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Repair of cracked holes using cold expansion

Robin Cook
Defence Evaluation and Research Agency
Farnborough, Hampshire, GU14 0LX, UK

Abstract

Fatigue tests have been conducted on open hole and bolted joint specimens with cold expansion applied at different stages of the life. The results showed that for the open hole specimens fatigue life enhancements would occur provided that cold expansion was carried out before a crack of 3mm had formed. The optimum enhancement occurred with cracks of less than about 1mm present. Directional expansion, where holes were preferentially expanded with the largest cracks at the mandrel outlet face, was shown to give much improved fatigue performance. Cold expansion of joints showed that life enhancements were dependent on load transfer and secondary bending characteristics. It was also shown that fatigue endurances of joints cold expanded when cracks of less than 2mm had formed were similar to those of joints where cold expansion had been carried out at manufacture.

1 Introduction

There is a continuous drive to improve cost effectiveness in the operation of civil and military aircraft structures. Methods of reducing costs include extending the service life of aircraft by life enhancement techniques and the use of repairs rather than costly replacement of structural components. Research has been in progress at DERA for several years examining such repair techniques as cold expansion of fastener holes, interference fit fasteners and adhesively bonded composite patch repair which can result in significant increases in residual fatigue endurances. This report describes some of the work concerned with using cold expansion as a repair technique when fatigue cracks have already formed. The conventional practice in such cases is to remove any fatigue cracks by reaming the hole oversize, cold expanding the hole and installing a larger diameter fastener. It may not always be possible to remove

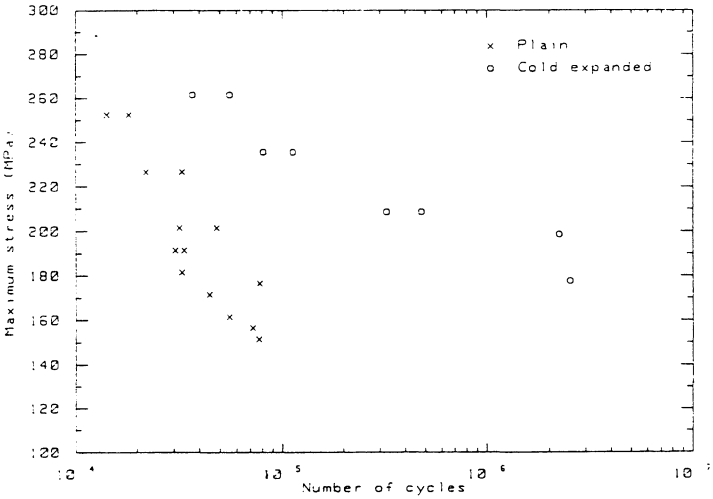

Figure 1 Endurances of plain and cold expanded open hole specimens

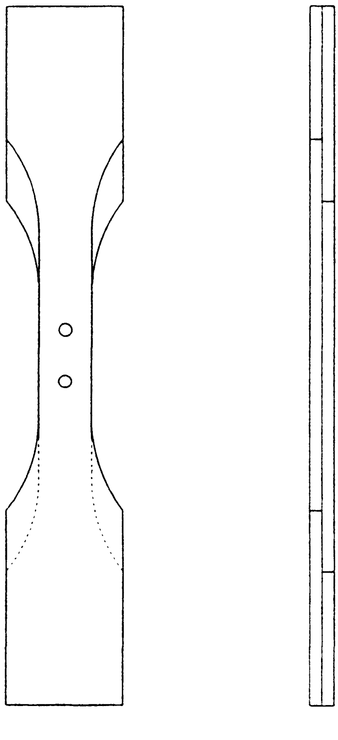

Figure 2 Low-load-transfer joint

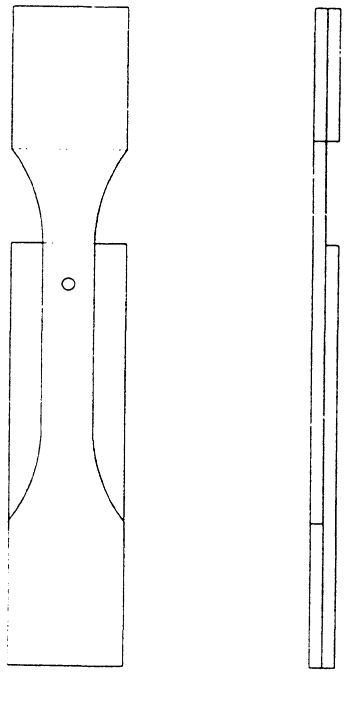

Figure 3 Medium-load-transfer joint

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such damage without degrading the durability of the structure and it is also possible that not all of the damage will be removed by the cleaning process. There is a requirement, therefore, to examine the effectiveness of hole cold expansion when fatigue cracks are present.

The objectives of the work are to determine the degree of enhancement which could be achieved in practice with residual cracks present and the sizes of such cracks which can be tolerated. It is also essential to understand the mechanisms which control life enhancements in order to assess the limitations and potential applications of the process. To meet these objectives two series of tests were carried out. The first investigated the mechanisms, limitations and optimisation of hole cold expansion using simple open hole specimens (section 2) and the second examined the degree of enhancement which could be achieved in practical situations using laboratory joints which simulate aircraft structures[1] (section 3).

2 Test programme on open holes

A series of fatigue tests were carried using simple open hole (6.35mm diameter) specimens 40mm wide, manufactured from 5mm thick 7050-T76 aluminium alloy plate. The central holes were drilled and reamed to the size for cold expansion recommended by FTI (CBSR-8-0-N). The specimens were then subjected to sinusoidal fatigue loading at a stress ratio of R=0.1. The applied stress has a significant effect on the efficacy of cold expansion so two stress levels were selected for initial investigation, resulting in peak net stresses of 200 and 236MPa. The lower stress level was selected as being close to the fatigue limit of cold expanded specimens and therefore approaching the maximum life enhancement that could be expected. The higher stress level had been used in a previous investigation[2] and was shown to give life enhancements by a factor of about 4 (see figure 1). The fatigue tests were stopped periodically to measure the length of any fatigue cracks, using an acetate replica technique. Cracks were allowed to develop to predefined surface crack lengths of about 0.5, 1, 2 or 3mm. Tests were then stopped and holes cold expanded using conventional FTI tooling. It has been demonstrated in previous investigations[2-4] that residual stresses induced by cold expansion vary through the component thickness and are less compressive near the mandrel inlet face than near the mandrel outlet face. Consequently, half of the specimens were cold expanded with the pre-crack at the mandrel inlet face and half with the pre-crack at the mandrel outlet face. Tests were then continued and subsequent crack growth monitored.

3 Test programme on joints

The test programme on joints was undertaken in collaboration with BAe Woodford and BAe Warton. Specimens of the type shown in figures 2 and 3 were used in this investigation, manufactured from four different typical aircraft aluminium alloys. Half of the specimens tested contained elements which had been pre-cracked, under constant amplitude loading, to produce a quadral crack at a single location of about 2mm in length prior to assembly; the other half had no damage present. The pre-cracks were located at the faying surfaces of both types of joint. Specimens were subjected to FALSTAFF loading[5] with peak stresses of between 280 and 375 MPa until failure occurred. The four types of test performed are described below.

Plain hole - Specimens with no artificial damage and no pre-crack.
CX hole - Specimens with no artificial damage, cold expanded at manufacture.
Pre-cracked plain hole - Specimens with pre-cracks but no cold expansion.
Pre-cracked CX hole - Pre-cracked specimens cold expanded after pre-cracking.

Five specimens were tested for each test type, resulting in twenty tests on low-load-transfer joints and twenty on medium-load-transfer joints on each of the four materials.

4 Results

4.1 Open hole tests

The fatigue endurances of open hole specimens with maximum stresses of 200 and 236 MPa are presented in figures 4 and 5 respectively. It can be seen from figure 4 that there is no benefit in cold expanding holes with cracks of 3mm or larger present as the life tends to that of plain specimens. However, at crack lengths of less than 3mm, significant improvements in fatigue endurances were achieved. The lives of specimens with pre-cracks approached those of specimens cold expanded at the start of testing for very short pre-crack lengths. It can also be seen that cold expansion with cracks located at the mandrel outlet face resulted in superior endurances to those cold expanded with cracks at the mandrel inlet face. Similar observations can be made from figure 5 which presents test results at a maximum stress of 236 MPa. In this case results suggest that fatigue lives can equal those of specimens cold expanded at the start of testing provided that the pre-crack length is less than 0.5 mm.

4.2 Joint tests

The fatigue test results are given in table 1, for low-load (LLT) and medium-load-transfer (MLT) joints, from which it can bee seen that the benefits of cold expansion without cracks present are between 2.8 and 8.9 for LLT joints and between 1.3 and 1.8 for MLT joints. Cold expansion increases the residual life of the joints by a factor of between 6.5 and 66.1 for the LLT joints and between 1.1 and 6.1 for the MLT joints.

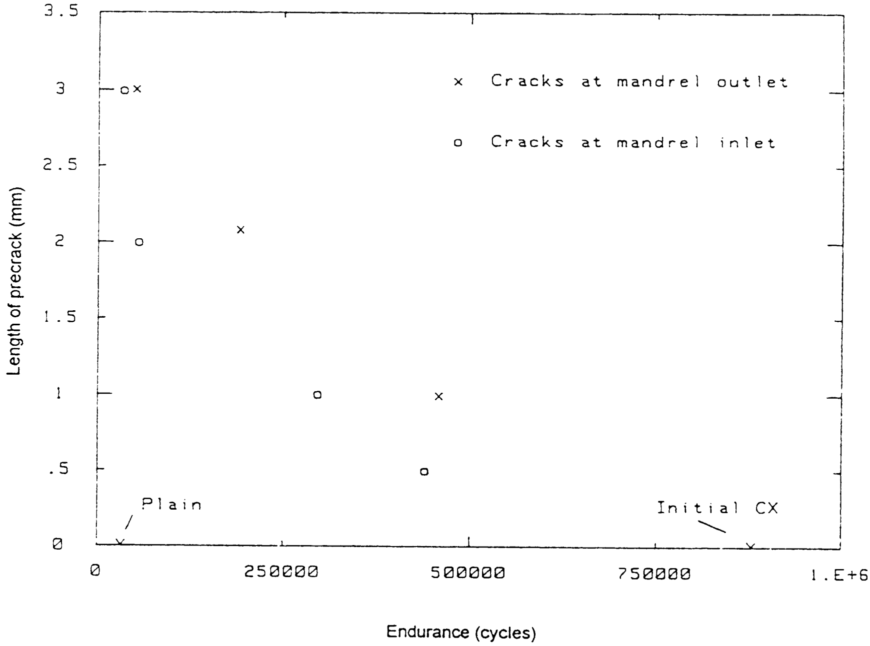

Figure 4 Endurances of pre-cracked specimens at peak stress of 200 MPa

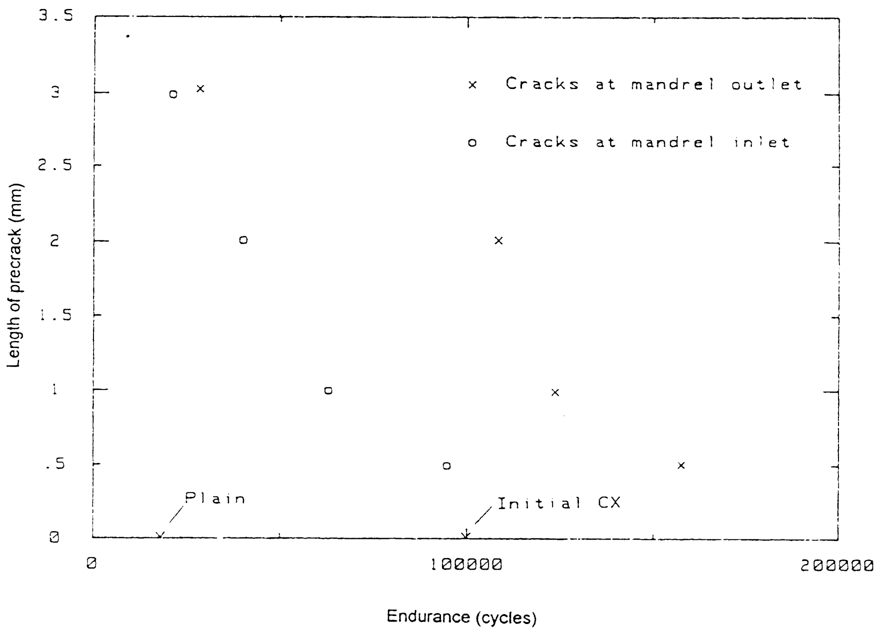

Figure 5 Endurances of pre-cracked specimens at peak stress of 236 MPa

Endurances reported for pre-cracked specimens are the lives to failure from the pre-crack length. In order to estimate the total lives of pre-cracked specimens, it is necessary to calculate the number of cycles to grow a crack to the pre-crack length under the FALSTAFF loading sequence. This was estimated by subtracting the endurances of pre-cracked plain hole specimens from the endurances of plain hole specimens. The results are shown in table 1 as 'Calculated life to pre-crack'. The total endurance for cold expanded pre-cracked specimens was estimated by adding this life to pre-crack to the measured life from the pre-crack. The results are presented in table 1 as 'Calculated total life CX hole'. It was then possible to estimate the overall life improvement of a component cold expanded part way through its life, when a crack of about 2mm in length had formed, and compare it with the life of a component cold expanded at build. The ratio of these two lives is the 'CX life ratio' given in table 1 and it can be seen that lives of specimens cold expanded part way through their lives can equal the lives of specimens cold expanded at build.

5 Discussions and Conclusions

5.1 Open hole tests

Fatigue life enhancement due to cold expansion results from the compressive residual hoop stresses formed by the process. It has been observed in a previous investigation[2] that little benefit occurs during crack nucleation but significant benefits are found during crack growth. This can be seen from figure 6 which shows crack growth from open hole specimens in the absence of a pre-crack. It can be seen that the time to initiation is very similar and that cracks in cold expanded specimens grow to a length of about 0.8 mm before the major delay in growth rate occurs. It follows that cracks shorter than this length should be tolerable at the point of cold expansion without any significant change to the benefit from cold expansion. This is supported by experimental observations (see figure 4). Cracks form initially at the mandrel inlet face[2] where residual stresses are least compressive, so the 0.8 mm refers to cracks at the mandrel inlet face. Longer cracks will be tolerable at the mandrel outlet face where more compressive residual stresses are found. At the higher applied stress of 236MPa, it can be seen from figure 7 that crack retardation is less marked than at the lower stress, but the delay in crack growth occurs at crack lengths slightly in excess of 1mm. It follows that slightly longer cracks (~1mm) can be tolerated, at the mandrel inlet face, at the higher applied stress without a significant reduction in benefit from cold expansion.

The above observations are only valid assuming that the residual stress fields created by cold expansion are similar with or without a crack present. Similar work using overloads rather than cold expansion suggests that this is not the case[6]. The residual stress distributions formed at pre-cracked holes are likely to be similar in shape and magnitude to those from uncracked holes but the origin

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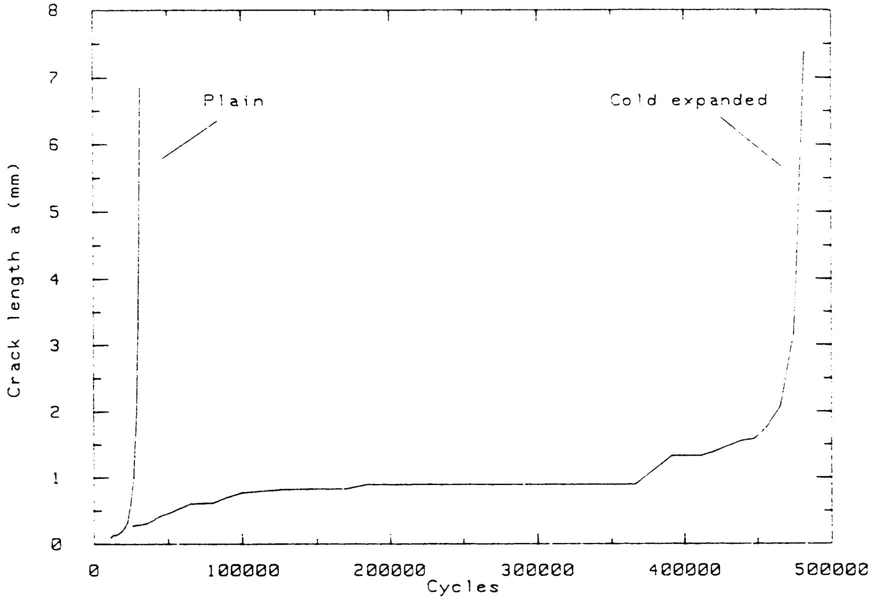

Figure 6 Crack growth in open hole specimens at peak stress 200 MPa

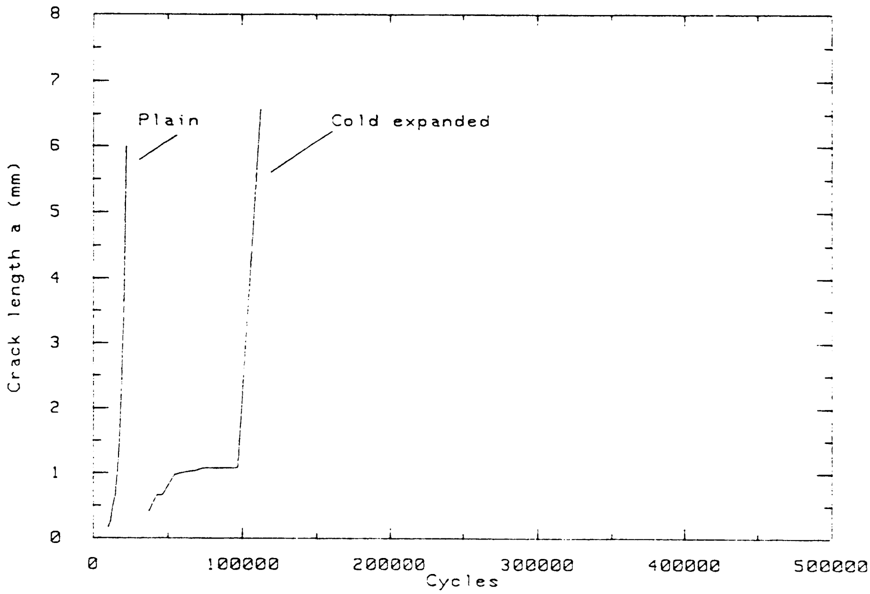

Figure 7 Crack growth in open hole specimens at peak stress of 236 MPa

of the distributions will move to the crack tip location. This explains the fatigue life enhancements observed with pre-cracks of greater than 1 mm in length. The benefits become smaller with increasing pre-crack length as the magnitudes of compressive residual stresses induced decrease with increasing pre-crack length, but also because the stress intensity factor due to the applied load increases with increasing pre-crack length.

Another interesting feature of these tests concerned the cracks which eventually caused failure. During pre-cracking, cracks generally formed at all four corner locations at the edge of the open hole. The cold expansion direction was based on the position of the longest crack only. In the case of cold expansion with cracks at the mandrel inlet face, cracks at the mandrel inlet face were always longer than those at the mandrel outlet face and the crack which caused failure was always the longest crack on the mandrel inlet face. However, when the longest crack was positioned at the mandrel outlet face, and shorter cracks were present at the mandrel inlet face, failure no longer occurred from the longest crack at the mandrel outlet face (in the case of 0.5mm and 1.0mm cracks) but due to a shorter crack at the more critical mandrel inlet face. In one case (0.5mm at mandrel outlet) the crack which caused failure had not initiated at the time of cold expansion.

It can be concluded that cold expanding components with cracks shorter than 3mm will result in an improvement in residual fatigue endurance. Provided that cracks are less than 1mm long, lives similar to those of components cold expanded at build can be achieved.

5.2 Joint specimens

The effects of secondary bending and load transfer are apparent from the test results (see table 1) where the life improvement factors (LIFs) are much smaller in MLT joints (average 1.5) than for the LLT joints (average 6) where the load transfer and secondary bending are significantly smaller. The effect of stress amplitude is less obvious; the average LIFs in MLT joints were 1.45 at 375 MPa, and 1.62 at 300MPa, and the LIFs in LLT joints were 5.3 at 350 MPa and 6.7 at 280 MPa.

These effects can be explained by considering the magnitudes of the local stresses present. At very low applied loads the alternating stress range may be mainly or entirely compressive, due to the compressive residual stress contribution, and no crack growth occurs. At greater alternating stresses, however, the summation of alternating and residual stresses is sufficient to make the stress intensity greater than the threshold value and crack growth occurs. As the alternating stresses are increased further, the contribution from the residual stress, which is not affected by the alternating stress, becomes less significant. Life improvement factors are therefore greater at smaller applied loads. Periodic large load excursions, particularly when coupled with high secondary bending stresses, can result in further plastic deformation around the

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fasteners, redistributing the residual stresses and reducing their effectiveness. The reduction in benefit due to cold expansion will, thus, be more marked in components with large secondary bending ratios and high load transfer where local stresses can be large.

The effects of pre-cracking show that the residual lives of the components, once cracks of 2 mm have formed, can be enhanced by an average factor of 23 for LLT joints and 3 for MLT joints. These enhancements only apply to the final 25% (MLT) to 35% (LLT) of the life from crack lengths of 2mm to failure. The resultant effect on the total fatigue life was shown to give overall lives similar to those found in specimens cold expanded during manufacture. This appears to contradict the findings of the open hole specimen, where cracks had to be less than ~1mm to restore the life of the component to the originally cold expanded life. However, it must be remembered that the open hole specimens were tested at lower maximum stresses and under constant amplitude loading. The critical crack length in the joints will be different because of this, and will depend on the distribution of applied alternating stresses within the loading sequence. Specimen fracture surfaces were examined in order to check that pre-cracks of the required length had been used, and in the case of the LLT joints, that failure had occurred at the hole with the initial damage. The estimated pre-crack lengths were found to be about 1.25 mm in the MLT joints and 1.63 mm in the LLT joints, where only half of the fractures had any visible pre-crack.

The method used to calculate the total life was not strictly valid in that the life to reach a crack length of 2mm cannot be simply estimated from subtracting the two lives described in 4.2 above. However, accepting this limitation, it can be concluded that cold expansion of simple joints with cracks less than about 2mm in length can restore the life to that of joints cold expanded at manufacture.

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Material	Peak Stress MPa	Plain hole endurance Flights	CX hole endurance Flights	Pre-cracked plain hole endurance Flights	Pre-cracked CX hole endurance Flights	Calculated life to precrack Flights	Calculated total life CX hole Flights	LIF uncracked	Residual LIF	CX life ratio (pre-cracked /uncracked)
MLTJ										
7010-T7651	375	4531	5904	1743	4426	2788	7214	1.3	2.5	1.2
7010-T7651	300	21465	38342	4445	27248	17020	44268	1.8	6.1	1.2
2014-T651	375	4232	6329	550	745	3682	4427	1.5	1.4	0.7
2014-T651	300	23928	35469	4166	16866	19762	36628	1.5	4.0	1.0
2024-T351	375	2196	3490	747	826	1449	2275	1.6	1.1	0.7
2024-T351	300	29401	42619	7861	32376	21540	53916	1.4	4.1	1.3
7475-T7351	375	4203	5844	1600	4621	2603	7224	1.4	2.9	1.2
7475-T7351	300	15890	29180	6684	33224	9206	42430	1.8	5.0	1.5
LLTJ										
7010-T7651	350	6516	18431	1798	41044	4718	45762	2.8	22.8	2.5
7010-T7651	300	17327	57584	5994	101744	11333	113077	3.3	17.0	2.0
2014-T651	350	3928	33109	967	15609	2961	18570	8.4	16.1	0.6
2014-T651	300	13250	93250	4415	90616	8835	99451	7.0	20.5	1.1
2024-T351	350	3836	9154	2697	20390	1139	21529	2.4	7.6	2.4
2024-T351	300	24444	216542	12770	83336	11674	95010	8.9	6.5	0.4
7475-T7351	350	4195	31940	905	23859	3290	27149	7.6	26.4	0.9
7475-T7351	300	13502	99752	2552	168729	10950	179679	7.4	66.1	1.8

Table 1 Fatigue endurances of joint specimens