

Ultrasonic fatigue testing of structural steel welded joints

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Abstract. In order to evaluate fatigue properties within the very high cycle fatigue ($>10^7$ cycles) regime in a feasible timeframe, ultrasonic fatigue testing is necessary. This involves exciting specimens at their natural frequency of 20 kHz. As the fatigue performance of welds beyond the conventionally assumed fatigue limit has not been extensively studied, this research aims to investigate the fatigue behaviour of structural steel welds up to the gigacycle (10^9 cycles) regime. A welded specimen that features the toe and root features that fatigue cracks typically originate from was developed. The design process and fatigue results obtained will be discussed.

Introduction

It has been demonstrated in industrial case studies [1] and the technical literature [2] that the assumption of a fatigue limit is not valid for steel welds, with fatigue failures occurring in the gigacycle (1 billion stress cycles) regime. Structures and components across a range of industries have service lives above 10^7 cycles, but there is limited fatigue data in this regime. To perform fatigue tests in the gigacycle regime, ultrasonic fatigue testing (UFT) machines that excite specimens at their natural frequency of 20 kHz are the only practical option. One issue with UFT is that some materials, such as steels with a ferritic microstructure, exhibit a strain-rate sensitivity, where fatigue strengths are typically elevated when assessed at ultrasonic frequencies [3].

Specimen design

Typically for UFT, an hourglass specimen is used and for this shape the dimensions required in order to achieve a longitudinal resonant frequency of 20 kHz can be easily calculated [4]. A small minimum diameter, usually 3 mm, is used in order to minimise specimen overheating during ultrasonic loading. The required machining of this sample type means that when testing welds, the toe and cap regions are eliminated. As these are often fatigue crack initiation sites, a specimen was developed which captures these features in the centre region. The geometry of the specimen was iteratively designed using modal finite element analysis so that it had the required longitudinal natural frequency, as shown in Figure 1.

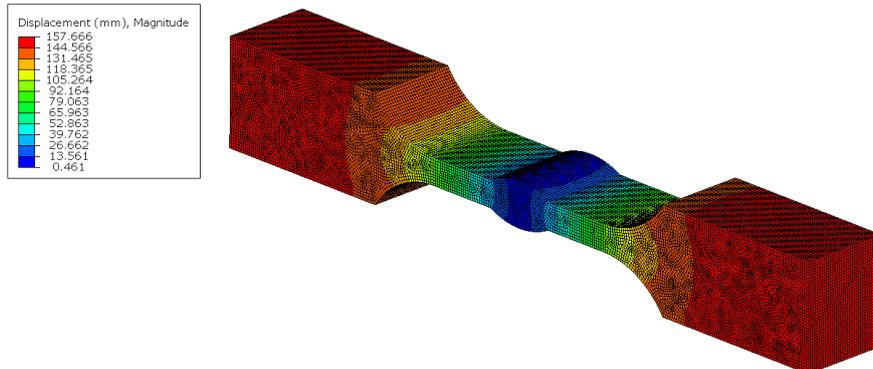


Figure 1: Modal analysis of specimen showing vibration mode at natural frequency of 20 kHz

Ultrasonic fatigue testing results

To test the specimen concept, a pilot study was conducted using EN3B low-carbon steel. Specimens were butt welded using the gas-shielded flux core arc welding process on a semi-automated welding rig. The specimens were tested under fully reversed loading using a Shimadzu USF-2000A testing machine, as shown in Figure 2a. The tests were cooled by compressed dried air and the specimen temperature was monitored using an IR spot sensor.

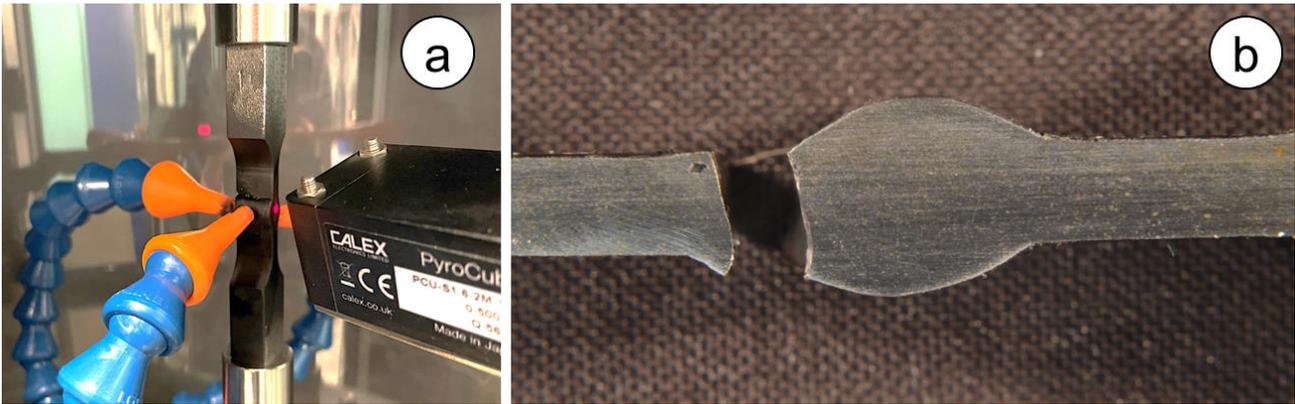


Figure 2: Ultrasonic fatigue testing specimen: a) Testing arrangement; b) Fracture mode in failed specimens

The tests were conducted at 20.04 kHz, therefore there was only an error of 0.2% between the natural frequency of the specimen calculated by finite element analysis and that of the physical specimen. Intermittent driving was applied to the specimens, with the pause times adjusted for the stress amplitude applied. The combination of intermittent driving and air cooling ensured that specimen temperature did not exceed 30°C during testing. All failed specimens displayed crack propagation from the weld toe, as shown in Figure 2b. The results from the pilot study are shown in Figure 3 in an S-N diagram. The fatigue testing results follow an expected trend, and the limited number of failed specimens show good correlation with a power fit. One specimen ran-out at 3×10^9 cycles.

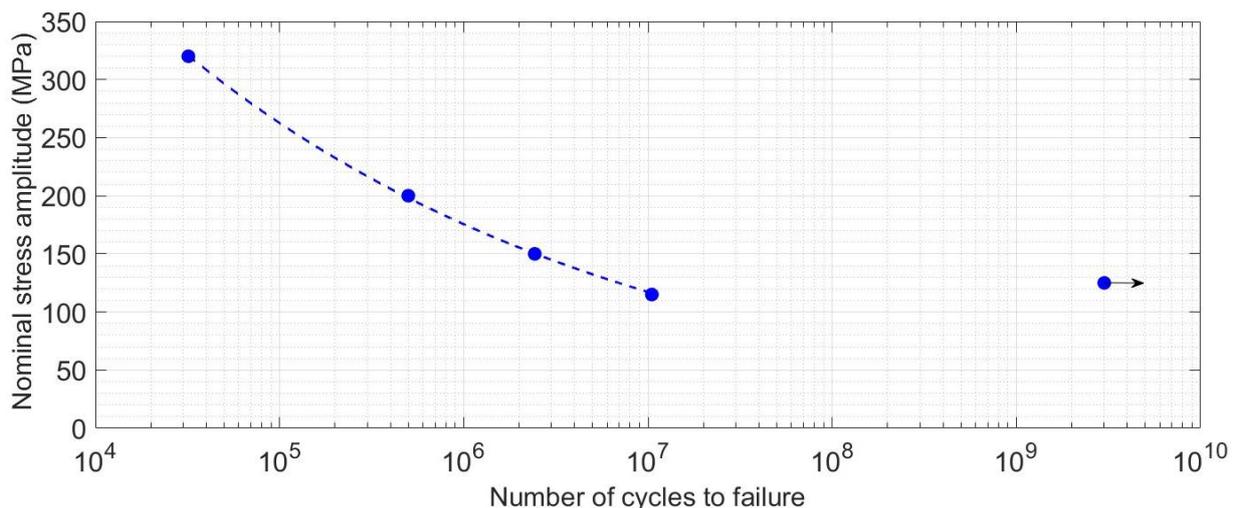


Figure 3: Ultrasonic fatigue testing results SN diagram

Conclusion

A specimen design was developed which allows for study of the gigacycle fatigue properties of as-welded joints. The specimen met the natural frequency and maximum testing temperature requirements of the relevant standard. Further work will investigate an expanded testing regime with a similar grade of structural steel. The strain-rate sensitivity of the welded specimen will be assessed by comparison to conventional frequency (20 Hz) fatigue tests using the same gauge geometry.

References

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