LIFE EXTENSION OF AN F/A-18 AILERON HINGE USING BONDED COMPOSITE REINFORCEMENT

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SUMMARY: F/A-18 inboard aileron hinges suffer from a fatigue cracking problem for which the only current solution is replacement of the component. This paper develops an approach which can be used to reinforce hinges that have not yet developed cracks as well as a method for restoring cracked hinges to an airworthy condition. The approach followed is to firstly use structural optimisation to reshape (using reworking) the hinge to reduce the stress concentration in the critical area. The rework profile detailed in this paper includes an allowance for the removal of cracks up to a depth of 2 mm. Secondly, a boron/epoxy composite reinforcement can be adhesively bonded over the reworked profile to further reduce the level of stress in the hinge. The curved nature of the reinforcement induces through-thickness (peel stresses) in the adhesive and these non-typical adhesive stresses have been considered in the design process. This approach is able to reduce the stresses at the critical location by 16% and a reinforced hinge has been tested satisfactorily to design ultimate load.

KEYWORDS: composite reinforcement, structural optimisation, boron/epoxy, adhesive bonding, structural repair, through-thickness stresses, peel stresses.

INTRODUCTION

F/A-18 inboard aileron hinges are susceptible to fatigue cracking in the aft strut fillet due to higher than originally expected flight loads. The hinge and the location of cracking are shown in Figure 1. The cracks are normally detected at less than half the anticipated life of the hinge and there is currently no repair possible for cracked hinges. The only currently accepted solution is to replace the cracked hinge. This procedure is difficult for some operators of this aircraft as the entire aileron has to be sent to the US for the hinge replacement to be undertaken. Because of the lengthy delays and costs involved for these replacements, the present investigation was undertaken to see if it would be possible to repair some of the cracked hinges without removing them from the aileron.

There are several possible ways to address the problem of fatigue cracking in these hinges. The first approach is to reduce the level of fatigue strain in uncracked hinges so as to delay the onset of crack initiation. In this case, depending on the level of strain reduction, it may be possible to extend the life of the current hinges out to the life of type of the aircraft and therefore avoid any further need to replace or repair hinges. For hinges that are already cracked a second approach is necessary. The fatigue cracks would firstly need to be removed and this could be done either without particular concern for the resulting shape of the strut or alternatively by calculating a precise new geometry for the strut which minimises the tensile stresses which cause cracking. This latter approach is known as Structural Optimisation. After the crack is removed, it may then be necessary to reinforce the strut to replace the stiffness that is lost by the removal of material.

Reduction of fatigue strain and reinforcement to replace stiffness lost due to reworking, are both possible through the use of advanced composite materials and adhesive bonding. The so-called Bonded Composite Repair Technology (BCRT) has been pioneered by DSTO-AMRL for many years and used successfully in many repairs to aircraft [1,2]. The significant advantages of bonded composite repairs over conventional mechanically fastened metallic repairs are discussed in Ref. 2. This paper describes the combined use of Structural Optimisation and BCRT to develop a repair for cracked F/A-18 aileron hinges.

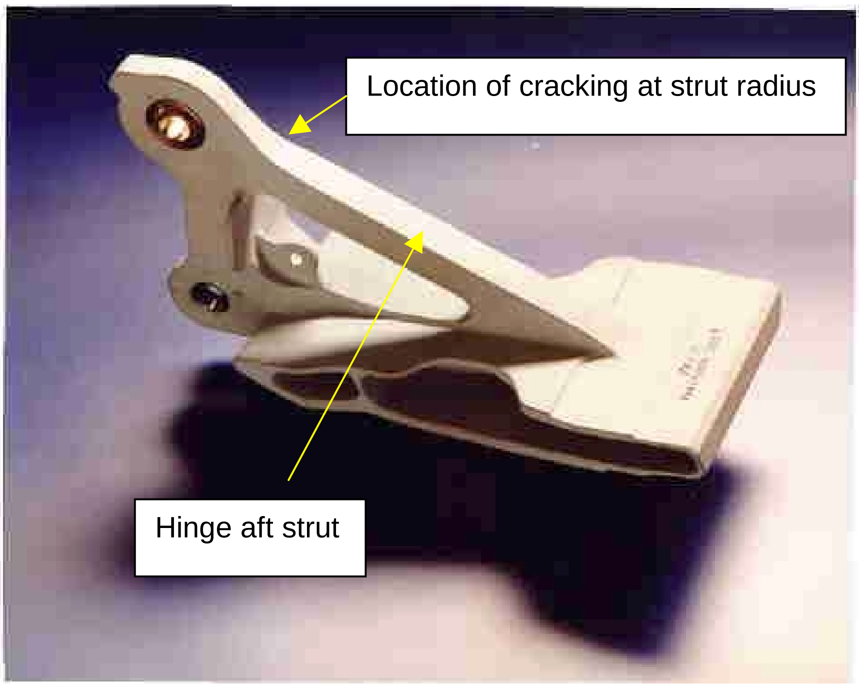


Figure 1. Photograph of the aileron, showing the hinge aft strut and location of fatigue cracking.

LOAD CASES

A significant amount of work has been undertaken by the aircraft manufacturer (Boeing) to determine the reason for the fatigue cracking. Part of this work was to establish the magnitude and nature of the critical loads for the aileron hinge [3]. Under certain flight conditions, the aerodynamic pressure on the aileron acts vertically upwards and this type of pressure distribution causes the aft strut of the hinge to be subjected to a tensile force. This force combined with the stress concentration caused by the radius in the aft strut fillet region, generates high stresses at the radius which is the location of the cracking. The critical load case for this tensile stress condition is known as WO 39. When the aileron is extended upwards during flight, the aerodynamic force acts to push the aileron back to the level condition and in this case, a compressive force develops in the aft strut. The critical load case for this compressive stress condition is known as WO 42. The absolute magnitude of this compressive stress is slightly higher than the tensile WO 39 stress, however, in service this is not a problem as it is only the tensile stress that causes fatigue cracking. However, when considering a bonded composite reinforcement, it is necessary to address both load cases as the shear stress that will be developed in the adhesive layer will be equally damaging for both tensile and compressive stresses in the strut. The shear stress in the adhesive layer will simply be reversed in sign. Two stress magnitudes are referred to in this paper for these load cases. Design Limit Load (DLL) is considered to be the maximum stress the aircraft is likely to see during it's life, while Design Ultimate Load (DUL) is 1.5 times DLL.

These two load cases were used in both the Finite Element (FE) design work as well as the static test program. The work described in Ref. 3 confirms that these two load cases are greater than the most severe loads that the aileron is exposed to in flight and therefore it is conservative to use them for this work.

DESIGN AND STRESS ANALYSIS

This section presents the numerical stress analysis undertaken to design an appropriate reinforcement for the aft strut of the aileron hinge. The fundamental approach followed is to first remove existing cracks with a suitable precise rework shape before reinforcement. This precise rework shape is determined using structural optimisation procedures, to minimise the peak stresses for an un-reinforced hinge. Since in practice various crack lengths will exist before possible enhancement, it is proposed here to consider the limiting case where the rework depth is 2 mm at the crack location. Secondly, this optimal shape for the no reinforcement case is further slightly adjusted to minimise peak adhesive stresses when a reinforcement is bonded on. All finite element stress analyses were performed using the MSC/NASTRAN Version 70 linear static analysis finite element code processor running on a Hewlett-Packard K series 9000 computer at AMRL. The MSC/PATRAN level 7.5 code was used for pre and post processing of the models. Unless otherwise stated, all analyses were performed with the assumption of linear elastic plane stress conditions, using a combination of eight-noded rectangular and six-noded triangular isoparametric elements. The basic mesh used in shown in Figure 2(a). For all analyses isotropic material behaviour under ambient conditions was assumed for the aluminium hinge, the steel bush, and the FM73 adhesive layer. Conversely for the elements comprising the boron/epoxy reinforcement the material was taken as orthotropic. The material properties were as follows; (i) for the aluminium hinge the Young's modulus, E, was taken as 70.38 GPa, Poisson's ratio, ν, was taken as 0.33; (ii) for the steel bush in the lower lug, Young's modulus was taken as E=213.90GPa, and Poisson's ratio was ν=0.30; (iii) for FM73 adhesive, E=1.43GPa, ν=0.35; (iv) for the boron, E_{11}=208.95 GPa, E_{22}=E_{33}=19.18 GPa, ν_{12}=0.21, ν_{23}=0.3 and ν_{31}=0.02 where 1 refers to the direction of the fibres and 2 and 3 are the transverse fibre directions.

Rework shape optimization

(A) Optimized for no reinforcement (Referred to as the 'O' profile)

Rework optimisation was achieved using a design sensitivity optimisation technique available in the MSC/NASTRAN code. This technique involves changing the position of nodes defining a boundary shape based on the computation of the rates of change of nodal stresses with respect to changes in nodal positions. This approach has been successfully developed and implemented in prior AMRL work, for the purpose of minimising peak stress at reworks for two dimensional idealisations [4,5]. Principal features of the shape optimisation procedure are concerned with the specification or calculation of the following; (i) a suitable objective function, (ii) appropriate constraints on the geometry and (iii) design variables, and structural responses. The objective function used in this work has been termed the least squares objective function in prior AMRL work [4,5] and is given as follows;

$$f = \frac{\sum (\sigma_i - \sigma_{av})^2}{k^2}$$

where : σ_i = nodal hoop stress along boundary to be moved.
σ_{av} = average nodal hoop stress around boundary.
k = number of boundary nodes to be moved.

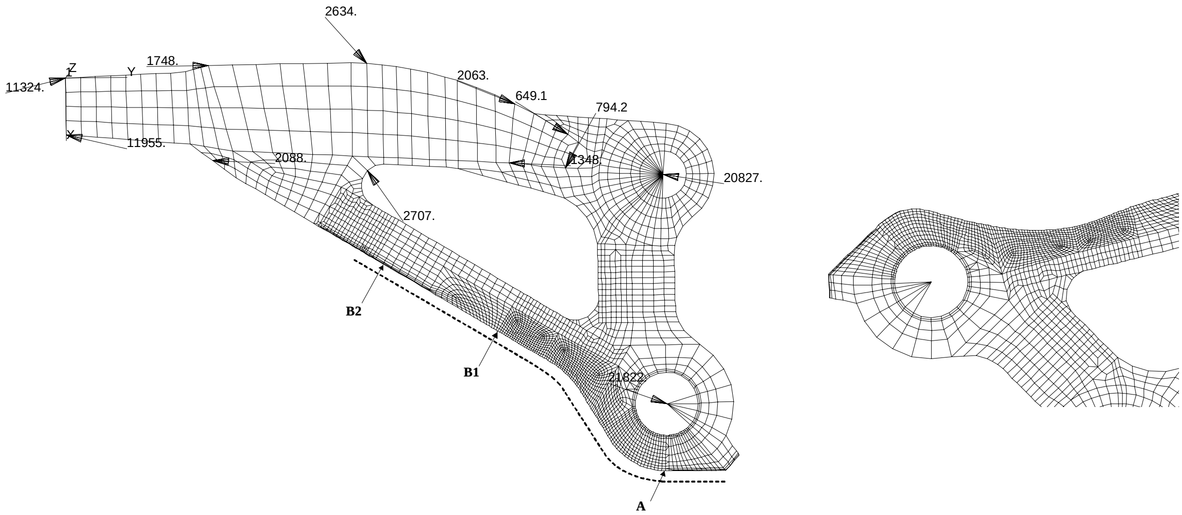
Meeting this objective effectively means that a more constant hoop stress is achieved along a boundary region being optimised, which corresponds to minimising the peak stress in that region. In this work the objective function convergence was defined when two consecutive optimisation iterations produced the same objective function result within a 1% tolerance. For all analyses the *constraints* employed are nodal movement constraints which effectively limit allowable boundary shape changes per iteration (ie to a maximum rework of 2 mm). The *design variables* are the locations of boundary nodes which are allowed to vary throughout the iterative optimisation process to achieve the required objective, while the *structural responses* are the individual nodal boundary hoop stresses. Also as part of the strategy to avoid significant internal mesh distortion, internal nodes are moved for each iteration, and this is achieved automatically by using shape basis vectors determined from the analysis of a separate auxiliary model. The resultant finite element mesh shape obtained after 7 iterations of the rework optimisation is shown in Figure 2(b). The shape obtained is compared to the initial boundary in Figure 3(a), while the corresponding stresses are given in Figure 3(b). It can be seen that the stresses for the rework have been rendered constant in the critical region, and are essentially the same magnitude as those for the nominal geometry, even though 2 mm of material depth has been removed. If a typical non-optimal rework shape had been used instead, the peak strut stresses could be expected to be about 20% higher.

(B) Optimised for subsequent reinforcement (Referred to as the ‘OSR’ profile)

The rework profile for a hinge that will be subsequently reinforced was further developed to meet the needs of minimal peel and shear stress in the adhesive, in addition to minimising the peak stress in the strut. If a reinforcement is applied directly to the rework as described previously, there is a local peak stress in the adhesive, at the location near x=40 mm (the peak is due to the local change in curvature of the optimal profile shape at x=40 mm) which would be greater than the adhesive yield stress, at DLL. Thus, in order to decrease the adhesive stresses, this slight curvature discontinuity in the O rework profile (near x=40 mm) is manually smoothed/removed, which then resolves this problem regarding this adhesive stress peak. Of course as expected, the trade off due to this profile change is a 9% increase in the strut stresses if the patch were to be removed. This effect is clearly shown in Figure 3(a) by comparing strut stresses for the ‘O’ and ‘OSR’ profiles.

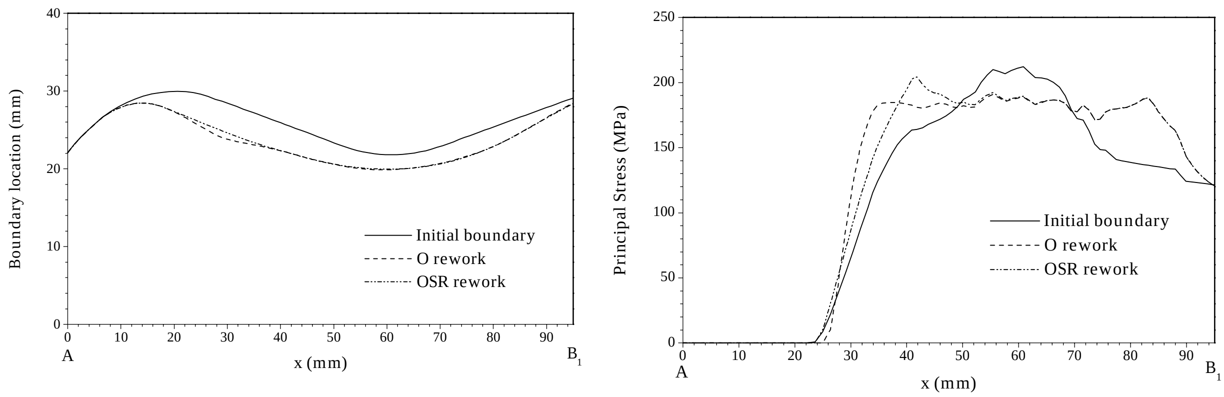
Reinforcement design

In the design of a typical bonded reinforcement to a component, there are two particular regions of concern for the adhesive layer. These are respectively; (i) near the end of the doubler where shear stresses can be very high, and (ii) locations under the doubler where it is



(a) (b)

Figure 2. Finite element mesh discretisation for (a) the nominal unworked hinge analysis, and (b) 2mm depth rework shape after completion of optimisation procedure. In (a) the load vectors shown are for the WO 39 load case and the dotted line represents the patch location. In (b) the diagram has been rotated with respect to Figure 2(a) so as to be consistent with the orientation of Figure 3(a).



(a) (b)

Figure 3. (a) The profiles of the 2 mm (O) and (OSR) reworks are compared with the unworked hinge; (b) the corresponding stresses along the strut edge are shown for the unworked and 0.2 mm (O), (OSR) and (OSR) reworks and the unworked hinge. A and B_1, are shown on Figure 2(a), indicating the range of these plots.

desired to reduce the stress concentration in the repaired component; typically shear and/or peel stresses are high here. Since the bonded reinforcement functions by transferring load from the strut to the doubler, the doubler effectiveness increases with increasing numbers of plies, while simultaneously the adhesive stresses at the two key locations also increase. Hence a suitable final reinforcement design will be a compromise between these two requirements, ie adequate reinforcement effectiveness for reasonable adhesive stress magnitudes. In view of the above, it was decided to undertake a ply by ply interactive design procedure for the multi-ply reinforcement. This enabled firstly the relationship between the number of plies and the peak adhesive stresses and the associated reductions in plate stresses to be determined. Secondly, it enabled the best non-uniform stepping of doubler plies near the end of the doubler to be designed to minimise peak adhesive shear strains. It should be noted that the position of the ends of the doubler were selected to be adequately remote from the critical strut region, such that they would not compromise the ability of the reinforcement to reduce the stress in the critical region. The patch location is shown by the dotted line in Figure 2(a).

Also, due to the higher stresses at the strut end of the doubler, the non-uniform stepping was only applied to this end of the reinforcement. The region at the lug end of the doubler has low stresses, and hence the step lengths at this end were simply made constant at 2 mm, except for the step length from the 1st to the 2nd ply, which was 4 mm. These step lengths are summarised in Table 1.

The initial FE model used an adhesive layer thickness of 0.4 mm, consisting of two layers of elements through the thickness of the adhesive. The strut end of the adhesive layer began 153 mm from the centre of the lower lug and continued to the end of the "horizontal" section around the lug, as indicated in Figure 2(a). The first ply of the boron/epoxy reinforcement was then applied where one layer of elements was used to represent each layer of boron/epoxy. The shear stress in the adhesive (in the local element axes) and the principal stress reduction in the strut were noted. An estimate of an appropriate first step length (17.8 mm) was made using the equations given in Ref. 6 and the second ply of boron/epoxy was added to the model, and the stress results recorded. The step length was then slightly altered (and the analysis re-run) such that the addition of the second ply did not increase the previous peak value of the adhesive shear stress at the start of the first ply. This process was then repeated, with step lengths being obtained such that the adhesive shear stress peaks at the beginning of each new step were well below the peak at the start of the first step. The addition of boron/epoxy plies was then stopped when adequate stress reductions in the critical region of the radius were achieved while also keeping the shear stress in the adhesive (at DUL) below the "knee"[a] value. This corresponded to an eight-ply reinforcement. As a direct comparison, Figure 4 shows the shear stress in the adhesive for an 8-ply reinforcement for both the non-uniform stepping described and a uniform 4 mm stepping arrangement. The advantages of the non-uniform stepping are clearly evident.

Table 1. Step lengths at strut end of doubler as determined from interactive FE design method

Layer	Step length at strut end (mm)	Step length at lug end (mm)
1st ply	1.7	2.1
2nd ply	18.6	4.2
3rd ply	15.8	2.1
4th ply	11.8	2.1
5th ply	7.9	2.1
6th ply	3.9	2.1
7th ply	3.9	2.1
8th ply	3.9	2.1

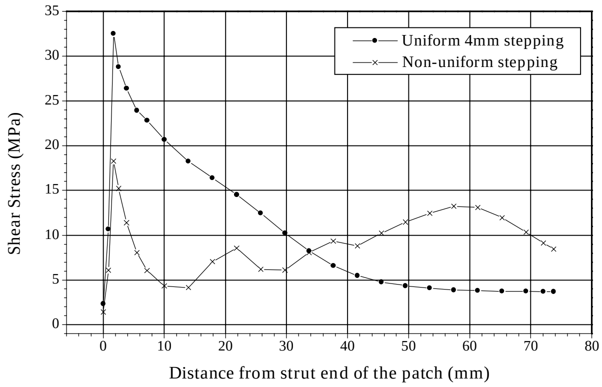


Figure 4. Adhesive shear stresses near the strut end of the stepped doubler

The beneficial effect of the reinforcement is demonstrated in Figure 5 which shows the principal stress along the aluminium edge for both the un-reinforced and reinforced cases. It can be seen that there is a predicted 20% reduction in stress at the crack location.

[a] The "knee" value is the point on the load deflection curve where two tangents to the curve are bisected (ASTM D5656 Test method for Shear stress behaviour of adhesives).

An important aspect of this reinforcement is the presence of through-thickness or peel stresses in the adhesive as well as the usual shear stresses. Peel stresses can arise in a bonded joint for a number of reasons and good design practice is to minimise them as adhesives do not perform well in through-thickness tension. In this case they arise from the curvature in the joint and it is not possible to design them out altogether. It should be noted that the magnitude of the peel stresses is influenced by various aspects of the design, such as the thickness of the composite reinforcement and the exact profile of the surface, and where possible the level of peel stress has been minimised. Other work at DSTO-AMRL has recognised the presence of peel stresses and sought to establish an indication of the allowable level of peel stress for a structural film adhesive [7]. From this work a preliminary figure of 35 MPa has been proposed for FM 73 adhesive under constrained tension [8]. Figure 6 shows the distribution of both shear and peel stresses for the adhesive along the strut radius at the DUL WO 39 condition. The shear stress is seen to peak at x=30 mm and the magnitude of the stress is high.

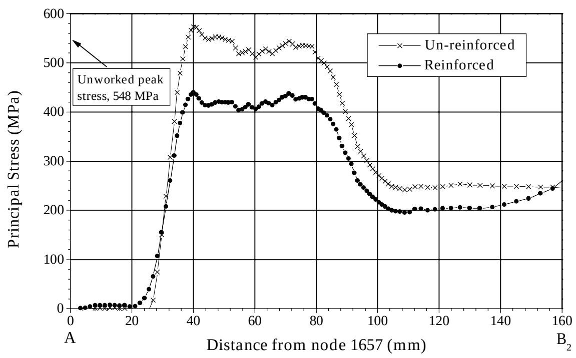


Figure 5. *FE prediction of principal stress along the strut edge for the OSR 2 mm rework geometry for the WO 39 load case. A and B_2 are the points shown in Figure 2(a).*

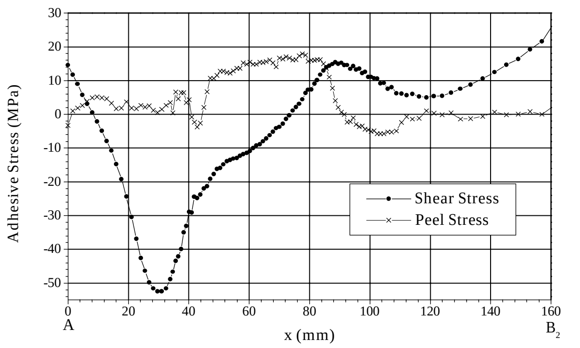


Figure 6. Adhesive stresses occurring along the adhesive bondline for the OSR 2 mm rework hinge for the WO 39 load case. A and B_2 are the points shown in Figure 2(a).

The adhesive will yield at these loads, however, this is acceptable providing failure does not occur at the DUL condition. While the adhesive has been shown to be capable of tolerating these static loads, consideration must also be given to the fatigue loading that the hinge will see. This is considered further in a later section. The peel stresses while high compared with a conventional flat joint, are comfortably below the proposed peel allowable. Note that the peel stresses become positive for the tensile WO 39 design load case.

The composite reinforcement was manufactured from Textron 5521/4 boron/epoxy pre-preg, because of the superior compressive properties, absence of galvanic corrosion problems and higher coefficient of thermal expansion of boron compared with carbon. This helps to minimise residual thermal stresses which result from the elevated temperature cure. The adhesive used in the test program was Cytec FM 73, although a combination of FM 300-2 co-cured with the boron and then secondarily bonded with FM 73 is also possible. This co-cured combination may be used for the future reinforcing of the hinges as it has previously shown excellent elevated temperature fatigue performance [7].

STATIC TESTING AND REPAIR VALIDATION

To validate the FEA, a static test program was undertaken on a series of hinges using both the WO 39 and WO 42 load cases. A test rig was constructed in which the hinges could be loaded at the correct angles as shown in Figure 7. The required series of fittings were fabricated and attached to the end of the hinges through which the applied loads were reacted. Strain gauges were applied to the hinges to measure the strains in the radius region during the test. One new hinge was tested in the original condition to validate the base FE model and very good correlation of strain in the critical region was achieved. Further tests were conducted on hinges which had been reworked to a variety of different rework depths as reported in Ref. 9 and then again after the composite reinforcement had been applied.

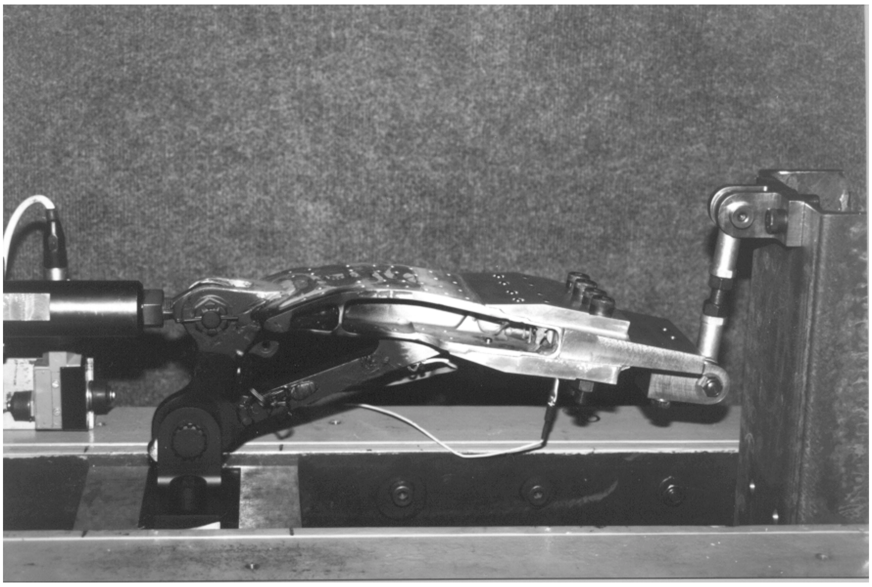


Figure 7. Close up photograph of test article in WO39 configuration. Test fixtures can be seen at the end of the hinge.

The tests were carried out at a range of different loads with checks made to ensure linear behaviour at low loads and consistency between different tests. The final tests were conducted to both DLL to check for no permanent deformation of the hinge and then to DUL to confirm that no failure occurred. These successful tests proved the structural integrity of the reworked and reinforced hinge.

The strain behaviour of the hinge under the different test configurations can be seen in Figure 8, where the strains along the radius can be seen. The original geometry shows the peak in tensile stress at 67 mm as described previously in the stress analysis section The effect of the 2mm deep rework can be seen as the region of high stress is broadened and the location of peak stress shifts closer to the lug end (compare Figure 8 with Figure 5). The subsequent effect of reinforcement is seen to significantly reduce the strain at all locations in the critical radius region with the peak stress having been reduced by 16% compared with the original uncracked hinge geometry.

This observed strain behaviour confirms and validates the predicted strains from the FE models of the hinge. Importantly the models are seen to correctly predict the location and magnitude of the maximum stress in the hinge for the various conditions (original, reworked and reinforced). This provides confidence in the accuracy of the observed stress behaviour of the hinge.

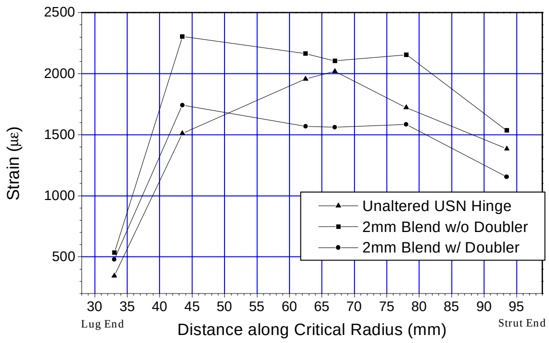


Figure 8 Measured strains for the unaltered, 2mm blended without reinforcement and 2mm blended with reinforcement ex-USN hinge at 50% DLL in the WO39 load configuration. These strains have been measured along the side of the strut.

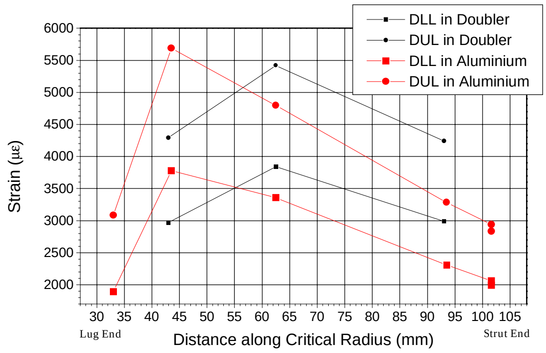


Figure 9. Measured strains from DUL test (WO 39) showing strains on both the aluminium (side of strut) and boron at 1.06 x DLL (14,800 lbs) and DUL (21,000 lbs).

The measured strains in the boron/epoxy composite reinforcement are shown in Figure 9, where the results from strain gauges mounted on the surface of the composite are compared with strains measured on the side of the aluminium hinge strut for both the DLL and DUL WO 39 load cases. The strains shown in this figure are higher than the strains that would normally be expected for a composite-reinforced aircraft component, however, this is often the case for repairs where less design freedom is available and geometrical constraints are more severe. On the other hand during the design of composite repairs there is often less uncertainty about the stress state than there is during the initial design of a much larger component, and therefore it is sometimes possible to use higher design allowables for a repair than for component design. The strains in the boron at DUL are around 75% of the ultimate material strain and no failure was observed during the DUL testing. Both WO 39 and WO 42 load cases were applied during these tests.

CERTIFICATION AND IMPLEMENTATION TO AIRCRAFT

Before the proposed reworking and/or reinforcement design can be applied to an aircraft, it will require certification by an airworthiness authority. Further issues such as fatigue durability of the reworked hinge and the composite reinforcement would need to be completed for certification as well as consideration of environmental durability and degradation possibly by hot/wet mechanical testing. An important aspect of the certification relates to the confidence in the long term structural integrity of the composite reinforcement. Consider the OSR profile for the 2mm blend which by itself slightly increases the stress at the critical radius as compared to an uncracked hinge of standard geometry. If it can be shown that there is an acceptably low probability of failure for the reinforcement, then full credit can be given for the stress reduction it provides and the original inspection intervals for the component could be maintained. If it could not be shown that the reinforcement was unlikely to fail, it would not be possible to rely on the reinforcing effect of the doubler. In this case it would be necessary to quantify the exact stress increase and calculate a reduced inspection interval. Less extensive reworks have been shown in this project [9] to reduce the stress concentration at the radius. For these cases there is no increased risk of fatigue cracking and the original inspections could be maintained. If a composite reinforcement was applied the additional stress reduction it permits could permit a reduction in the inspection intervals.

CONCLUSIONS

A design approach is described which combines structural optimization methods with bonded composite repair technology. This approach was used to design a proposed reinforcement for fatigue cracked F/A-18 aileron hinges. This design includes high through-thickness stresses in the adhesive layer which have been minimized where possible. The design was validated using a full-scale static test program, and the test hinges and composite reinforcements have satisfactorily been tested to design ultimate load. Further work including fatigue and environmental degradation studies will be required before the proposed reinforcement could be certified.

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