Recent Advances in Ultrasonic Fatigue Testing of Structural Steels and Their Welds

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Abstract. There are limited data on very high cycle fatigue (VHCF) for common structural steels and their welds for over 10 million cycles. The purpose of this continuing research is further development of confidence in accelerated fatigue testing and expertise in the fatigue performance of steel grades S355JR, Q355B, S275JR, S275J2, C45, 080A15 and their welds. The goal of reaching gigacycle fatigue domain is achieved using the ultrasonic fatigue testing at 20kHz. The fatigue samples are prepared for two main purposes: (1) to investigate the frequency sensitivity of parent metal, and (2) to capture the geometric stress concentration at the weld toe in welded samples. Fatigue failures in the parent metal samples are driven primarily by the conventional surface deterioration mechanism typical for VHCF, and all the cracks initiating at the weld toe captured by fracture mechanics in the welded samples. All obtained fatigue testing results are important for further adaptation of accelerated fatigue testing at 20kHz to the design practices and codes applied to the welded structures operating at normal loading conditions ~15-20Hz.

Introduction

Unalloyed low-carbon steel grades S355JR, Q355B, S275JR, S275J2 (EN 10025) are common structural materials for the heavy machinery in minerals, sand & aggregate applications. A medium carbon steel C45 (EN 10083) offers exceptional tensile strength, a key feature for components that must withstand intense forces, with a good machinability similar to that of mild steels, however reduced weldability. Steel 080A15 (EN10277) is a mild steel for general engineering use with weldability characteristics, but poor hardenability, therefore suitable for the production of low-stressed components such as shafts, gears and threaded bars. Currently, heavy machinery components are designed with high safety factors against SN curves with an assumed asymptotic fatigue limit above >10^7 load cycles. Nevertheless, fatigue cracks are seen even at the high number of cycles (>10^8), producing a big data scatter (over an order of magnitude) as the stress reduces. While high-cycle fatigue failure occurs at the surface, fatigue cracks at the very high number of cycles (>10^8) may initiate at oxides or intermetallic inclusions below the surface (or slag and flux inclusions for welds) typical for Very High-Cycle Fatigue (VHCF) regime. Recently, comprehensive ultrasonic fatigue (USF) testing results have been published for S275JR+AR [1] with insights into corrosion, mean stress and frequency effects. The frequency effect is a commonly encountered challenge in USF testing of low-carbon steels, that was investigated using two comparable grades of ferritic steels Q355B and S355JR+AR [2]. However, the fact is that availability of data on the fatigue behaviour of welded joints in the VHCF regime is limited, which was addressed in the review [3] that provides perspectives on future directions of investigation with the aim of encouraging further research in the field of VHCF of welds. An important progress for USF testing of structural steel welded joints has been achieved [4] by designing the sample that includes a realising joint geometry with a weld toe. So this presentation will report on the further progress in adaptation of accelerated fatigue testing results for structural steels and welds to the existing design practices.

Frequency sensitivity effect

It is known that the increased testing rate and corresponding reduced test duration inherent in USF testing can have a significant influence on the fatigue response of the tested material. Particularly, for Body Centered Cubic (BCC) materials such as ferritic steels, the dislocation glide mechanisms are known to be very sensitive to strain rate, leading to the material appearing to be much stronger when tested at ultrasonic frequencies. This results in the apparent fatigue resistance of structural steels being much higher in USF testing than at conventional frequencies. Until a method can be used to estimate and correct this frequency discrepancy, the resultant USF data for structural steels is of limited practical use.

In this experiment, the fatigue response of several structural steel grades: S355JR, Q355B, S275JR, S275J2, and C45 were evaluated at 20kHz frequency using a Shimadzu USF-2000A machine using samples geometry in Fig.1a, and at conventional 20-50Hz frequencies using an Instron Electropuls E3000 testing machine using samples geometry in Fig.1b for S355JR and Fig.1c for Q355B. Test parameters such as the specimen geometry and test temperature were kept consistent between the two frequencies to limit the difference in test conditions to just the test frequency. Additionally, high strain rate tensile tests were carried out to evaluate how the materials' strength vary with strain rate.

The frequency sensitivity was evaluated for each of the tested materials based on both the finite life region and the fatigue limit value of the SN curves. Several previously proposed frequency sensitivity models from literature were evaluated for the tested materials, along with empirical comparisons. The accuracy of these models applied to the tested materials is discussed.

VHCF of structural steel welds

Welds are of high importance when considering the structural integrity of cyclically loaded components, as stress concentration regions, inhomogeneous microstructures, residual stresses, and defects that they may incorporate make them susceptible to fatigue failure. Presently, welded structures and components have service lives in the VHCF regime across a range of industries, but there is a lack of research and information provided in design standards concerning the fatigue behaviour above 10^7 stress cycles. Initially this research addressed the design of a novel specimen which captured the geometric stress concentration at the weld toe, as an alternative to typically used cylindrical "hourglass" shaped specimens. The gas-shielded flux-core arc welding method was used to manufacture butt joints of 080A15 structural steel. Those specimens were tested in fully-reversed axial loading at room temperature, and proved the validity of the suggested samples design. Currently this research focuses on the VHCF behaviour of butt-welded joints of S275J2+N structural steel plate, joined with flux-cored and metal-cored arc welding methods. Both welding methods are variants of the widely used gas-metal arc welding method and offer high quality joints with increased productivity. USF tests were conducted up to a runout of 5×10^9 stress cycles using fully reversed cyclic loading at 20 kHz. Testing results are presented alongside complementary metallography, microhardness and fractography results, as show in Fig.2. Ultimately, a comparison of the VHCF behaviour of the welds joined using the two different weld methods is presented.

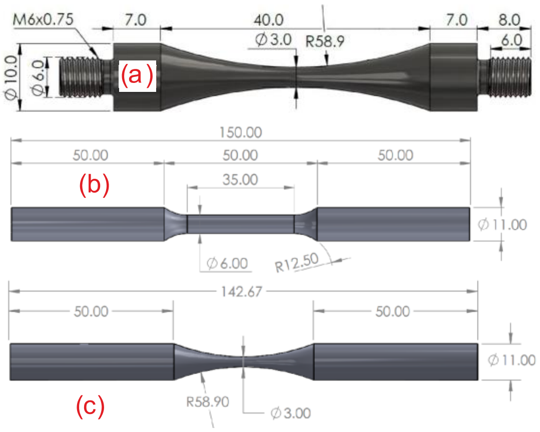

Figure 1: Dimensions of the (a) USF testing specimen; (b) S355JR 20Hz specimen; and (c) Q355B 20Hz specimen.

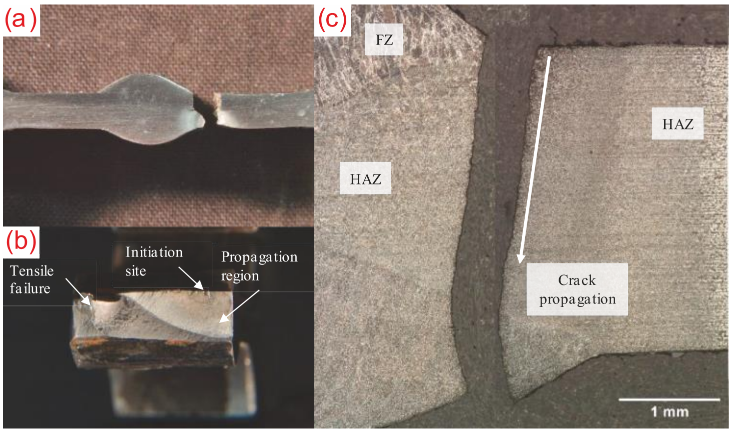

Figure 2: Fractography of failed specimens: (a) side view showing characteristic failure from weld toe; (b) fracture surface; (c) cross-section transverse to crack propagation direction.

Conclusion

In this research, the fatigue results for several grades of structural steels were evaluated at conventional 20Hz test frequencies and at 20kHz test frequencies. Several different methods were applied to evaluate the frequency sensitivity of the materials and to relate the USF data to the conventional frequency data. By comparing the frequency sensitivity results for the tested materials, alongside similar materials in literature, the influence of the material parameters on the model parameters is investigated. The aforementioned models were also adapted and applied as a correction factor to the USF data to attempt to relate the USF response to conventional frequency fatigue response, with the efficacy of this approach being discussed.

The proposed novel specimen design detailed herein, which included the weld toe in the region of highest stress, was shown to be suitable for USF testing and studying the fatigue properties of structural steel welded joints up to the gigacycle domain. Specimens showed consistent testing characteristics and failed specimens displayed low scatter to a power fit curve. All fatigue cracks initiated from the weld toe and propagated through the HAZ. Future work will include an expanded testing regime and comparator fatigue tests with the same specimen geometry at conventional frequency (20 Hz) to assess the frequency effect with this material and welded specimen design.

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References

[1] Y. Gorash, *et al.*: *Ultrasonic Fatigue Testing of Structural Steel S275JR+AR with Insights into Corrosion, Mean Stress and Frequency Effects*, MDPI Materials, vol. 16(5), 1799, 2023. https://doi.org/10.3390/ma16051799

[2] L. Milne, *et al.*: *Application of Finite-Life Frequency Sensitivity Evaluation Methods to UFT of Ferritic Structural Steels*, Procedia Structural Integrity, vol. 57, pp. 365-374, 2024. https://doi.org/10.1016/j.prostr.2024.03.039

[3] A. England, A. Toumpis, Y. Gorash: *Very High Cycle Fatigue of Welds: A Review*, MDPI Metals, vol. 13(11), 1860 2023. https://doi.org/10.3390/met13111860

[4] A. England, *et al.*: *Specimen Design for Gigacycle Fatigue Testing of Structural Steel Welded Joints*, Procedia Structural Integrity, vol. 57, pp. 494-501, 2024. https://doi.org/10.1016/j.prostr.2024.03.054