Evaluation of the Strain Rate Effect in UFT Testing of Structural Steels

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Abstract

Traditionally in the fatigue design of steels, a fatigue limit is considered at around 10^6 cycles, beyond which it is assumed the plastic strain generated within the material is negligible and the fatigue life is therefore infinite. In recent years, however, it has become apparent that this infinite life assumption is not accurate [1]. Thus, to ensure the extended service lives of industrial components, the fatigue behaviour beyond the traditional fatigue limit and into the so-called "very high cycle fatigue" (VHCF) regime must be evaluated. The VHCF regime is typically defined as the 10^6 – 10^{10} cycle region, however testing to this number of cycles using traditional fatigue testing methods is prohibitively time consuming and expensive.

As such, a faster method of fatigue testing has recently been developed, known as Ultrasonic Fatigue Testing (UFT). Through the use of piezoelectric actuation and specimens tuned to vibrate at their resonant frequencies, UFT machines can achieve cyclic loading at 20 kHz. As such, fatigue results can be produced in a fraction of the time of traditional methods, reaching 10^{10} cycles in just 6 days.

UFT, however, has several drawbacks which are yet to be fully understood. Chiefly among these is the strain rate effect. The increased strain rate inherent in the 20 kHz loading will significantly influence the material properties, leading to variations in the fatigue behaviour of the materials which are yet to be fully explored [2,3]. This strain rate effect varies between materials, but is particularly notable in body-centred cubic metals such as ferritic structural steels [2,3]. As such, S-N curves produced through UFT for structural steels are difficult to compare to traditional S-N curves and are as of yet unusable for design purposes. Therefore, until a method can be developed which takes the strain rate effect into account and allows comparison of fatigue data at a range of different frequencies, UFT has limited usability for this ubiquitous class of materials.

The aim of this investigation is therefore to investigate the influence of strain rate on the material properties of several different structural steels and thus quantify the corresponding effect on their UFT behaviour. To achieve this, S-N curves will be produced at a range of different load frequencies for each steel, which will then be normalised with respect to the material properties at the corresponding strain rates. Ultimately, a method will be developed which allows the UFT S-N curve to be related to the traditional S-N curve in order to produce a master curve which can be used for component design in the VHCF regime.

Firstly, a suitable specimen geometry for the UFT test specimens was developed. This was achieved through the use of analytical equations provided with the UFT machine and verified using modal and harmonic finite element analyses using ANSYS Workbench, as shown in Fig. 1, to ensure resonance at 20 kHz. To mitigate any influence from the size effect, the same gauge section geometry was used for testing at all load frequencies. Once designed, the specimens were manufactured by waterjet cutting blanks from steel plates, turning to produce the desired geometry in a CNC lathe and polishing to a mirror finish.

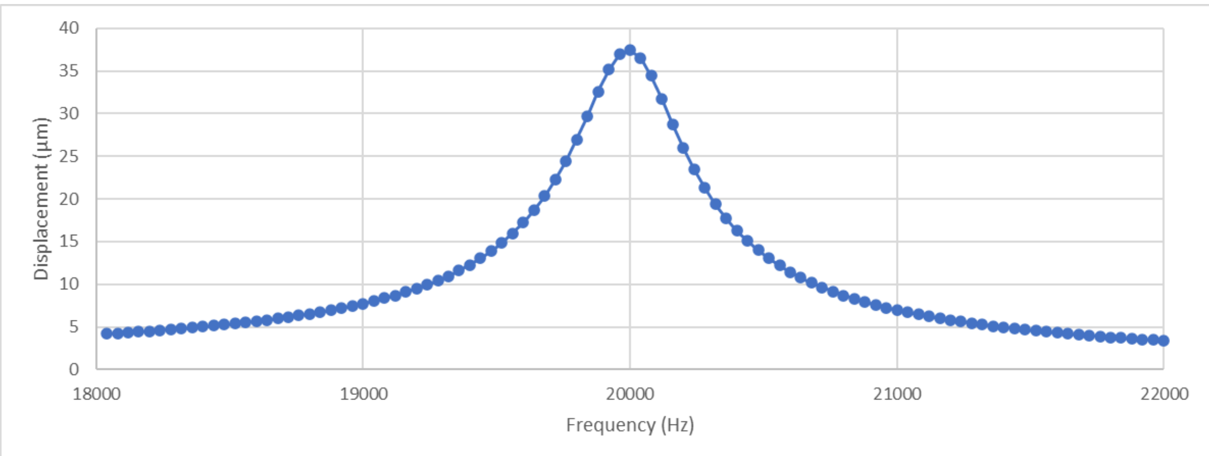

Figure 1: Vibration Amplitude vs Frequency for UFT Specimen

To compare the fatigue behaviour at different test frequencies, specimens of the structural steels were tested under fully reversed loads at frequencies of 20 Hz, 100 Hz and 20kHz using Instron 8801, E3000 and Shimadzu USF-2000A testing rigs respectively. These testing rigs are shown in Fig. 2 below. In order to achieve reversed loading in the E3000 machine, a new set of adapters were designed to allow the use of threaded specimens. To avoid any heating effects in the Shimadzu machine, a cooling system was developed to keep the test temperature below 30 °C. After testing, the difference between the S-N curves at low and high loading frequencies was compared for the different steels, in order to evaluate how the influence of the strain rate varies between the materials.

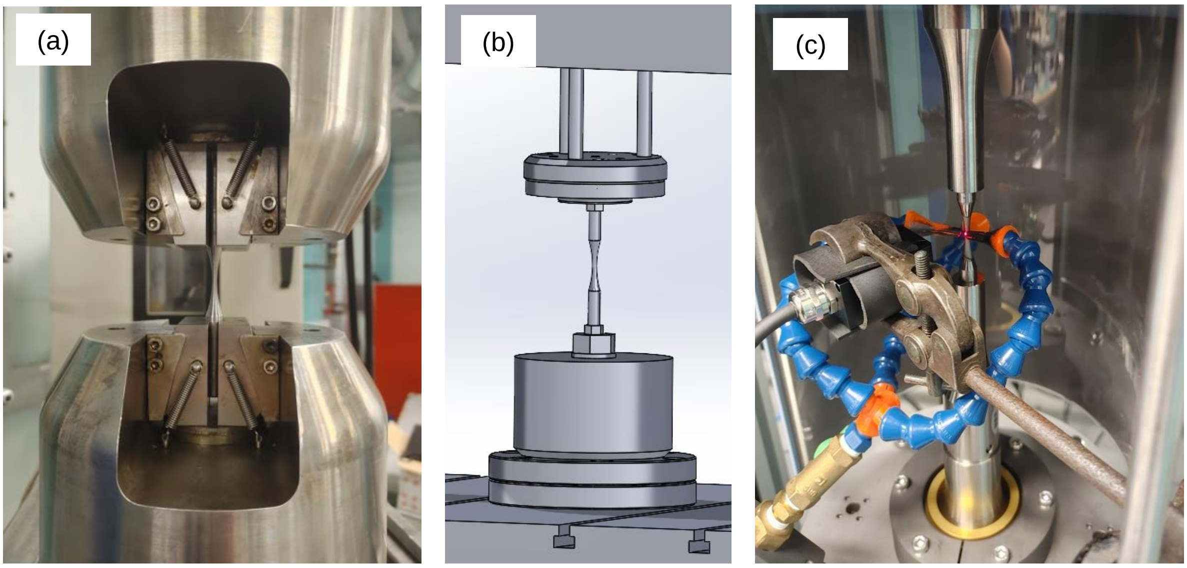

Figure 2: Fatigue Samples in the (a) Instron 8801, (b) Instron E3000 and (c) Shimadzu USF-2000A test machines

To determine the variation of material properties with strain rate, the stress-strain behaviour of the steels will be evaluated at a range of strain rates from 50 - 300 s^{-1} through high strain rate tensile testing. Specimens were manufactured from the material plates through CNC machining and electrical discharge machining the profiles, then grinding to remove any surface microcracks. From the results, the locus of material properties such as yield strength and ultimate strength will be plotted against the strain rate, producing curves which describe how the properties change with strain rate.

The SN curves at different frequencies will then be compared using two methods. Firstly, the SN curves will be normalised to the material strengths at the corresponding frequencies. Additionally, an adaptation of the Johnson-Cook plasticity model proposed by Hu et al. [3] will be derived from the high strain rate test results and applied to the produced SN curves.

References

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