Evaluation of Frequency Effect for Fatigue using High Strain Rate Tensile Testing

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Abstract. This research addresses the discrepancy in fatigue resistance between the test data for conventional test frequency and accelerated frequency for common structural steels. As the most commonly attributed factor for the difference is the increase in strain rate at elevated test frequencies, high strain rate tensile tests were carried out to evaluate the influence of strain rate on material strength. The tested steels exhibited an increase in yield strength of 28-48% at strain rates corresponding to 20kHz. Normalising the SN curves by the dynamic yield strength was not sufficient to account for the discrepancy in fatigue resistance, however, pointing to the existence of some other factor influencing the frequency sensitivity.

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. In the beginning of this research, comprehensive ultrasonic fatigue (USF) testing results have been published for S275JR+AR [1] with insights into corrosion, mean stress and frequency effects. Recently, the summary of the research outcomes [2] were published with focus on the fatigue performance comparison of the steels S355JR+AR and S275JR+AR considering welding and surface effects, specifically welding porosity and pitting corrosion. The availability of data on the fatigue behaviour of welded joints in the VHCF regime is limited was shown in the review [3]. Also USF testing has been proven [3] to be a viable method to study the VHCF of welded joints in a reasonable timeframe. An important progress for USF testing of structural steel welded joints has been achieved by designing the sample that includes a realising joint geometry with a weld toe. It was applied to study the VHCF behaviour of S275J2+N flux-core arc welded joints [4] using the USF testing method. An important part of the accelerated fatigue testing is the evaluation of the frequency effect, which is critical for a wider adoption of the USF testing method as a reliable approach to investigate fatigue. 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]. More recently this investigation extended to include other steel grades (S275JR+AR, S275J2+N and C45) and establishing the relation between frequency effect and various material attributes like ferrite content, yield strength, UTS, etc. So this presentation will report on the further progress in understanding and evaluation of frequency effect with focus on recently obtained experimental results for high strain rate tensile testing of structural steel grades.

High strain rate tensile testing

To investigate the influence of strain rate on the material properties of the steels of interest, high strain rate tensile testing was carried out in conjunction with the Henry Royce Institute in Manchester, using a Zwick HTM 5020 High-speed Testing Machine, which is capable of carrying out tensile tests from 0.2m/s to 20m/s. High strain rate tensile tests were successfully carried out for the S275JR, S355JR, S275J2 and C45 materials following the procedure in the standard BS EN ISO 26203-2. Specimens were a custom dual gauge length dog-bone specimen shape. Tests were carried out at 0.2, 2, 6 and 18 m/s, which corresponds to nominal strain rates of 10, 100, 300, and 900 s^{-1} respectively in the smaller gauge section of the specimen. Strain was measured using DIC with a speckle pattern painted on the specimen's surface shortly before testing. A Photron SA1.1 FastCam high-speed camera was used with a Nikon 24-85mm zoom lens. To process the DIC data, Zeiss Inspect Correlate was used. Once DIC strain measurements were aligned with the stress measurements from the load cell, the full stress-strain curve could be plotted. A representative set of the results for S355JR at each test rate is given in Fig.1. To extract useful values from the stress-strain curves, curve smoothing was therefore necessary. To achieve this, the plots were split into 3 regions as shown in Fig.2: the elastic region, the yield plateau region, and the plastic region.

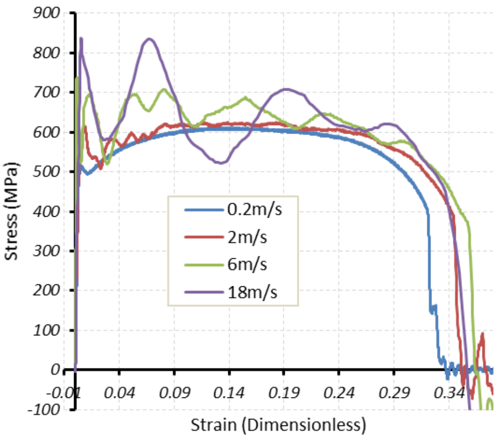

Figure 1: Stress-strain curves for S355JR.

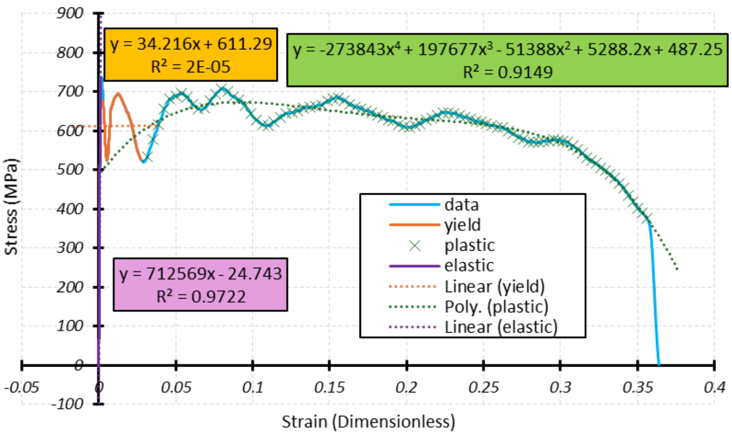

Figure 2: Curve smoothing approach demonstrated on S355JR sample at 6m/s.

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.
The fatigue response of several structural steel grades was evaluated at 20kHz frequency using a Shimadzu USF-2000A machine and at conventional 20-50Hz frequencies using Instron Servohydraulic 8802 and Instron Electropulse E3000 machines. Attempts to characterise the discrepancy in fatigue resistance with test frequency were carried out. As the most commonly attributed factor for the difference is the increase in strain rate at elevated test frequencies, high strain rate tensile tests were carried out to evaluate the influence of strain rate on material strength. The tested steels exhibited an increase in yield strength of 28-48% at strain rates corresponding to 20kHz. Normalising the SN curves by the dynamic yield strength was not sufficient to account for the discrepancy in fatigue resistance, however, pointing to the existence of some other factor influencing the frequency sensitivity. Several frequency sensitivity models from literature were applied to the fatigue results from this investigation and from literature. Generalised forms of the models were developed based on the material properties, with mixed results. These generalised models were applied as correction factors to the USF data, however none were able to reliably match with the conventional frequency results. The most successful correction method was found to be adjusting the exponent of the USF SN curve by a value based on the ferrite content and tensile strength of the steel. This provided a lower-bound estimate of the conventional frequency fatigue curve in all cases, although the degree of difference between the corrected USF and the conventional frequency data was heavily variable.

Conclusion

this research has significantly improved the confidence in carrying out accelerated fatigue testing of structural steel grades which exhibit a pronounced frequency sensitivity. A better understanding of the strain rate effect on material strength and fatigue resistance, alongside its characterisation and quantification is a key achievement of this research. Several methods which allow for the correction of frequency effects were proposed, allowing the application of fatigue data produced at ultrasonic test frequencies to be applied at the frequencies more common in industrial applications.

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