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Composite Repairs To Cracked Metallic Components- Experiment and Theory

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Abstract: In this paper we show how the published literature reveals that the analytical solution for a composite repair to a cracked metallic plate is inconsistent with experimental data, and that the fibre bridging effect is often a second order effect. The result is that prediction of the effect of a composite repair on the structural integrity of cracked components repaired by an externally bonded composite repair is dramatically simplified.

Keywords: Frost-Dugdale, fatigue crack growth, fatigue testing, composite repairs.

1 Introduction

"The history of science, like the history of all human ideas, is a history of irresponsible dreams, of obstinacy, and of error. But science is one of the very few human activities- perhaps the only one in which errors are systematically criticised and fairly often in time, corrected. This is why we can say that, in science, we often learn from our mistakes, and why we can speak clearly and sensibly about making progress there." Popper *1963* [1]. With this in mind let us now reflect on the science of composite repairs to cracked metallic structures.

There are several methods used to design composite repairs to cracks in thin metallic skins, i.e. typical thickness less than 3 mm. The finite element method was the first to be developed [2], and has been used to design several complex repair schemes, such as the repair of fatigue cracks in the lower skin of Mirage aircraft [3], and cracks on the upper surface of the wing pivot fitting of F111C aircraft in service with the Royal Australian Air Force (RAAF), see [4]. Following the development of this approach Rose [5] proposed that the stress intensity factor for a patched crack approached a constant value as the crack length increased. This approach was based on the premise that, for a sufficiently long crack in a structure which is subjected to a remote uniform stress field, the central region of the patch, i.e. the central section of the patch that lies over the crack, behaves like an adhesively bonded overlap joint. Variants of this idealised solution are discussed in [6].

In recent years the validity of the assumptions underpinning this approximation have been questioned [7-9]. Jones, Barter, Molent and Pitt [7] and Jones and Pitt [9] revealed that the growth of cracks under composite repairs often conforms to the Frost-Dugdale law, and that for small to medium crack lengths, i.e. from ~ 0.1 to 20 mm, the effect of the patch appeared to be dominantly due to the reduction in the stress field in the metallic component. Jones, Krishnapillai, and Pitt [8] subsequently revealed how the crack growth rate in a plate repaired with a composite patch could be predicted using the generalised Frost-Dugdale crack growth law. In this paper we will show that the assumptions inherent in the approximate solutions presented in [5, 6] for crack growth under a bonded composite repair are inconsistent with experimental measurements.

2 Composite Repairs to cracked metallic components

Composite repairs to cracked metallic structures are believed to act in two fashions:

1) They reduce the net section stresses in the (cracked) structure.
2) The fibres bridging the crack restrict the opening of the crack faces.

It is widely accepted that for small cracks the reduction in the net section stresses is the primary mechanism reducing the stress intensity factor, and thereby crack growth.

There are very few experimental studies where the stress intensity factor for a patched crack has been directly measured. Most work has attempted to infer the stress intensity factor from crack growth measurements. To the best of the authors' knowledge the work by Baker et al [10, 11] and Aktepe and Baker [12] are the only studies that have attempted to directly measure the stress intensity factor. In

[10, 11] X ray back reflection was used to determine the stress intensity factors in 1.5 mm thick 7075 T6 aluminium alloy specimens patched on both surfaces with a 0.49 mm thick graphite epoxy laminate. Both uncracked and centre cracked panels, with total crack lengths (2a) of 10, 30 and 40 mm, were examined. As a result of this study it was found [10, 11] that the experimentally determined stress intensity factor for a patched plate was given by

$$K = \sigma_T \sqrt{(\pi a)} \qquad (1)$$

where σ_T is the stress field in the skin under the patch, and hence that crack bridging effects were negligible. Unfortunately, the results presented by Aktepe and Baker [12] are questionable since the analysis used in [12] may contain an error, see [7].

This finding was echoed in the recent papers [7-9] which concluded that: For composite repairs to small to medium length through cracks in thin sheets, that have low to mid range ΔK's, where bending effects are negligible the effect of the patch is primarily due to the reduction of the net section stress. To illustrate this we will consider the following test cases.

Case 1: Baker [11] presented the results for crack growth from an initial 5 mm long edge crack in a 160 mm wide and 3.14 mm thick 2024-T3 aluminium alloy specimen patched with a seven ply (0.889 mm thick) semi-circular uni-directional composite patch which had a radius of 80 mm. The specimen was subjected to constant amplitude fatigue testing with a remote uniaxial stress with σ_{max} = 138 MPa and R= 0.1, see Baker [11], Figure 6.23 page 155. The fibres were perpendicular to the crack and as such lay in the direction of the load. Bending, due to neutral axis offset effects, was eliminated by testing two specimens joined back to back. The resultant crack growth data, from [11], is shown in Figure 1. This figure reveals a (near) linear relationship between the log of the crack length and the number of cycles. The initial flaw size used in this test was 5 mm, and the size predicted from the log-linear fit was 4.88 mm.

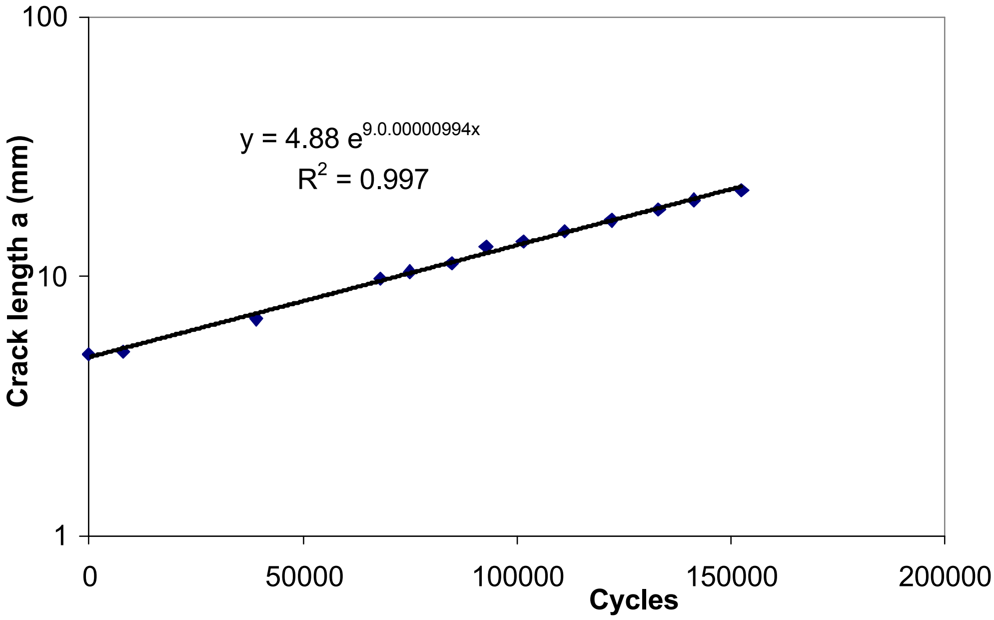

Figure 1 Crack length versus number of cycles, from Baker [11]

Case 2: Baker [13] also presented the test results, in Figure 13.7 on page 385, for the seven ply boron epoxy repair described in Case (1), with the exception that the initial flaw size was 10mm, subjected to constant amplitude loading with Δσ of 76 MPa, but with the R values that were successively increased from 0.1 to 0.55, 0.64 and finally 0.75 as the test continued. The resultant crack growth data is plotted in Figure 2, where it can be seen that as postulated in [13] crack growth was relatively insensitive to the R ratio and that the data is essentially log-linear, i.e. there was a near linear relationship between the log of the crack length and the number of cycles.

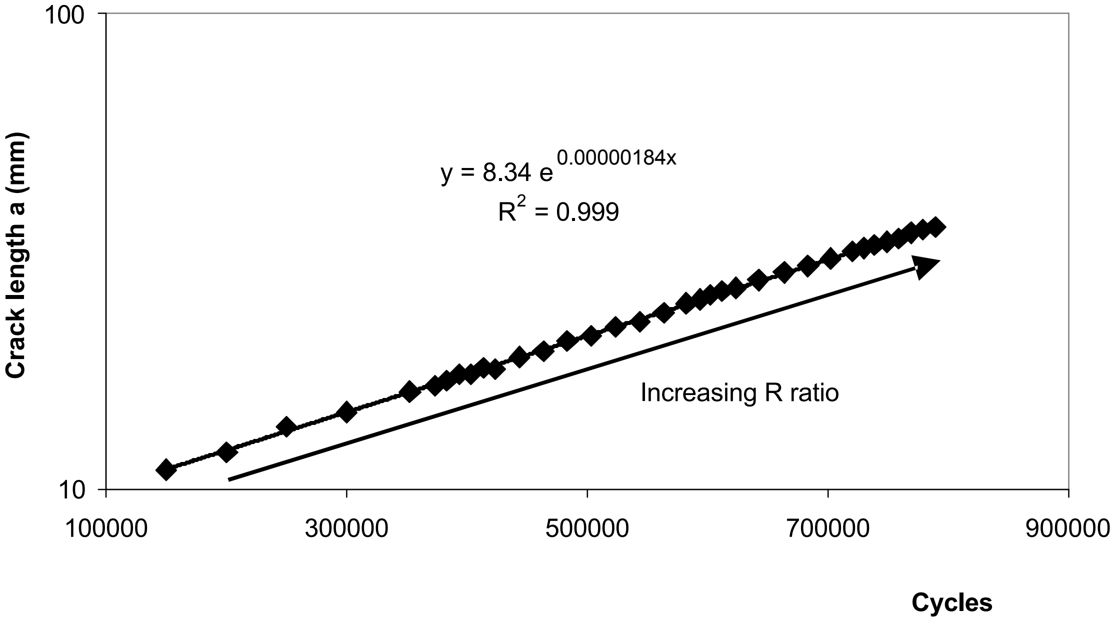

Figure 2 Crack length versus number of cycles for the edge cracked 2024 T3 aluminium plate, repaired with a seven ply boron epoxy patch, under variable R ratio from Baker [13].

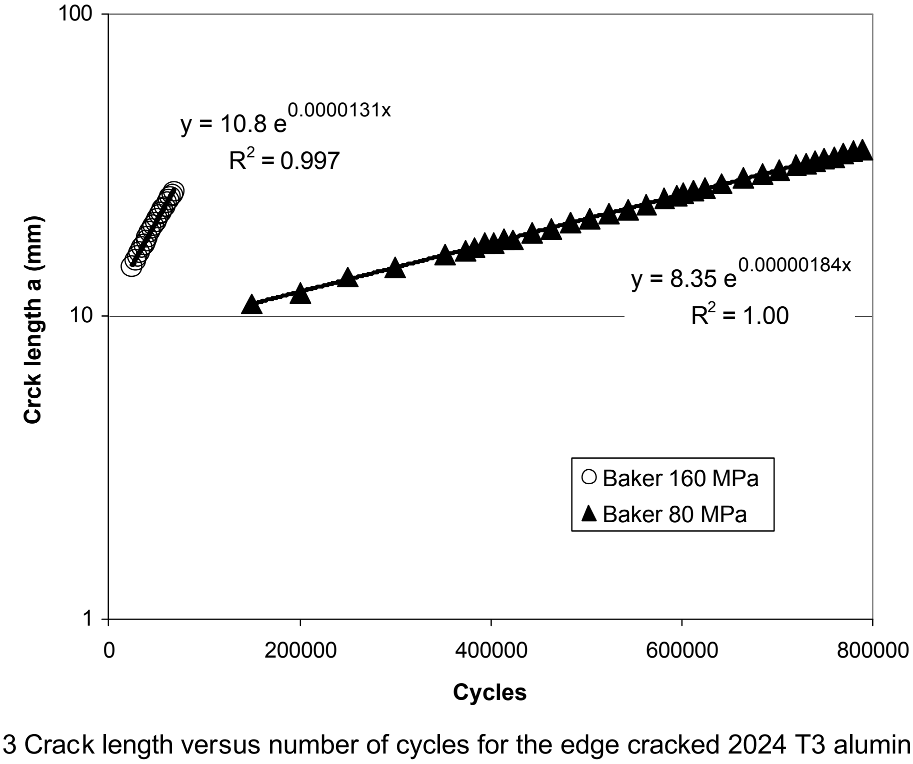

Figure 3 Crack length versus number of cycles for the edge cracked 2024 T3 aluminium plate, repaired with a seven ply boron epoxy patch, with σ_{max} equal to 160 and 80 MPa , from Baker [13].

Case 3: Baker [13] also presented crack growth data for this test specimen geometry with R = 0.1 and various σ_{max} levels, see Figure 13.6 on page 383. The crack growth data for the cases σ_{max}= 160 and 80 MPa, and where there were no inbuilt disbonds, are presented in Figure 3. Here we again see that the measured data was essentially log linear, i.e. there is a near linear relationship between the log of the crack length and the number of cycles.

The above examples show that for small to medium length cracks repaired with an externally bonded composite repair there is a near linear relationship between the log of the crack length and the number of cycles and that this relationship holds for crack lengths (a) in the range 5 mm< a < 40 mm. (In the field of fatigue crack growth the term small crack is used somewhat flexibly. However, it is generally taken to mean less than ~ 1 mm. In this paper we use the term medium length cracks to mean length of the order of 10 mm.) As a result it follows that, as first shown in the extensive USAF test programs outlined in Naboulsi and Mall [14] and Schubbe [15], the increment in the crack length per cycle (da/dN) is essentially proportional to the crack length.

For small cracks it is accepted that the dominant effect of the patch is due to the reduction in the net section stress. The log-linear relationship shown in Figures 1-3, over the range 5 mm< a < 40 mm, which corresponds to a (near) linear relationship between da/dN and the crack length (a), reveals that over this range of crack lengths the dominant mechanism is essentially unchanged. This in turn means that the dominant mechanism is essentially that seen for a composite repair to a small crack, i.e. it is (essentially) due to the reduction in the net section stress beneath the patch. This finding when taken together with the results presented in [10, 11], the experimental results presented above and in [7-9, 14, 15] reveals crack bridging effects to be a secondary effect over this range of crack lengths and hence invalidate the theoretical model presented by Rose and co-workers [5, 6].

When developing this model Rose and co-workers [5, 6] assumed over the crack the stresses in the patch were constant through the thickness of the patch, and that the maximum stresses in the patch occurred over the crack. The experimental and numerical results presented in [16-19] invalidates these assumptions. In [16, 17, 18] it was found that over the crack the stress field in the patch is highly three dimensional, i.e. the maximum principal stress varies through the thickness, and that there is a dramatic reduction in the (surface) stresses in the patch directly over the crack. This conclusion, i.e. that the stress field over the crack in the patched structure is highly three dimensional and that there is a dramatic reduction in the (surface) stresses in the patch directly over the crack, has been confirmed via three dimensional finite element analysis [17, 18] and by strain gauge measurements [19]. In [19] a series of strain gauges were located along a line on the surface of the patch that lay at a distance of 32 mm from the edge of the specimen, see Figure 4, which in this study was as described in Case (1). The gauges, which as mentioned above lay on a line that was perpendicular to the line of the crack, were located at distances of 0, ± 2, ± 4, ± 6, ± 8 and 10 mm from the centre line of the specimen. (As shown in Figure 4 the line of the crack was nominally along the centre line of the specimen.) In this study it was found that the surface fibre strain directly over the crack dropped dramatically as the crack grew underneath the central gauge and that the surface fibre strain in the patch directly above the crack was significantly lower than that on either side of the crack, see Figure 4. As such the assumption adopted in [5, 6] that the stress distribution in the patch resembles the 2D lap joint solution is invalid. Furthermore, the assumption adopted in [5, 6] that over the crack the stress in the patch is constant through the thickness of the patch is also invalid.

To further evaluate that the hypothesis that the stresses in the central region looked like that associated with a lap joint tests were performed on the specimen geometry tested in [11] which contained a 32 mm long edge crack repaired with a seven ply uni-directional boron epoxy patch. This specimen geometry is identical to the edge cracked specimen outlined in Case (1) above except that the (seven ply) uni-directional boron epoxy patch was on the inner surface so that the cracked panel could be monitored during testing. A picture of the bulk stress field in the plate, obtained using lock-in infra-red thermography, for a cyclic remote stress $\Delta\sigma$ = 100 MPa and R= 0.1, near the crack is shown in Figure 5. Here we see that the stress field does not resemble that of a lap joint, i.e. the iso-stress lines are not parallel to the crack. Hence the Rose assumption that the region behaves like a lap joint is invalid.

Noting that the near tip cyclic stress bulk stress ($\Delta\sigma_x + \Delta\sigma_y + \Delta\sigma_z$) can be written as

$$\Delta\sigma_x + \Delta\sigma_y + \Delta\sigma_z = \{\Delta K_1 / \sqrt{(\pi r/2)}\}\cos(\theta/2) + A + B\sqrt{r}\cos(\theta/2) \quad (2)$$

where A and B are constants and r is the distance from the crack tip, it is possible to use the bulk stress data to determine the stress intensity factor. Analyzing the data at an angle θ = 0°, i.e. directly ahead of the crack, we obtained a value of ΔK_1 = 17.9 MPa $\sqrt{m}$, whilst a value of ΔK_1 = 16.0 MPa $\sqrt{m}$ was obtained when analyzing the data along the line perpendicular to the crack plane, i.e. θ = 90°. These values compare reasonably well with the corresponding solution of ΔK_1 = 21.2 MPa $\sqrt{m}$ obtained assuming that the reduction in the stress intensity factor was only due to the reduction in the net section stress. In contrast Aktepe and Baker [12] reported that for this repair configuration to a 30 mm long crack subjected to a remote stress amplitude of 78.6 MPa the Rose solution for this test is approximately ΔK_1 = 6.8 MPa $\sqrt{m}$ so that for a stress amplitude of 100 MPa the Rose solution yields a value of 8.6 MPa √m. Even if we allow for the fact that the crack in this test was approximately 32 mm long we see that the measured values are significantly greater than the value of approximately 8.6 MPa √m obtained using the Rose theory. This is due to the fact that the stress field in the patch over the crack is very three dimensional, i.e. it varies through the thickness of the patch, and the two dimensional approximation used by Rose, which assumes that all of the plies over the crack are equally effective in restraining the opening of the crack, is invalid.

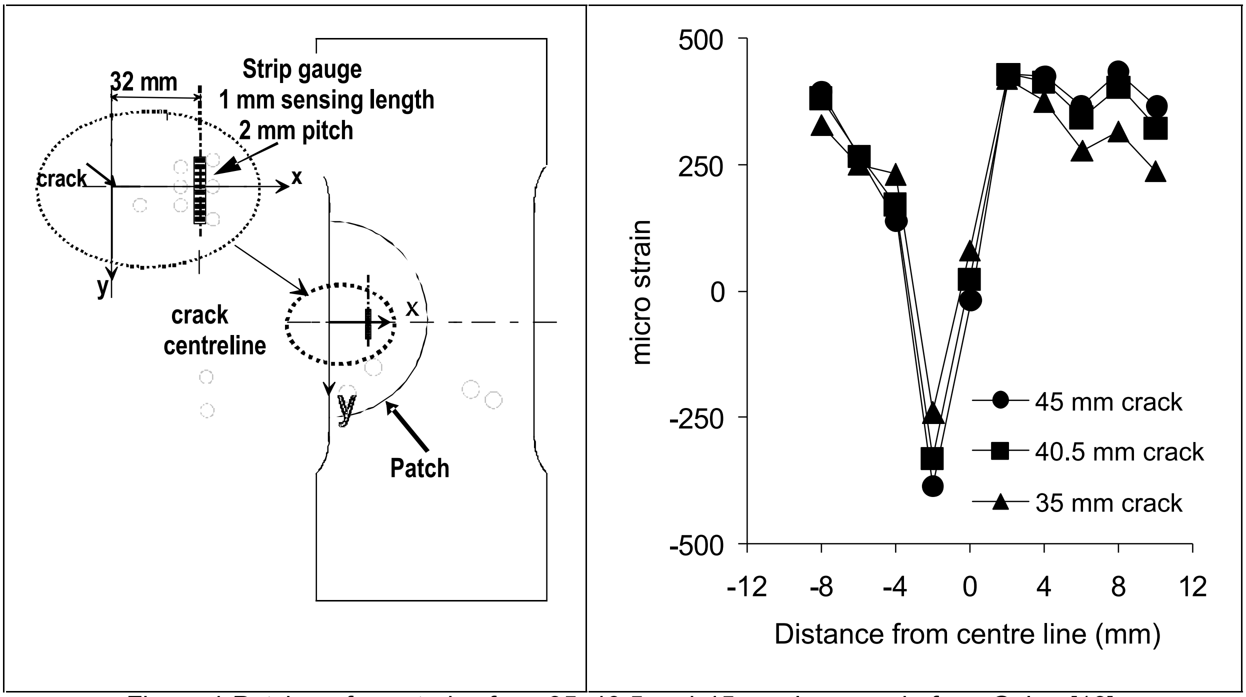

Figure 4 Patch surface strains for a 35, 40.5 and 45 mm long crack, from Galea [19].

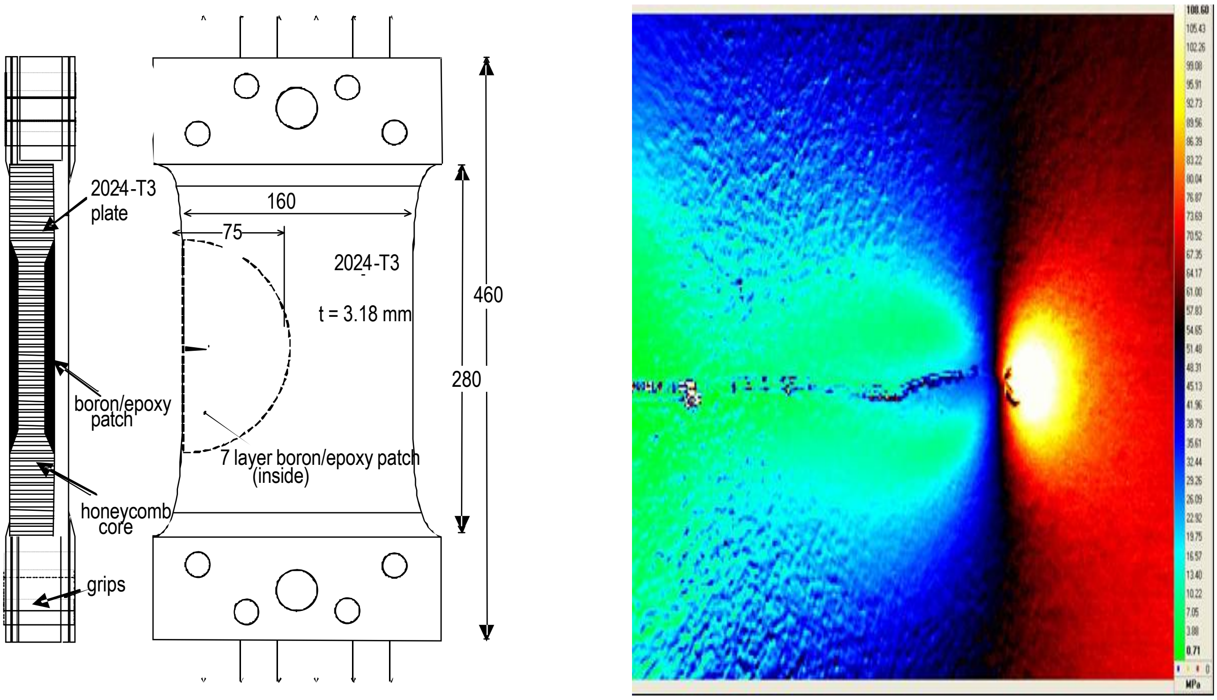

Figure 5 Geometry of the test specimen and the stress field around the crack

This example supports the findings presented in [7-9] that, as a first approximation, crack bridging effects can often be ignored. One advantage of this approach is that the solution will always be conservative. A less conservative approach would be to assume that only the first few plies over the crack play a role in preventing its opening.

3 Conclusions and recommendations

In this paper we have shown how the published literature reveals that the Rose solution for a composite repair to a cracked metallic plate is inconsistent with experimental data, and that for the problems examined in this paper the fibre bridging effect is a second order effect that for practical purposes can be effectively ignored. As a result the prediction of the effect of a composite repair on the structural integrity of cracked components repaired by an externally bonded composite repair is dramatically simplified.

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