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Composite repairs to bridge steels demystified

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ABSTRACT

This paper examines crack growth associated with carbon fibre reinforced plastic (CFRP) repairs to cracked bridge steels and boron epoxy composite and fibre metal patch repairs to cracked aluminium alloy structures. It is first shown that the da/dN versus ΔK curves associated with bridge steels is very similar to that seen in the high strength aerospace steel D6ac. The importance of 1st ply failure, which was first observed on a boron epoxy repair to the F-111 D6ac steel wing pivot fitting, and how to alleviate this failure mechanism is then discussed as is the common design approach whereby after patching the repair is designed to have a ΔK beneath the ASTM long crack threshold ΔK_{th}. It is shown that crack growth in bridge steels repaired with CFRP patches and in aluminium alloy structures repaired with either boron epoxy or glare patches exhibit a near linear relationship between the log of the crack length and the number of cycles. We then show that crack growth in these repairs can be represented by the same simple master curve relationship that has been found to hold for cracks growing in both operational aircraft and full scale fatigue tests. These findings are important since they suggest that the methodology used by the Royal Australian Air Force to certify structural modifications to operational aircraft may also be applicable to composite repairs/modifications to steel bridges, which are generally experience significantly lower stresses.

1. Introduction

It is now known [1,2] that the fatigue life of operational aircraft is governed by the growth of lead cracks, i.e. the fastest cracks in the structure, that have the following characteristics, from [1], viz:

i. Typical initial discontinuity sizes are about equivalent to a 0.01 mm deep fatigue crack.
ii. They start to grow shortly after the aircraft is introduced into service.
iii. The majority of the life is consumed growing to a size that can be detected using existing non destructive inspection techniques.

The US Federal Highway Administration Steel Bridge Design Handbook [3] makes similar statements, viz:

a) “.. it is inevitable that cracks or crack-like discontinuities will be present in fabricated steel elements. Thus, the engineer is responsible to consider the consequences of potential fatigue and subsequent brittle fracture. The fatigue behaviour of a fabricated steel structure is controlled by the presence of pre-existing cracks or crack-like discontinuities, which most often occur at welded connections or other areas of stress concentrations. Consequently, there is little or no time during the life of the structure that is taken up with “initiating” cracks.”
b) “Experience in the laboratory shows that as much as 80% of the fatigue life has been consumed by the time a fatigue crack emanating from an internal flaw reaches the surface and can be observed.”

The similarity associated with cracking in bridges and cracking in aircraft is reinforced in Figs. 1 and 2 which shows cracking in a bridge section and cracking in the D6ac steel wing pivot fitting in the 1969 General Dynamics, now Lockheed, F-111 wing fatigue tested under a representative F-111 usage spectrum[1] respectively.

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[1] This example was chosen since the in-flight failure of a F-111 was largely responsible for the USAF adopting a damage tolerance approach [6].

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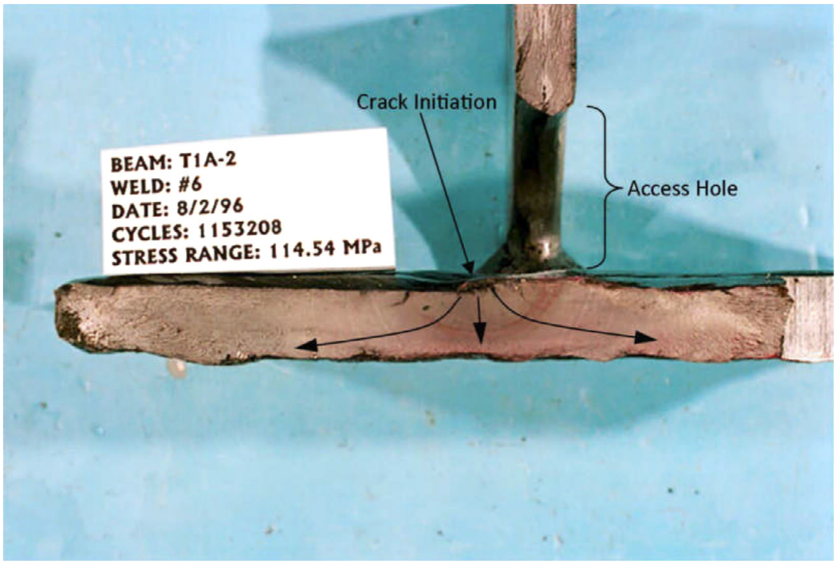

Fig. 1. A typical bridge steel crack, from [4].

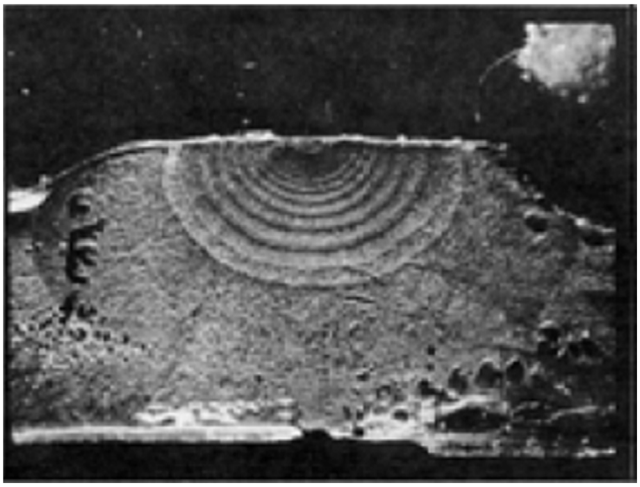

Fig. 2. Cracking in the D6ac wing pivot fitting, from [5].

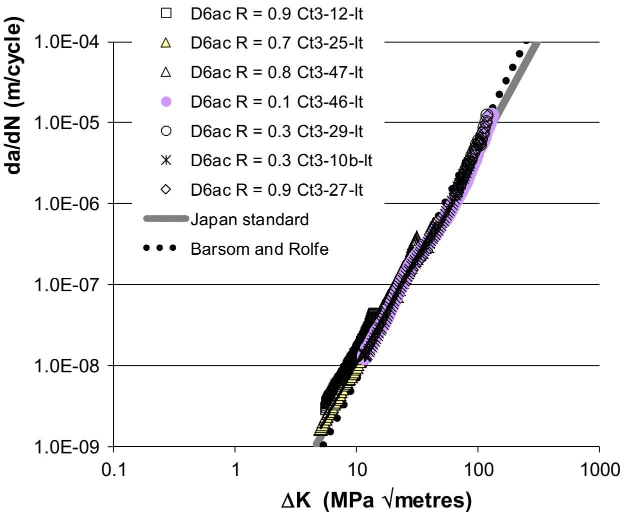

Fig. 3. Comparison of the crack growth curves for D6ac steel and bridge steels.

Both figures show how cracking grew from small sub mm material discontinuities.

Of particular interest is the fact that the da/dN versus ΔK curves for bridge steels are similar to that of the high strength aerospace steel D6ac steel. To illustrate this Fig. 3 presents the da/dN versus ΔK relationship suggested by the Japan Society of Steel Construction (JSSC) [7], viz:

$$da/dN = 1.5 \times 10^{-11} (\Delta K)^{2.75} \tag{1}$$

and the da/dN versus ΔK relationship suggested in [8], viz:

$$da/dN = 6.86 \times 10^{-12} (\Delta K)^{3} \tag{2}$$

together with the da/dN versus ΔK curves presented in [9] for D6ac steel tested at R values that ranged from 0.1 to 0.9.

Here we see that, allowing for experimental error, the da/dN versus ΔK relationship suggested by the Japan Society of Steel Construction (JSSC) and by Barsom and Rolfe for bridge steels are similar and essentially coincide with the experimental data associated with D6ac steel. Furthermore, the da/dN versus ΔK is essentially R ratio independent, as are both Eqs. (1) and (2). The lack of an R ratio dependency means that there is no crack closure and hence that crack growth in bridge steels should not be modelled using crack closure based crack growth equations.

1.1. First ply failure

The similarity between crack growth in bridge steels and operational aircraft coupled with the similarity seen in the crack growth behaviour of bridges steels and D6ac steel is particularly interesting since the origin of the application of bonded carbon fibre reinforced polymers (CFRP) to repair/rehabilitate civil infrastructure can be traced back to the use of bonded patches to repair military aircraft [10–16]. In this context the ability of an eternally bonded composite repair[2] to successfully reduce the strain in the highly loaded[3] D6ac steel wing pivot fitting by approximately 30% [11], the steel wing pivot fitting transmitted the flight loads through

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[2] These doublers were approximately 120 plies thick and took approximately 30% of the load in the critical section of the wing pivot fitting.

[3] The magnitude of the load carried by the wing pivot fitting was such that the critical region experienced strains in excess of 26,000 με.