Technical Challenges in Accelerated Very High Cycle Fatigue Testing of Structural Steels and Welds

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Abstract. There is a limited data on VHCF for structural steels and their weldments for >10^7 cycles. The purpose of this research is an investigation of structural steels with the fatigue life duration up to gigacycle domain >10^9 cycles. This is achieved using accelerated ultrasonic fatigue testing of steels and weldments in both as-manufactured and pre-corroded conditions. As ultrasonic testing runs at 20 kHz as a natural frequency of the sample, it creates a number of technical challenges. Amongst them are vibration-induced heating, pronounced frequency effect, temperature control arrangement, machining samples from welds, etc. This presentation will focus on the discussion of the whole set of technical challenges associated with both implementation of ultrasonic testing and interpretation of the obtained results and how they are mitigated.

Introduction

Unalloyed low-carbon steel grades S235, S275 and S355 (EN 10025) are common structural materials for the components made for the minerals and mining applications. Currently, these 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, ultrasonic fatigue testing results have been published for S275JR+AR grade [1-3] that demonstrated a number of effects and technical challenges associated with high frequency of testing.

Heat generation and temperature control

As the heating is a massive challenge for ultrasonic fatigue testing in case of structural steels attributed with a pronounced frequency effect, temperature control arrangement (see Fig. 1) is crucial for proper implementation of testing. The use of VORTEC cold air gun and intermittent driving with load blocks and cooling pauses was required to address the intensive heating. The temperature monitoring is done using PyroCube thermometer by CALEX Electronics that includes infrared temperature sensor PCU-S1.6-2M-1V and touch screen display PM030. To decrease the sampling interval below 1s and implement an emergency test stopping using LabView program when temperature increases over 30°C, PyroCube thermometer has been connected to the PC via NI USB Multifunction DAQ data acquisition card. The duration of the cooling pause (from 0.1 s to 5 s) is selected manually for each test in the test setup to keep it below 25°C.

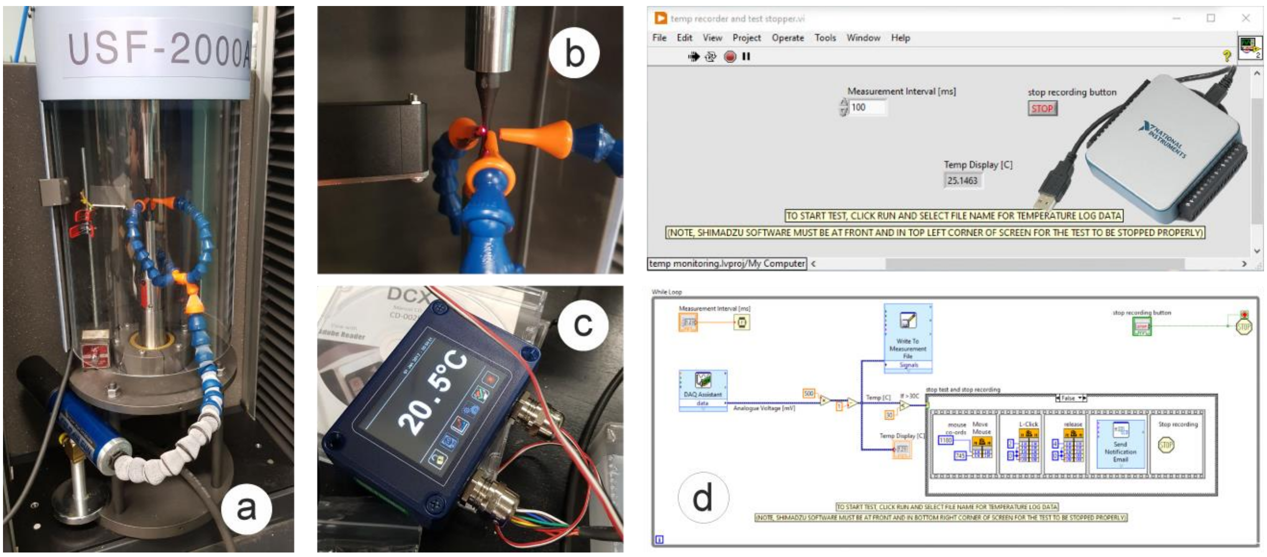

Figure 1: Modified arrangement for temperature control of the ultrasonic test: a) USF-2000A with average stress loading mechanism and VORTEC cold air gun; b) Pyrocube IR temperature sensor; c) touch screen display for PyroCube; d) NI USB Multifunction DAQ data acquisition card and LabView program.

Frequency effect and interpretation of results

Pronounced strain rate effect is a big challenge for the determination of SN curves with accelerated fatigue testing and especially the fatigue limit that strongly depends on the frequency of testing. Testing at 20 kHz using ultrasonic machines significantly exaggerates fatigue strength compared to normal loading conditions. For S275JR+AR steel grade, the quantitative difference between SN curves obtained at 15 Hz and 20 kHz was measured in terms of stress amplitude as 167.7 MPa on average [3].

Other technical challenges

Impact of crack initiation and propagation. The fatigue lifetime before failure can be divided into stages of crack initiation, crack propagation and final fast fracture in most of the metals including structural steels. The assumption would be that higher yield strength improves crack initiation fatigue resistance, which is opposite to higher ductility that improves crack propagation fatigue resistance. Structural steels have decreasing ductility with increasing yield strength, so which grade is better in total life considering environmental effect?

Manufacturing of the samples. The ultrasonic samples are manufactured following the standard WES 111215 with a minimum recommended diameter of 3 mm and surface roughness of 0.8µm in the gauge location. They are designed to resonate at 20 kHz and provide efficient air cooling within the allowable range of horn end displacements. To improve the accuracy of non-contact temperature monitoring, the samples are painted in black matt colour using Rust-Oleum Stove&BBQ spray paint.

Preparation of the pre-corroded samples. To study the effect of corrosion on the fatigue resistance, two batches of pre-corroded samples are prepared. They have the same dimensions, but they are subject to 3.5% NaCl solution as the corrosion medium in 0.5L beakers to simulate “still seawater” treatment. The threads on the ends of the samples were protected from corrosion using RS PRO White PTFE thread seal tape. When taken out of the water, samples have a thick rust layer, but it is not mechanically stable and can be easily washed out. Under a greasy layer of rust pre-corroded sample reveals a nice grey matt surface with an emissivity of 0.3-0.5. The pre-corroded surface is evenly covered with pits, as a result of material loss, that can be seen without additional magnification. The surface roughness of pre-corroded samples was measured using the surface roughness machine Mitutoyo SV 600 and appeared to be Ra=12.6 µm on average after 2 weeks of corrosion and Ra=13.4 µm after 1 month with a variation of ±0:5 µm.

Finding crack origin on the fracture surface. The fracture surfaces are investigated using both using optical stereo-microscopy and SEM microscopy. The advantage of the first method is a capture of surface colouring that help to understand the history of the crack propagation. The disadvantage is uneven focus and variable resolution quality for the whole fracture surface images. On other hand, second method produces a perfect resolution images of the whole fracture surface, but colour information is completely lost.

Noise protection and soundproofing. Working USF-2000A machine is a source of significant level of noise, produced by the attached cooling system. While standard cooling nozzles supplied by Shimadzu produce a moderate level of noise, an additional VORTEC cold air gun increases the noise level to uncomfortable levels when subject to it for a long time. In order to make the working environment in the hosting laboratory safe and comfortable, an additional noise protection is required. This is done by isolating the testing chamber of USF-2000A with the acoustic foam slabs having the thickness of 100mm and the noise reduction coefficient of 1.15.

Conclusion

Parent / dry / pre-corroded / non-zero mean stress conditions of structural steel grades and their welds are investigated. By overcoming multiple technical challenges, confidence and competence in running ultrasonic fatigue tests with Shimadzu USF-2000A has been obtained. The duration of fatigue tests has been extended to 10 billion cycles with a cold-air gun able to reduce the temperature by 45°C. Heat generation remains the most significant technical challenge, but further investigation into more efficient air coolers and water cooling is in progress. Basic quantification of the frequency effect contribution has been done using the difference in stress amplitude between SN curves. Basic extrapolation / down-scaling of the ultrasonic fatigue testing results into low frequency domain can be applied to the data from pre-corroded samples. Fracture surfaces of failed specimens can be examined using both optical stereo-microscopy and SEM microscopy.

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