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Determinatıon of stress magnification factor in welded joint by experimental and numerical analysis using ultra-high-strength steel

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ABSTRACT

The use of ultra-high strength steels (UHSS) is increasing in many industries. These steels are gaining importance in structural applications due to their advantageous properties of high strength and low weight. However, the reliability and durability of welded joints are often questioned due to uncertainties that may occur in the manufacturing process and the use of different modeling techniques. Therefore, it is important to conduct experimental and numerical studies to determine the performance of welded joints and to optimize weld design. In this study, two T weld joint specimens, 20 mm and 30 mm in length, were prepared using S960QL UHSS. Loading was carried out by attaching strain gauges to the samples, and normal stress values varying over time were measured. Different finite element analysis (FEA) modeling techniques were prepared, and numerical analyses were performed using Ansys software. The stress magnification factor (km) was determined for different models. As a result of the study, the average km was determined to be 1.05 for stresses above 500 MPa in the modelling technique closest to the experimental study. Error rates and km values were found to be high for values below 500 MPa stress. As a result of the results obtained, modeling techniques were determined to accurately determine the reliability and durability of welded joints in UHSS, Additionally, new km values have been suggested.

Keywords: *Stress Magnification Factor; Welded Joints; Finite Element Analysis; Ultra-High Strength Steel*

INTRODUCTION

In recent years, many industries have been increasing the use of UHSS (Ultra High Strength Steels). These steels are special steel alloys that stand out for their combination of high strength and low weight. The use of ultra-high strength steels (UHSS) is on the rise in various industries, thanks to their properties of high strength, good environmental durability, high machinability, low weight, and high wear resistance. These steels allow for the design of structures with smaller cross-sections and reduced weight. As a result, they are widely used in industries such as defence, aerospace, automotive, construction, offshore structures, and shipbuilding [1, 2]. However, the reliability and durability of welded joints of such high-strength steels are often questioned due to uncertainties in the manufacturing process and the use of different modeling techniques.

Welded joints are crucial for ensuring the structural integrity of UHSS. Ultra-high strength fine-grained structural steels, which possess high yield strength, can also provide sufficient material toughness [3]. Welded joints are a method of joining materials and play a critical role in ensuring structural integrity. Therefore, in UHSS welded joints, it is important to evaluate and verify their integrity through proper sample preparation and testing.

A critical factor in determining the performance of joints is a parameter called the stress magnification factor [4, 5]. The stress magnification factor refers to the local concentration of stress in welded joints. Particularly in high-strength materials like Ultra High-Strength Steel (UHSS), stress levels tend to escalate in welded joints, which is a crucial consideration for durability. Therefore, achieving precise determinations of the stress magnification factor is paramount for comprehending the performance of welded joints and enhancing weld designs. The stress magnification factor (km) is a parameter that indicates the local concentration of stress in welded joints. This factor measures how the stress in the weld region varies with respect to the surrounding regions. Stress concentration in the weld zone can

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lead to problems such as stress concentration and crack formation. Therefore, the correct determination of km is important to ensure the strength and longevity of welded joints. km is used in the design and analysis processes of welded joints. In the design of the joint, controlling the stress density at an appropriate level is critical to ensure structural integrity and meet expectations. The km is a factor used to calculate the stress density and reflects how the stress in the weld zone changes compared to the stress in the peripheral zones. Experimental and numerical methods are used to determine km. Experimental studies are carried out by direct measurements with strain gauges or strain sensors. In these experiments, the stress values in the weld zone are determined and used in km calculations. In addition, numerical analysis also plays an important role in the determination of km [6]. Finite element analysis (FEA) models the stress distribution in the weld zone and allows calculation of km. FEA is used to evaluate the impact of different weld designs or material combinations on km. An accurate km detection provides an accurate assessment of the performance of welded joints. This facilitates the correct material selection and determination of welding parameters during the design process. Also, an accurate calculation of km helps predict problems such as possible crack formation or fatigue damage in welded joints [7]. This plays an important role in ensuring structural integrity and reliability.

The analysis and modelling of welded joints are important in ensuring structural integrity. There are many ways to model these connections, but each method may yield different results, affecting the accuracy when assessing the stresses of the welded joint [8]. Incorrect evaluations can cause unexpected damage, especially at the welding toe [9]. Therefore, it is important to choose the correct modelling method and use an appropriate stress magnification factor to calculate the correct stress values [10, 11]. These coefficients are used to calculate predictions for material fatigue or crack propagation, making them important for material selection and design optimization. Stress magnification factors can be determined by changing the dimensions in the weld geometry [12, 13]. The determination of these values is made by comparing experimental studies with FEA results [14, 15]. As the use of new materials such as UHSS increases, it becomes more difficult to determine accurate stress magnification factors for these materials, requiring further work by researchers to determine the correct coefficients.

The Finite Element Analysis (FEA) welding modeling technique involves creating a mathematical model that accurately represents the geometry and material properties of the weld zone through calculations [16-18]. This model is then subjected to analysis under specific loads to compute stress concentrations within the weld zone. The fundamental principles of FEA revolve around subdividing structural elements into small segments (finite elements) and utilizing mathematical expressions of these elements to calculate stress, deformation, and other physical behaviors. The FEA welding modeling technique offers a comprehensive toolkit for conducting stress analyses on welded joints. This versatile approach allows for obtaining realistic results while considering various weld types, weld parameters, material properties, and geometries. Additionally, it enables the comparison of different weld designs and material combinations to assess performance [19]. An accurate FEA welding modeling technique is indispensable for precisely predicting stress concentrations and deformations within welded joints. This critical step is essential in ensuring structural integrity and optimizing weld design. Furthermore, one of the notable advantages of FEA is its ability to elucidate the influence of various parameters (such as weld sizes, material properties, and loads) during the analysis process, facilitating the identification of optimal design choices.

This study prepared two welded joint specimens using S960QL steel, attaching strain gauges to the samples, and loading them until they broke. Time-dependent stress values were compared with experimental studies and numerical analysis results. Stress magnification factors were extracted according to the analysis modelling types. As a result, new stress magnification factors were proposed for UHSS according to different analysis modelling types. This study contributes to the accurate modelling of welded joints for UHSS, determining new stress magnification factors according to the applied model.

EXPERIMENTAL SETUP AND SAMPLES

The sample used in the study for the determination of natural frequencies was constructed using S690QL high strength steel. For the stress determination, an experimental setup was prepared, which utilized a hydraulic cylinder as an actuator. A pressure sensor in the hydraulic cylinder was used to obtain the force values applied to the sample. Strain gauge sensors were attached to the weld ends of the welded joint specimens to obtain stress values. Dewesoft was used as a data acquisition card and software to obtain data from the sensors. Force values were randomly applied and recorded over time. The force values were increased until the sample was damaged. Figure 1 shows the experimental setup used for the determination of stress values and the Dewesoft software used for data collection.

Two welded joint specimens were prepared using S960QL ultra high strength steel with a weld throat thickness of 5 mm in both samples. While the weld thickness was 3 mm in a study in the literature, 5 mm was chosen according to the test sample here [20]. Additionally, in this study, data was taken only by connecting a strain gauge sensor to the welding toe. Workpiece had a height of 120 mm and a thickness of 20 mm, with a main material thickness of 20 mm and a length of 150 mm. Joint holes were applied to both parts to fix the sample, with a distance of 110 mm between the two connection holes and a hole diameter of 20 mm. The geometric dimensions of the samples were chosen based on a study found in the literature [21]. The piece widths were 20 mm in Sample 1 (SP1) and 30 mm in Sample 2 (SP2), which are also the weld lengths. The parts were cut with a laser cutting machine. After cutting, MAG welding parameters were set to 20-25 volts, 200-210 amperes, a preheating temperature of 100 °C, an advance speed of 30 cm/min, and an 80% Ar and 20% CO_2 shielding gas. The carbon equivalent (Ceq) of S960QL, base material, and workpiece material was calculated according to Equation 1 and found to be 0.54. The preheat temperature was selected based on this carbon equivalent. Aristorod89 (ESAB) was used as the welding filler wire, which has properties similar to those of the workpiece and base material.

$$C_{eq} = C + MN/6 + (CR + MO + V)/5 + (NI + CU)/15 \quad (1)$$

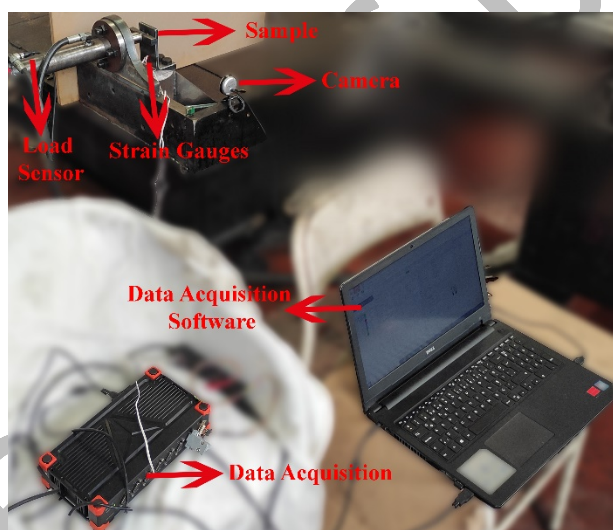


Figure 1. Experimental test setup.

NUMERIC ANALYSIS WELDED JOINT MODELLING

Finite element analysis (FEA) Finite element analysis (FEA) was performed using Ansys 2022 R2 software for numerical analysis. The contact called "share topology" was defined for the welded connections. Three resource models were prepared for comparison: the Weld toe 1 mm radius model (SLD-1) [22, 23] in the effective notch method, the non-radius model (SLD-2) at the weld toe, and only share topology (SLD-3) [24] models without welding geometry [25]. The FEA models of the welded joints were prepared as shown in Figure 2. The force values obtained as a result of experimental studies were defined as force conditions at a distance of 105 mm from the center of the hydraulic actuator cylinder to the welding toe. The boundary condition was fixed support from the connection holes.

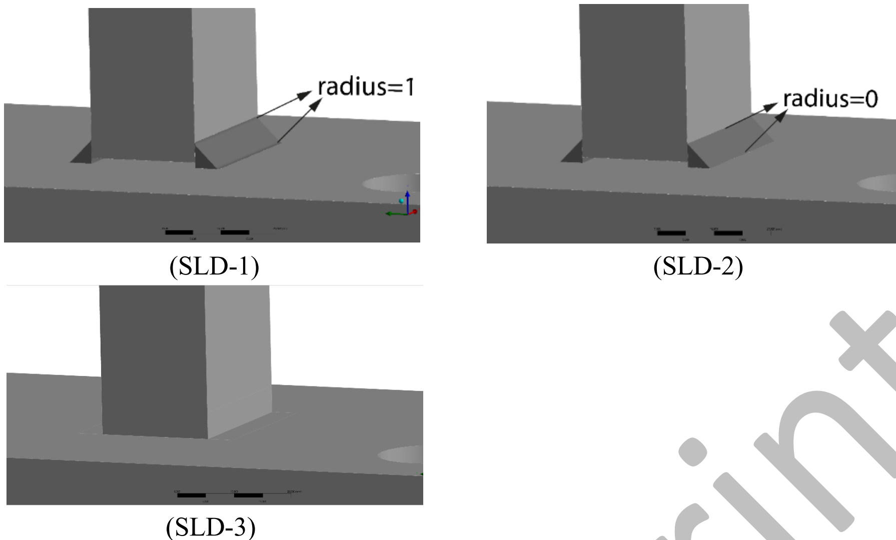


Figure 2. Welded joints FEA Modelling

In the FEA models, all mesh types were represented as 20-node hexahedral and 10-node quadratic tetrahedral elements. The number of mesh nodes and elements varied depending on the models used for SP1 and SP2. For SLD-1, there were 69,497 nodes and 40,997 elements for SP1 and 88,189 nodes and 50,600 elements for SP2. For SLD-2, there were 63,337 nodes and 36,355 elements for SP1 and 78,172 nodes and 43,497 elements for SP2. For SLD-3, there were 26,627 nodes and 16,336 elements for SP1 and 27,004 nodes and 16,324 elements for SP2. Mesh quality was ensured by improving the average element quality criterion, with a minimum quality of 0.8 achieved. The final mesh type, quality, and size were used in the FEA analysis.

RESULTS AND DISCUSSION

In the experimental setup, hydraulic cylinders were connected to SP1 and SP2 samples to apply force. The force was increased until the samples broke, and strain gauge and load cell data were collected over time. To ensure that the duration of both samples was the same, the loadings were increased manually by following the interface and the results were recorded. The parts were damaged with a maximum force of 11,225.24 N in SP1 and 12,620.48 N in SP2. According to the data obtained from the strain gauge sensors, the maximum normal stress was 748.35 MPa in SP1 and 841.37 MPa in SP2. The force and normal stress results of the experimental work carried out until failure are shown in Figure 3. In the experimental study, the fracture of the welded joint under dynamic loading occurred in 186 seconds.

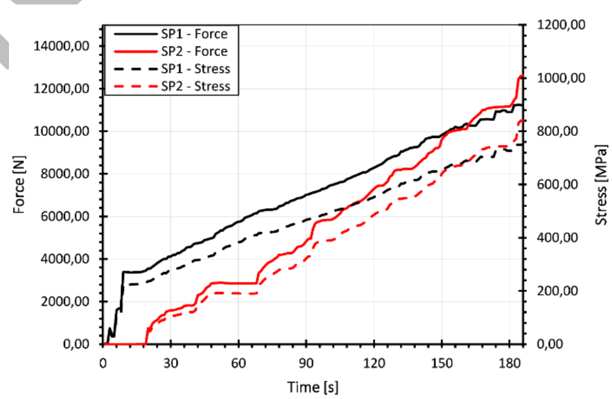


Figure 3. Values of force applied and normal stress values obtained from the strain gauge sensor in the experiment

The force data obtained after the completion of experimental studies, which is time-dependent, was used as the input for the FEA. Separate geometries were prepared for SP1 and SP2, and models such as SLD-1, SLD-2, and SLD-3 were used for both samples, and the force values for SP1 and SP2 were defined. In the numerical analysis performed with FEA, the results according to the color scale for SLD-1, SLD-2, and SLD-3 compared to SP1 are shown in Figure 4. The stress scale distribution of the models according to SP2 is also similar to the scale in SP1. Time-dependent strain results of SP1 and SP2 are shown in Figure 5.

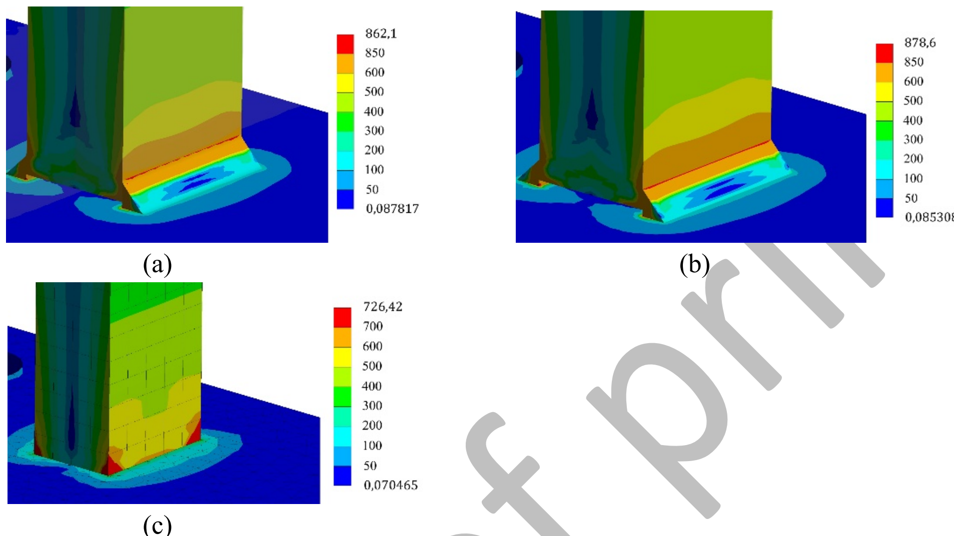
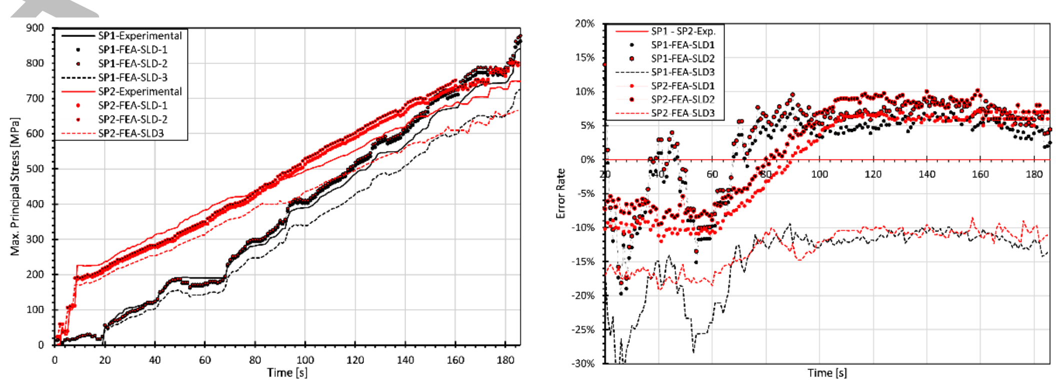


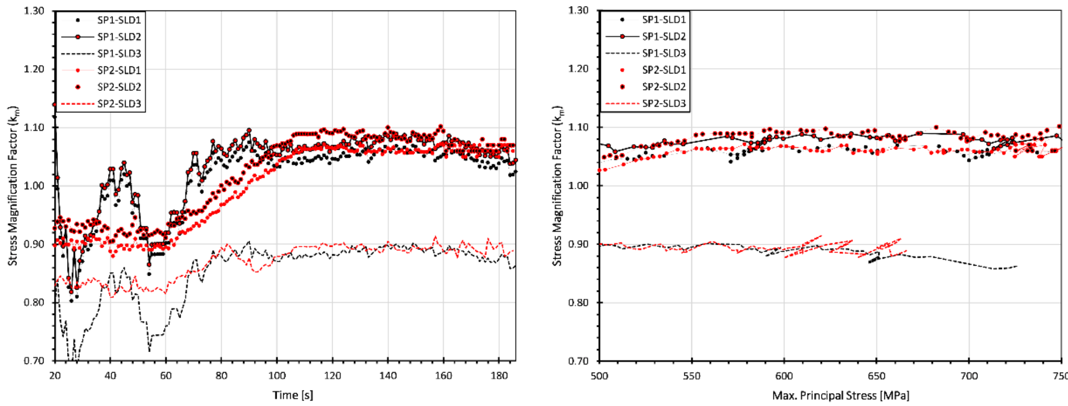
Figure 4. FEA analysis results at 186 s (a) SP1-SLD-1 (b) SP1-SLD2 (c) SP1-SLD3

Stress distributions are equally distributed at the weld end in SLD-1 and SLD-2. In SLD-3, it seems to be more intense at the edges. Definitions were made with share topology to combine weld geometry modeling with other structures. In the experimental study, cracks were observed at the weld end where the stress was high in SLD-1 and SLD-2. As a result of numerical analysis, the stress values at fracture for SP1 were determined as 862.1 MPa in SLD-1, 878.6 MPa in SLD-2, and 726.42 MPa in SLD-3. In SP2, normal stress values were determined as 801.93 MPa in SLD-1, 807.6 MPa in SLD-2, and 666.01 MPa in SLD-3. Since there were different loadings depending on time, different stress values were found at each time. Accordingly, stress magnification factor values also differ.

Differences between the experimental study and numerical analyzes were also identified. Average differences were taken based on the entire loading time. Mean differences were determined at SP1 as 1.29% for SLD-1, 3.23% for SLD-2, and -14.74% for SLD-3. In SP2, the mean differences were -0.15% for SLD-1, 2.20% for SLD-2, and -12.98% for SLD-3. The numerical analysis weld model closest to the experimental study was determined as SLD-1. Figure 5(a) compares the experimental studies with time-dependent maximum principal stress values obtained as a result of the FEA analysis. Figure 5(b, c, d) shows the error rates and stress magnification factors.



(a) (b)



(c) (d)

Figure 5. Comparison of experimental and numeric analysis (a) Maximum principal stress (b) Error rate (c) Stress magnification factor (d) Stress magnification factor above 500 MPa

After comparing the results, stress magnification factors were found to be 1.05 in SP1 for the SLD-1 model and 1.05 in SP2, 1.07 in SP1, and 1.09 in SP2 for the SLD-2 model for stresses above 500 MPa. The variation was observed for stresses below 500 MPa and stable results were not obtained. Therefore, when examining the dynamic stress state of ultra-high strength steels, stresses below 500 MPa should be carefully analyzed. For such cases, stress magnification factors between 0.9 and 1.10 can be used for the SLD-1 model. However, for the SLD-2 model, there may be uncertainties due to singularity stresses. Examining the weld end by creating a radius provides more accurate results by reducing the singularity stresses and using the stress magnification factors. Overall, the SLD-3 model was found to be not consistent with the experimental results. If the SLD-3 model is used, stress magnification factors specified in Figure 5 can be utilized, but this model is not recommended. Statistical data determined as a result of comparing experimental and numerical results are given in Table 1.

Table 1. Statistical data of experimental and numerical results

Stress Range	Statistical Type	SP1-SLD-1	SP1-SLD-2	SP1-SLD-3	SP2-SLD-1	SP2-SLD-2	SP2-SLD-3
Stress 0-750 MPa	Standard Deviation	0.064	0.065	0.053	0.072	0.069	0.029
	Correlation	0.9992	0.9992	0.9992	0.9973	0.9964	0.9988
	Average Error Rate	1.29%	3.23%	-14.74%	-0.15%	2.20%	-12.98%
	Average Stress Magnification Factor	1.013	1.032	0.853	0.999	1.022	0.870
Stress 0-500 MPa	Standard Deviation	0.071	0.073	0.058	0.043	0.039	0.028
	Correlation	0.9979	0.9979	0.9980	0.9907	0.9908	0.9967
	Average Error Rate	-1.30%	0.48%	-16.00%	-7.00%	-4.63%	-14.42%
	Average Stress Magnification Factor	0.987	1.005	0.840	0.930	0.954	0.856
Stress 500-750 MPa	Standard Deviation	0.012	0.012	0.041	0.009	0.013	0.007
	Correlation	0.9975	0.9975	0.9975	0.9978	0.9942	0.9954
	Average Error Rate	5.13%	7.14%	-13.53%	6.03%	7.93%	-10.67%

	Average Stress Magnification Factor	1.051	1.071	0.885	1.048	1.068	0.880

As a result of the comparison of experimental and numerical analyses, different stress magnification factor values were determined in different stress ranges. In some studies in the literature, it was examined especially for misalignment values and different stress magnification factor values were determined [13, 26]. Stress magnification factor values can also be found according to different misalignment values. IIW recommends stress magnification factor parametric formulas according to different misalignment stress values [10, 11]. For a fillet weld, it recommends a value of 1.20 if it does not exceed certain criteria. In this study, it was found to be 1.051 for the SP1 sample with the geometry in the approach of the effective notch stress method. There are studies where it varies depending on the thickness of the butt weld, material or misalignment parameters [27-29]. Additionally, different values appear depending on different thickness and weld cooling times [30]. In this study, the length difference between SP1 and SP2 was examined.

CONCLUSION

In this study, dynamic loadings were applied to 2 T-Shape weld joint specimens made of S960QL steel, which is UHSS, until they were broken. In particular, the stress magnification factor value used in fatigue life estimation was determined in this study for the stresses that occur until fracture by taking data from random dynamic loads. Time-dependent normal stress values were obtained using stress measuring devices and these values were compared with weld joint models created by FEA. Three different models were examined in the study: SLD-1, SLD-2 and SLD-3. By comparing the experimental results with the FEA analysis results, stress magnification factors were determined for three different models at different stress ranges. According to the research results, it was found that the SLD-1 model gave more accurate results, especially for stress levels of 500 MPa and higher, with a stress magnification factor of 1.051. It was observed that the average stress magnification factor of the SLD-2 model was 1.071. It is concluded that for normal stress levels below 500 MPa, it is recommended to use a value of the stress magnification factor between 0.85 and 1.10 for both SLD-1 and SLD-2 models. As a result, it has been observed that more accurate stress prediction can be made with geometry definitions using the effective notch stress method. These results provide an important guide for the design and evaluation of weld joints made of S960QL steel in engineering applications.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

NOMENCLATURE

Subscripts

FEA	Finite element analysis
km	Stress magnification factor
$UHSS$	Ultra-high strength steels
Ceq	Carbon equivalent
SLD	Solid model

SP	Sample
IIW	International institute of welding

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