# Effects of Thickness and Varying a/W Ratios on Fatigue Crack Growth Rates at High ΔK for 316 H Stainless Steel

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## Abstract

Assessing the fatigue crack growth rate of components in nuclear reactors can contribute to reactor life extensions and adapted maintenance. However, over conservatism in the recorded crack growth laws can lead to unnecessary costs. It has been observed that the crack growth laws used to inform the design of such components, may not be adapted to their in-situ geometries and stress conditions. Parameters like the crack length over specimen width, remaining ligament length and stress intensity factor range can impact the measured crack growth rates. In this work, large compact tension specimens were used to assess the fatigue crack growth rates of 316H stainless steel at 550 °C at high $\Delta K$. Experiments and simulations of the large specimens were compared to previous data.

## Background

The R5 and R6 design codes inform reactor component design in the UK and are used in conjunction with the R66 material database [1][2]. It was seen that the valid $\Delta K$ range of the crack growth law for stainless steel 316 H in the R66 Database is valid up to 45 MPam$^{0.5}$ [3]. In service, stress concentrations of reactor components can exceed this limit. Previous work on this subject lead to a fatigue experiment using a large compact tension specimen (LC(T)) to observe crack growth rates at $\Delta K$ above this limit, over larger crack extensions, all while attempting to minimise ductile tearing [3]. This was to address the problem that standard constraints on specimen geometry do not allow for the validation of high $\Delta K$ measurements because the required specimen thicknesses become too large to test in practice [4]. Crack growth rates of the LC(T) did not agree with that of the C(T) at intermediate $\Delta K$ [5]. Hence, the aim of this work was to investigate the use of LC(T) as a way to measure fatigue crack growth rates at high $\Delta K$; to see whether their use is valid and meaningful in assessing over conservatism in crack growth laws of design databases.

Previous experimental work has shown that the crack growth rate of 316 H at high temperature increases strongly approaching 45 MPam$^{0.5}$ using a C(T) with an a/W ratio of 0.5 [5]. There were concerns that despite the thickness criterion being obeyed, the relatively large a/W ratio could induce ductile tearing. Following this observation, another experiment was performed this time with a non-standardised LC(T) [3]. The LC(T) was designed to be loaded at a much higher $\Delta K$ predominantly elastically and with a shorter initial defect (a/W = 0.2) over a longer crack growth range. The LC(T) crack growth rates at high $\Delta K$ agreed with low $\Delta K$ elastic C(T) data but did not with C(T) data approaching 45 MPam$^{0.5}$: it seemed that the LC(T) successfully eliminated plasticity effects at high $\Delta K$ at the different a/W ratio.

## Experimental

The experiments aforementioned were reproduced, this time implementing digital image correlation (DIC) to assess plastic deformation at the surface of the specimen and to compare it with simulations. Crack mouth opening displacement was measured using a standard clip gauge. Crack growth was monitored with a potential drop technique, calibrated with a model developed with COMSOL Multiphysics. Fracture surfaces were analysed via microscopy to check for tearing, crack tunnelling and final crack lengths.

## Simulation

The C(T) experiments were reproduced in fatigue simulations via a node-release method in Abaqus [6], to extract plastic zone sizes which could confirm the validity of the LC(T) and enquire on that of the C(T) data at various $\Delta K$. This was done using 2D meshes in plane strain, to check the plastic zone sizes against requirements, and plane stress conditions, to compare to DIC. A crack growth incrementation study found that the incrementation sensitively affects the resultant stress field and plastic zone size as the crack is grown, so the elements size had to be selected according to experiment crack growth incrementation. The LC(T) fatigue simulation was run over a $\Delta K$ range of 60 to 85 MPam$^{0.5}$ while the C(T) simulations were done over a range of 12 to 20 MPam$^{0.5}$ and 38 to 60 MPam$^{0.5}$. The C(T) plastic equivalent strain contour at intermediate $\Delta K$ on initial loading is shown in Figure 1, which highlights that the plastic zone size at the start of the fatigue cycling is already excessive. This suggests that the R66 crack growth law is influence by ductile tearing. The a/W ratio of 0.5 and remaining ligament length W-a were compared to the following LC(T) simulation.

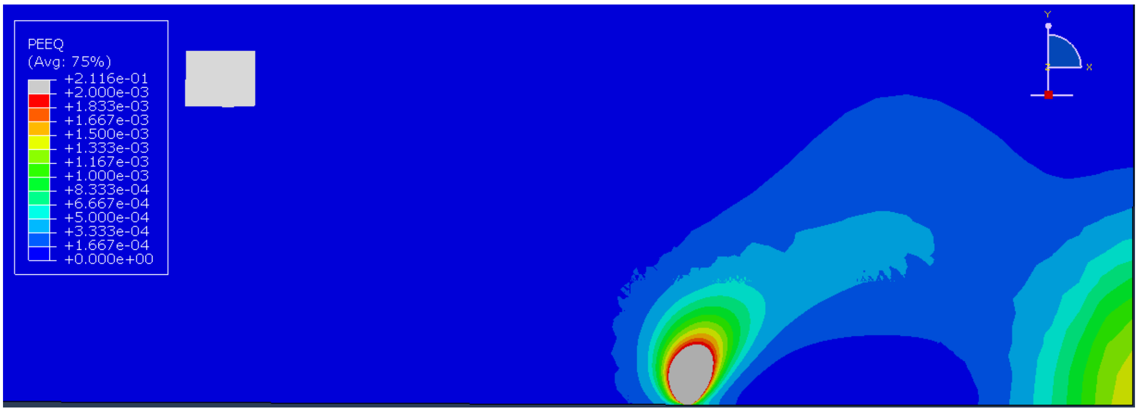

*Figure 1: Plastic equivalent strain contour of the CTS simulation at $K_{max}$ = 38.3 MPam$^{0.5}$ and a/W = 0.5 in plane strain. The contour limit is set to the 0.2% plastic strain. The plastic zone size is 2.5 mm tall: too large to consider the specimen in small scale yielding compared to a net thickness of 15.20 mm.*

The LC(T) simulation was run at an a/W ratio of 0.2 and with a much larger remaining ligament length compared to the C(T). Figure 2 shows that the LCTS did not eliminate plasticity effects as was expected. Nevertheless, the recorded crack growth rate for the LC(T) still agreed with the theoretically elastic crack growth law, which warrants further investigation into the effects of the a/W ratio and remaining ligament lengths.

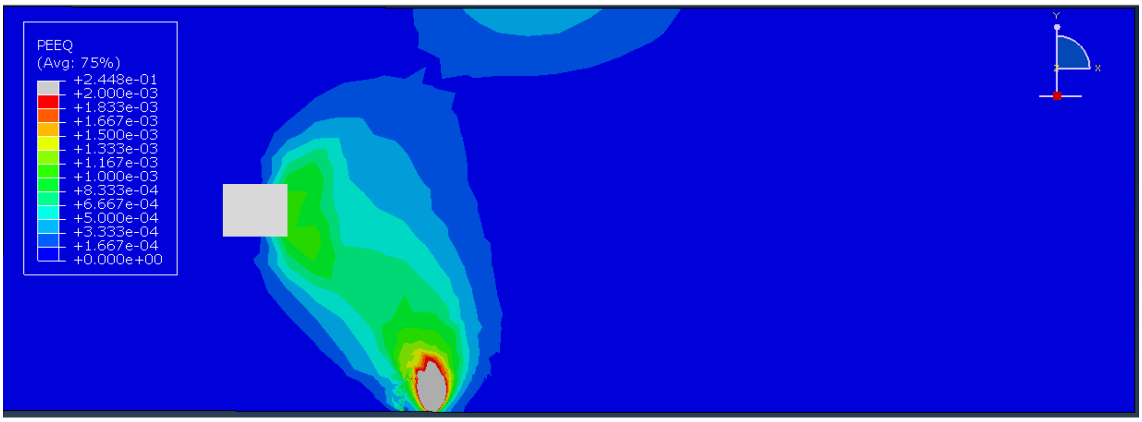

*Figure 2: Plastic equivalent strain contour of the LCTS simulation at $K_{max}$ = 60 MPam$^{0.5}$ and a/W = 0.2 in plane strain. The contour limit is set to the 0.2% plastic strain. The plastic zone size is 8 mm tall which invalidates the specimen net thickness of 25 mm.*

## Conclusion

In this work, the use of a large compact tension specimen in fatigue at high $\Delta K$ was investigated by comparing new simulations and experiments to previous data. The plastic zone sizes were used to confirm whether fatigue crack growth rate data incorporated ductile tearing. Experimental DIC data was used to verify the simulated plastic zone sizes at the crack tips.

## References

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