint calculated by means of the FE-Fatigue program was equivalent to 235.4 x 10^3 cycles.

3.5. Experimental fatigue life

In the tests performed in laboratory, the fatigue life of the welded joints was associated with the detection of crack initiation by liquid penetrant testing, resulting in the specimen unloading. The mean fatigue life of the welded joints was determined as 204.5 x 10^3 cycles. Figure 10 shows an example of crack detection during the fatigue testing.

3.6. Fatigue life according to BS7608 and Eurocode 3

The fatigue life curves of the standards BS7608 [10] and Eurocode 3 [11] were used to obtain the fatigue life of the joint of the present study, regarding the calculated (Ansys) and experimental stresses at the hot spot region. The results are given in Table 7.

Table 7.
Fatigue life (cycles) according to fatigue recommendations

Approach	BS7608	Eurocode 3
Ansys	459 x 10^3	429 x 10^3
Experimental	469 x 10^3	545 x 10^3

a) b)

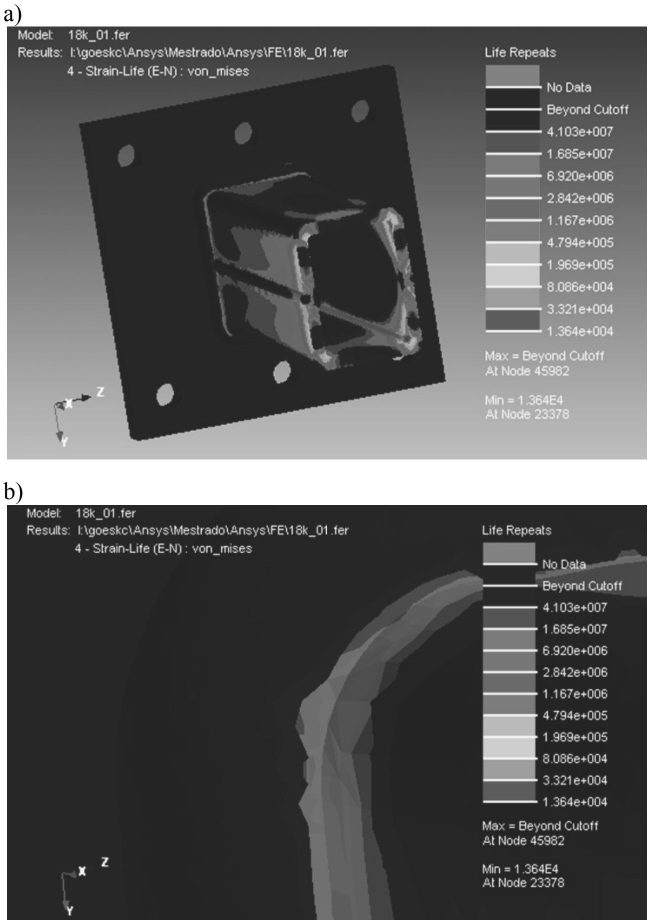

Fig. 9. Fatigue life distribution by FE-Fatigue (a) and detailed in the critical region (b)

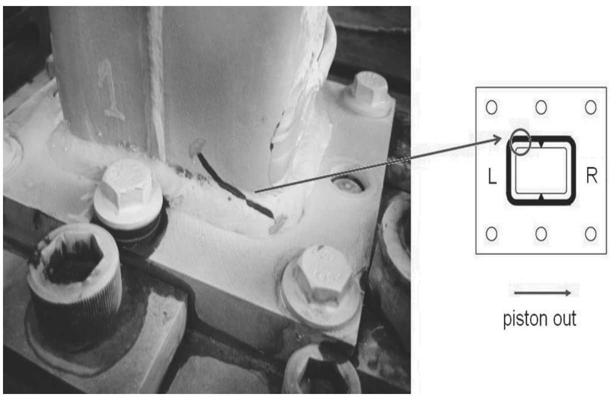

Fig. 10. Fatigue crack detection during the tests in laboratory

3.7. Fatigue life comparison

Tables 8 and 9 summarize the fatigue life concerning the stress approaches and fatigue codes.

Table 8.
Fatigue life (cycles) according to calculated hot spot stresses

FE-Fatigue	BS7608	Eurocode 3
235.4 x 10^3	459 x 10^3	429 x 10^3

Table 9.
Fatigue life (cycles) according to experimental hot spot stresses

Experimental	BS7608	Eurocode 3
204.5 x 10^3	469 x 10^3	545 x 10^3

The laboratory test results presented considerable variation that can be attributed to the weld process, residual stresses not considered in the analysis and to samples number.

4. Conclusions

The objective of this paper is to present a practical methodology developed to evaluate the fatigue life of seam welded joints under combined cyclic loading. Fatigue analysis was conducted in virtual environment and then compared with fatigue test results. The virtual durability analysis result was calibrated based on these laboratory tests and design codes. Regarding the study described herein, the following conclusions can be drawn:

- The FE model was validated due to results obtained in fatigue tests. The stress results presented upper value due to the approach used that considered the fillet weld supported all work. The model presented a good representation of failure and load correlation.
- The model presented in this work is practical and robust to develop combined load fatigue test and reproduced field issues.
- Integrating fatigue analysis and finite elements, it is possible to analyse several welded joint configurations in the design phase, providing development time and cost reduction, increasing the project reliability.

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