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STRUCTURES REPORT 407

ON THE STRESS ANALYSIS OF BONDED INSERTS

by

R. Jones and M. Heller

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STRUCTURES REPORT 407

ON THE STRESS ANALYSIS OF BONDED INSERTS

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SUMMARY

Recent experimental work has shown that adhesively bonded inserts can significantly increase the fatigue life of fastener holes. This paper concentrates on developing an understanding of the mechanisms which give rise to the observed increase in life. Cracked as well as uncracked fastener holes are considered. It is shown that both the stress concentration factors, and the stress intensity factors are significantly reduced by the use of either bonded rivets or bonded sleeves. It is also shown that the stress intensity factor, for a cracked hole repaired by a bonded insert, can be obtained by analogy with readily available solutions.

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CONTENTS

A1

NOTATION

a	Length of crack in specimen
E	Modulus of elasticity
K	Mode I stress intensity factor
r	Distance from crack tip
t	Adhesive thickness
u	Displacement of point on crack face at distance r from crack tip
ν	Poisson's ratio
x,y	Cartesian co-ordinate axes system
σ	Remote stress applied to specimen
θ	Angular rotation from x axis

1. INTRODUCTION

This report describes work done as part of the continuing fatigue-life enhancement program at the Aeronautical Research Laboratories, Australia. In the past, considerable effort has been spent on developing adhesively bonded repairs to aircraft structural components. One area of particular importance is the fatigue life enhancement of fastener holes, since these are common sites for fatigue crack initiation in aircraft structural components.

In recent years a new method has been proposed for the fatigue-life enhancement of fastener holes [1, 2]. This approach involves bonding an insert, either a fastener or a sleeve, into the fastener hole. The idea is based on the premise that the adhesive improves the load transfer in the component, thereby reducing the stress concentrating effect of the hole, and subsequent to crack initiation, reduces the stress intensity factor at the crack tip. Experimental work has shown that this method significantly reduces the rate of fatigue crack propagation from fastener holes, and is superior to other life enhancement schemes [2].

Analytical solutions for the stress analysis of fastener holes with bonded inserts are not available, due to the geometric complexity and material discontinuity occurring in such components. This necessitates the use of either numerical or experimental methods for the study of this class of problem.

In this report we carry out stress analyses of fastener holes with bonded inserts (both rivets and sleeves) by using the finite element method [3, 4], with fracture mechanics [5, 6] playing a key role. The influence of variations in both adhesive thickness and crack length are considered in detail.

In Section 2, a background to the finite element method used is given. This is followed in Section 3 by numerical investigations of single hole specimens with bonded rivets and bonded sleeves. The results are then discussed in Section 4.

2. METHOD OF ANALYSIS

In this paper, we carry out elastic stress analyses of cracked and uncracked specimens, to investigate the effects of bonded inserts, using the finite element method. For uncracked specimens, the stress concentrating effect of the hole is particularly important, since this governs the time to crack initiation, while for cracked specimens, the stress intensity factor is of key importance, since this governs the rate of fatigue crack propagation.

To carry out the stress analysis using finite element methods, three complications need to be addressed, namely,

(i) correct modelling of the crack tip displacement singularily, to allow the stress intensity factor to be determined,

(ii) modelling of the very thin adhesive layer, and

(iii) consideration of the possibility of adhesive failure.

2.1 Determination of Stress Intensity Factor

A number of finite element methods can be used to model two-dimensional crack-tip behaviour. The best of these methods are reviewed in references [7] and [8]. We use small triangular isoparametric elements at the crack tip, with their mid-side nodes shifted to the quarter point [9]. These elements give the required $r^{1/2}$ displacement singularity, are accurate, and are easy to implement. Thus, from near tip displacements, the stress intensity factor is determined using the equation given in reference [5], namely

$$K = \frac{uE}{4(1-\nu^2)}\sqrt{\frac{2\pi}{r(1+r/2l)}} \tag{2.1}$$

where u is the displacement of a point on the crack face, r is the distance of that point from the crack tip and l is the crack half length as defined in reference [5].

2.2 Modelling of Thin Adhesive Layer

In the analysis of fasteners with bonded inserts, it is apparent that the thickness of the adhesive is very small compared with characteristic values of hole radii. This necessitates the use of high aspect ratio elements to model the adhesive, if unduly refined element meshes in the rest of the structure are to be avoided. In modelling the adhesive, eight-noded isoparametric elements are used and to overcome the problems associated with high aspect ratio elements, reduced integration is used, and the stiffness matrices are computed using double precision. The problems associated with the use of high aspect ratio elements are discussed in detail in reference [10].

2.3 Adhesive Failure

In the majority of the work done in this investigation, it was assumed that the adhesive remained intact with no adhesive failure criterion being adopted. However, some analyses were done using a simplistic approach, whereby the adhesive was allowed to debond over 50% of the contact area with the specimen, as shown in Figure 1.

3. NUMERICAL INVESTIGATION

Detailed finite element analyses of typical single-holed tension specimens were done to investigate the possible benefits of using bonded inserts as a life enhancement method. The geometry of these specimens was chosen so as to coincide with those for which test results are given in reference [2]. Both cracked and uncracked specimens were considered, and the effects of variation in adhesive thickness and crack length were studied. The analyses were done using the PAFEC suite of programs on the ARL VAX 11/780 computer. The finite element stiffness matrices were computed using reduced integration and double precision and the solution was performed using double precision.

The analyses of two different specimens, which we designate No. 1 and No. 2, were undertaken for elastic plain-strain conditions, and these are shown in Figure 2. Both specimens were loaded by a remote tension stress of 265 MPa, and are aluminium alloy, with the material properties $E = 73$ GPa and $\nu = 0{\cdot}32$. For all cases, the adhesive material properties were taken as $E = 1{\cdot}89$ GPa and $\nu = 0{\cdot}35$.

Various analyses were conducted for specimens with both bonded rivets and bonded sleeves, and are discussed in detail in the following subsections. Stress intensity factors were determined using equation 2.1.

3.1 Bonded Rivet

For all cases discussed, the rivet is aluminium alloy, with material properties $E = 73$ GPa and $\nu = 0{\cdot}32$. Also for comparison purposes, some analyses were done without the rivet, and some with the glue allowed to fail in tension (as explained in Section 2.3).

3.1.1 Specimen 1: Uncracked

Specimen 1 was first considered to be uncracked. Due to symmetry only 1/4 of the structure was modelled, as shown in Figure 3. The resultant finite element mesh consisted of 38 eight-noded isoparametric quadrilateral elements, and 8 six-noded isoparametric triangular elements. The values of the maximum principal stress in the specimen are given in Table 1.

3.1.2 Specimen 1: Cracked on One Side

Here the specimen was considered with a crack along its centreline, emanating from the hole edge, as shown in Figure 4*a*. Due to symmetry only 1/2 of the structure was modelled, as shown in Figure 5. The resultant finite element mesh consisted of 74 eight-noded isoparametric quadrilateral elements, and 34 six-noded isoparametric triangular elements. The results for stress intensity factors at the crack tip are given in Table 2. Further analyses were also done with the rivet rigidly attached to the specimen, this being equivalent to the specimen being cracked, but having no hole. These results are also given in Table 2.

3.1.3 Specimen 1: Cracked on Both Sides

In this case the specimen was considered with symmetric cracks along its centreline, emanating from the hole edge, as shown in Figure 4*b*. Due to symmetry only 1/4 of the structure was modelled. The finite element mesh used was identical to that shown in Figure 5, except that the left half of the structure was omitted and nodes on the y axis were restrained in the x direction. The values of stress intensity factors are given in Table 3.

3.1.4 Specimen 2: Cracked on One Side

Due to symmetry only 1/2 of the structure was modelled. The finite element mesh was identical to that used in Section 3.1.2, except that the structure was double that size. Stress intensity factors are given in Table 4.

3.2 Bonded Sleeve

In this case the insert was a steel sleeve with the material properties, $E = 210$ GPa and $\nu = 0{\cdot}32$, and of 1 mm thickness. The structure modelled was specimen 2 with a crack on one side, emanating from the hole edge, as shown in Figure 4*a*. Due to symmetry only 1/2 of the structure was modelled, as shown in Figure 6. The resultant finite element mesh consisted of 78 eight-noded isoparametric quadrilateral elements and 23 six-noded isoparametric triangular elements. The results for stress intensity factors are given in Table 5.

4. DISCUSSION

From the results of the numerical investigation in Section 3, a number of interesting trends have become evident, and are described in the following subsections.

4.1 Uncracked Specimen

The results in Table 1 indicate that using a bonded rivet gives rise to a reduction in the maximum principal stress in the specimen of the order of 50%. This reduction is a maximum for the thinnest adhesive thickness, and decreases as the adhesive thickness is increased. When the adhesive is assumed to have failed by debonding over part of the interface the reduction in the stress level is approximately 40%.

4.2 Cracked Specimen

There are a number of important points which arise from this analysis, viz.:

(i) A bonded rivet or sleeve significantly reduces the stress intensity factor. This is true even after a significant proportion of the adhesive has failed.

(ii) The values of the stress intensity factors for a crack on one side of a bonded rivet hole and for a crack of the same length, on both sides of the hole are very similar, as can be seen from Tables 2 and 3.

(iii) From Table 2, by comparing the values in the 'No Hole' column with the other values, we see that as the crack length increases, a crack at a bonded rivet hole behaves very much as if the specimen does not contain a hole at all. For specimen 1 this asymptotic behaviour is effectively reached at a crack length of approximately 2·5 mm. This is particularly important since a hand-book solution is available for the 'No Hole' case [11]; it appears then that this solution could be conveniently used in some instances for estimating the stress intensity factor for a cracked hole containing a bonded insert.

4.3 Experimental Results

The large reductions in the stress intensity factors indicated in our numerical investigation should give rise to a significant increase in the fatigue life of a specimen with an adhesively bonded insert. This effect has been confirmed in a companion paper [2], as can be seen from the experimental results given in Table 6, which deal with the life of specimen number 1 under a typical service-load spectrum.

5. CONCLUSION

This paper has shown that the stress concentration factors at a hole and the stress intensity factors at a cracked hole are significantly reduced if the hole contains a bonded rivet or a bonded steel sleeve. It has been shown that, as the crack length increases, the solution for a cracked hole containing a bonded insert approaches that for a crack alone, i.e. with no hole in the specimen. For the latter case a hand-book solution is readily available.

The next stage of this project involves a joint numerical and experimental investigation into the repair of a quadrant crack emanating from a fastener hole.

6. ACKNOWLEDGEMENT

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TABLE 1

Maximum Principal Stress for Uncracked Specimen No. 1 at $\theta = 0$ with Bonded Rivet

Case Considered	Maximum Principal Stress MPa
Unfilled hole	853
Bonded Rivet	
$t = 0{\cdot}0127$ mm	337
$t = 0{\cdot}0254$ mm	387
$t = 0{\cdot}0381$ mm	456
Bonded Rivet—	
Partial debonding of adhesive	
$t = 0{\cdot}0127$ mm	427
$t = 0{\cdot}0254$ mm	483
$t = 0{\cdot}0381$ mm	580

t = adhesive thickness

TABLE 2

Stress Intensity Factors for Specimen No. 1 Cracked on One Side

Crack length a mm	Stress Intensity Factor K MPa$\sqrt{m}$							
	Bonded Rivet						No hole	Open hole
	$t = 0{\cdot}0127$ mm		$t = 0{\cdot}0254$ mm		$t = 0{\cdot}0508$ mm			
	A	B	A	B	A	B		
0·5	9·1	12·1	10·6	14·2	12·7	16·9	–	25·6
0·9	11·3	15·0	12·8	16·9	14·8	19·5		27·8
1·5	14·3	18·4	–	—	–	–	13·1	29·9
2·0	15·9	20·1	–	—			14·8	30·9
2·6	17·1	21·4	–	—	19·8		16·0	32·1

A = No adhesive failure.
B Partial debonding of adhesive.

TABLE 3

Stress Intensity Factors for Specimen No. 1 Cracked on Both Sides, $t = 0{\cdot}0127$ mm

Crack length a mm	Stress Intensity Factor K MPa$\sqrt{m}$		
	Unfilled hole	Bonded Rivet	Bonded Rivet—Partial debonding of adhesive
0·5	26·4	9·1	12·2
0·9	29·7	11·3	15·3
1·5	33·9	14·5	18·8
2·3	39·2	17·6	22·6

TABLE 4

Stress Intensity Factors for Specimen No. 2 Cracked on One Side with Bonded Rivet, $t = 0{\cdot}0254$ mm

Crack length a mm	Stress Intensity Factor K MPa
1·0	12·9
1·8	16·0
3·0	20·2
4·0	22·5
4·6	24·2

TABLE 5

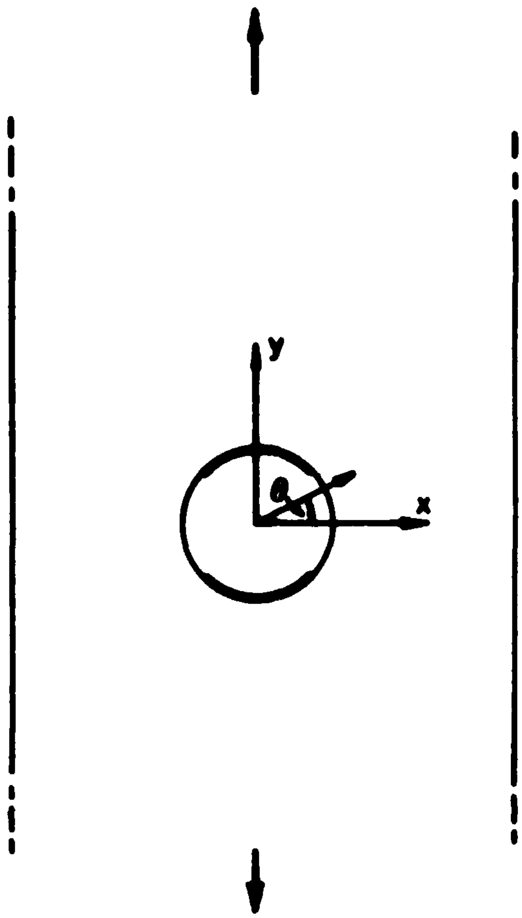
Stress Intensity Factors for Specimen No. 2 Cracked on One Side, $t = 0 \cdot 0254$ mm

Crack length a mm	Stress Intensity Factor K MPa$\sqrt{m}$	
	Bonded steel sleeve	Bonded sleeve—Partial debonding of adhesive
1·0	13·35	16·3
1·8	16·5	20·3
3·0	20·7	25·3
4·6	26·0	28·9

TABLE 6

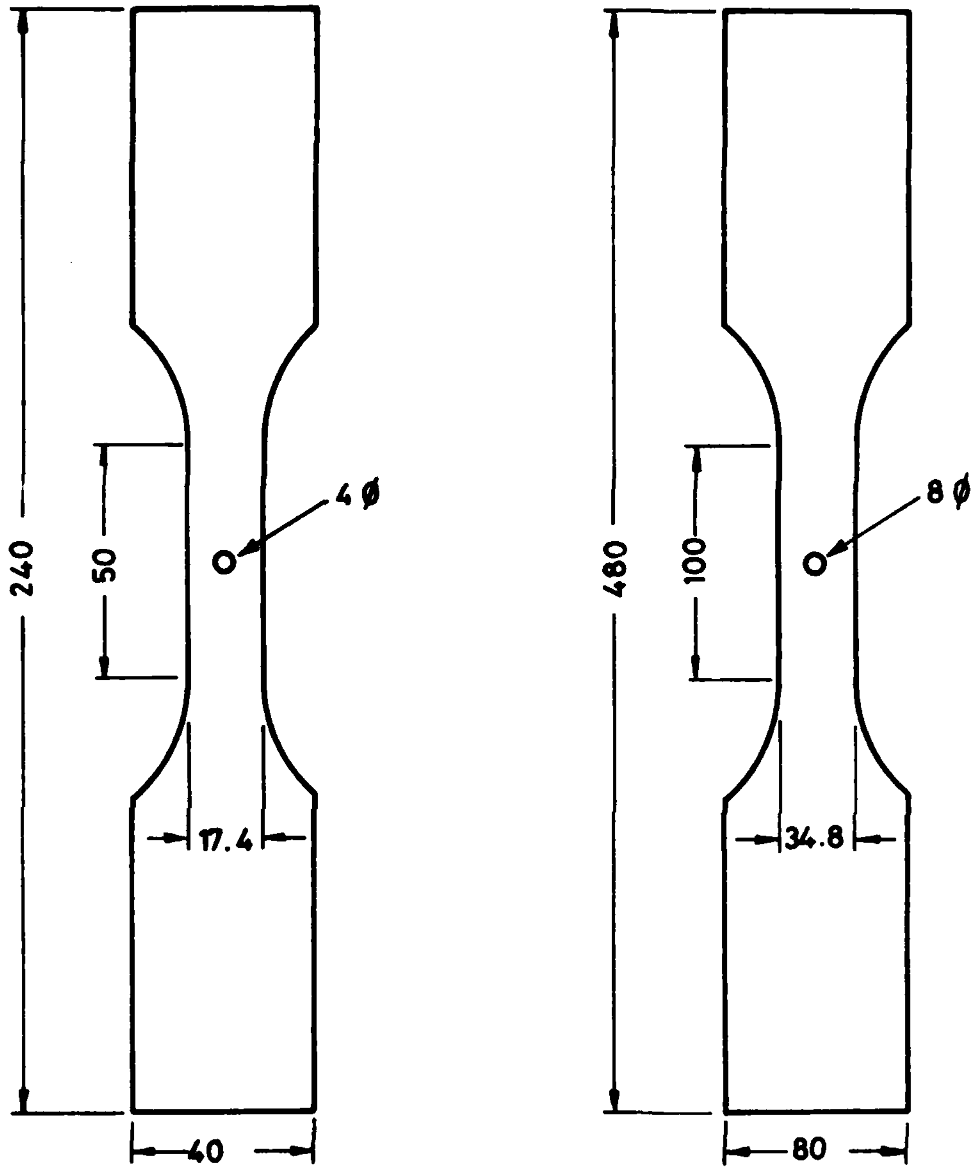
Experimental Fatigue Test Results for Specimen No. 1

Specimen Condition	Fatigue life (flights)
Open hole	5929
Cold worked open hole	8212
Hole with bonded rivet	15688



Debonding between; 45° < θ < 135° and 225° < θ < 315°

FIG. 1 DEBONDED REGION FOR ADHESIVE FAILURE ANALYSIS



(a) Specimen No 1

(b) Specimen No 2

All dimensions in mm

FIG. 2 DIMENSIONS FOR SPECIMENS 1 AND 2

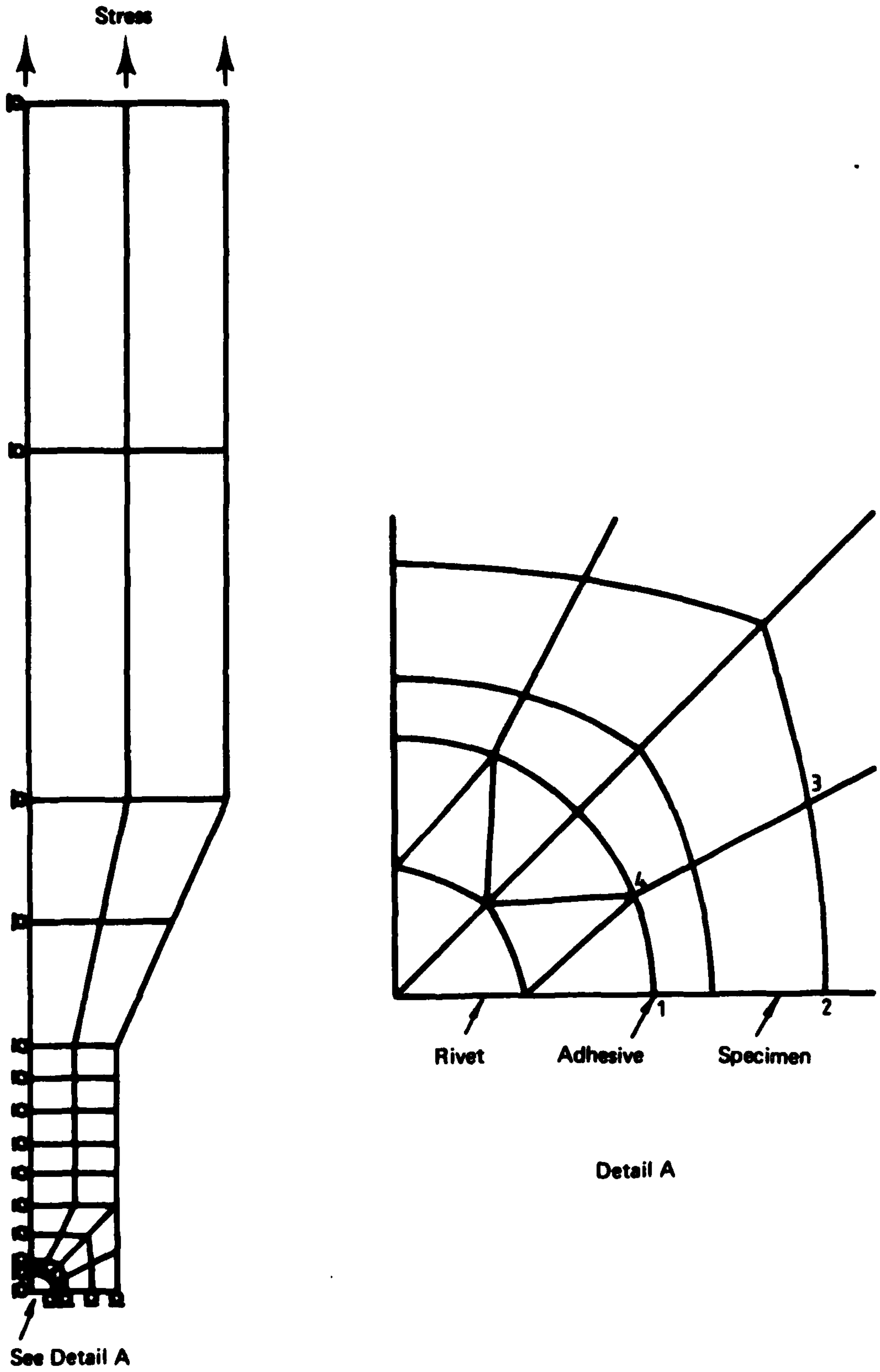
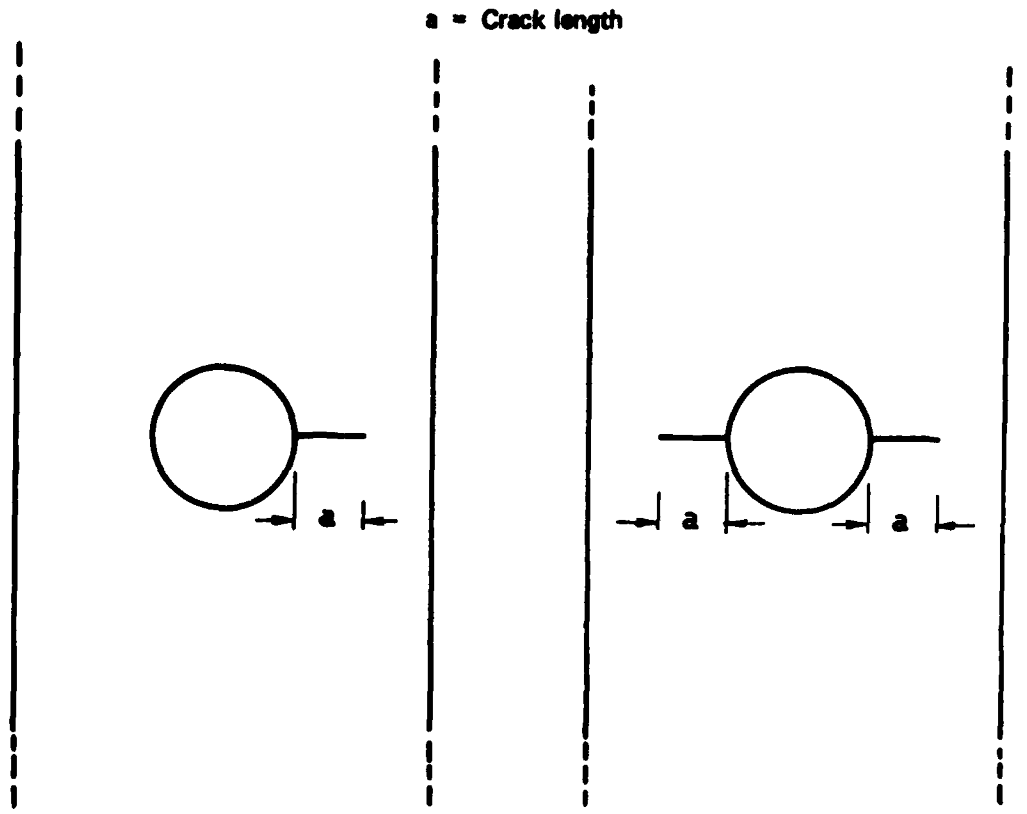


FIG. 3 FINITE ELEMENT MESH FOR SPECIMEN NO.1
UNCRACKED WITH BONDED RIVET



(a) Specimen cracked on one side only

(b) Specimen cracked on both sides

FIG. 4 CRACK GEOMETRY CASES

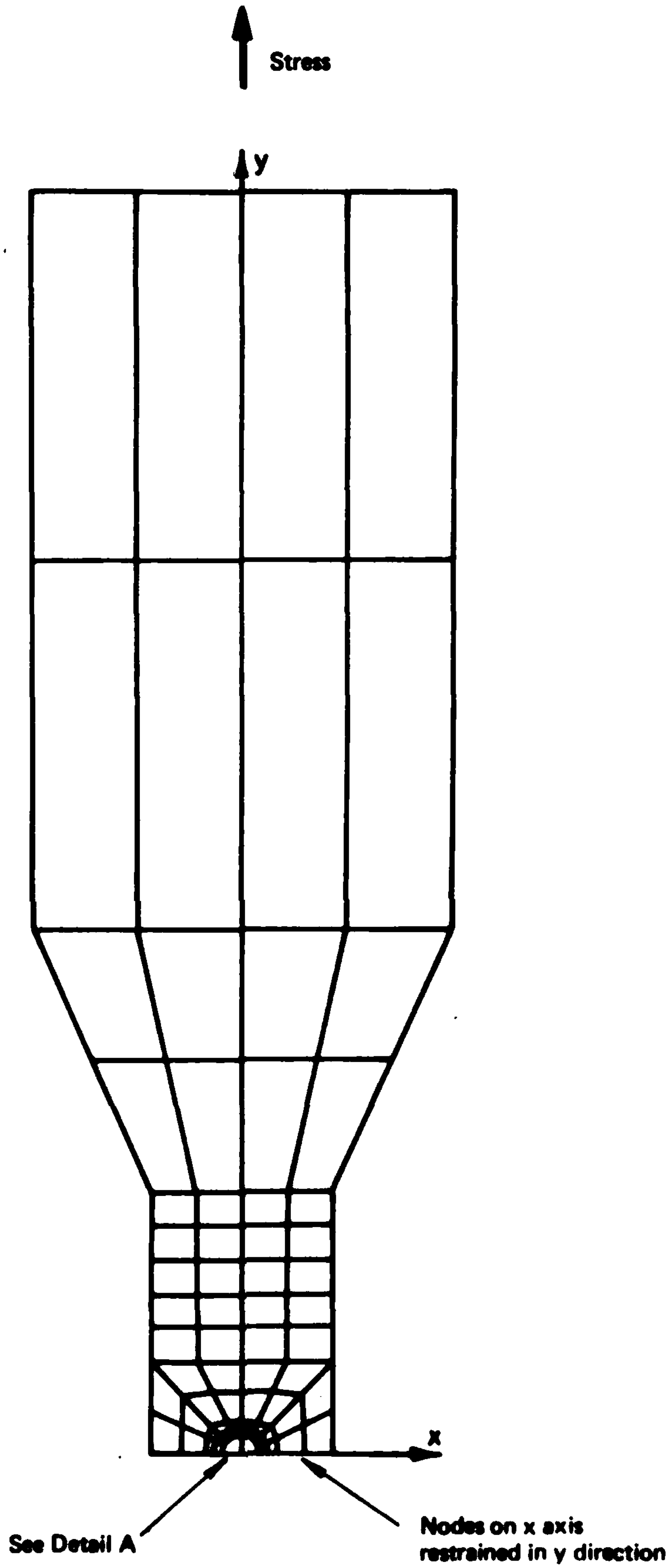


FIG. 5(a) FINITE ELEMENT FOR SPECIMEN NO. 1 CRACKED ON ONE SIDE WITH BONDED RIVET

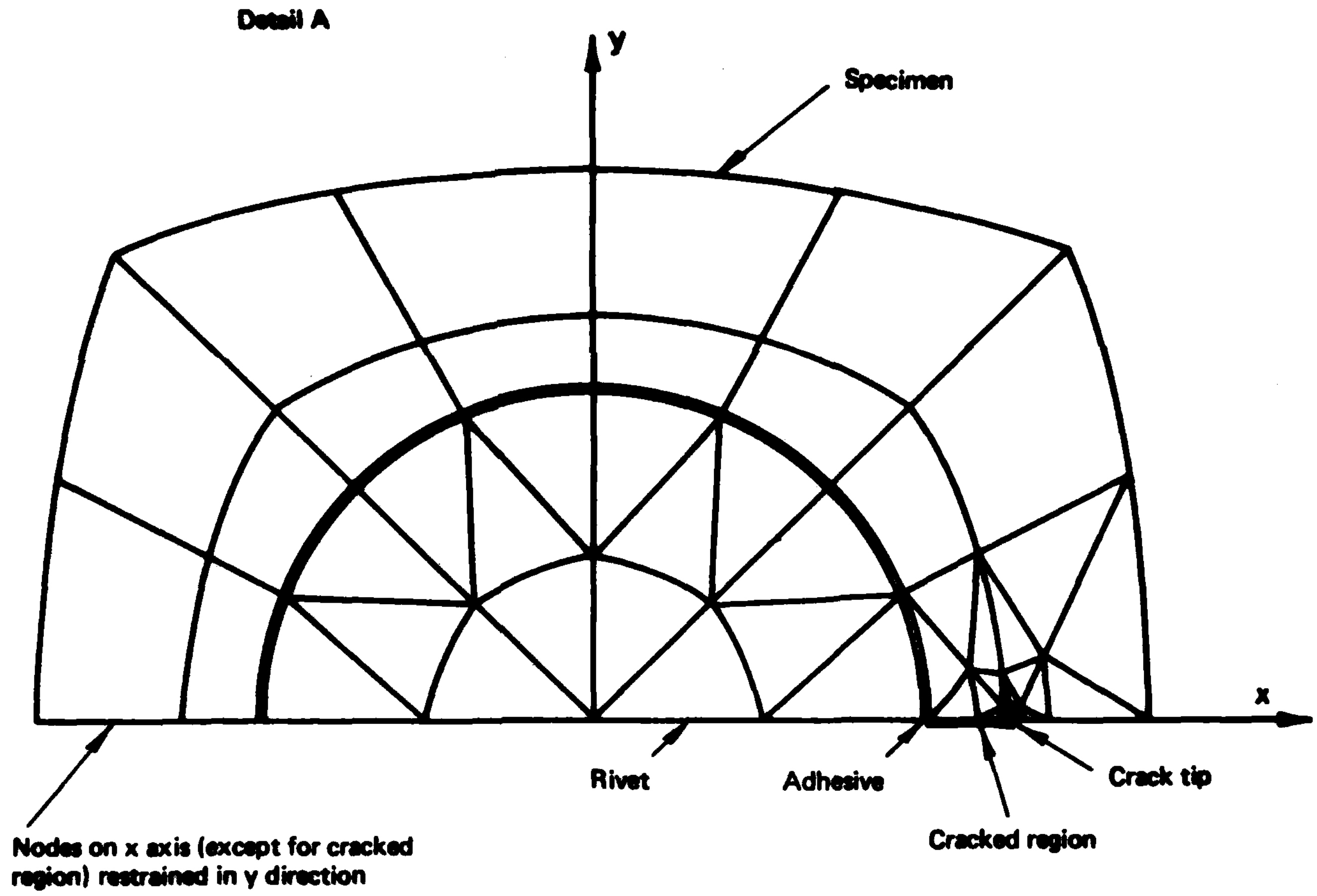


FIG. 5(b) FINITE ELEMENT MESH FOR SPECIMEN NO 1 CRACKED ON ONE SIDE WITH BONDED RIVET

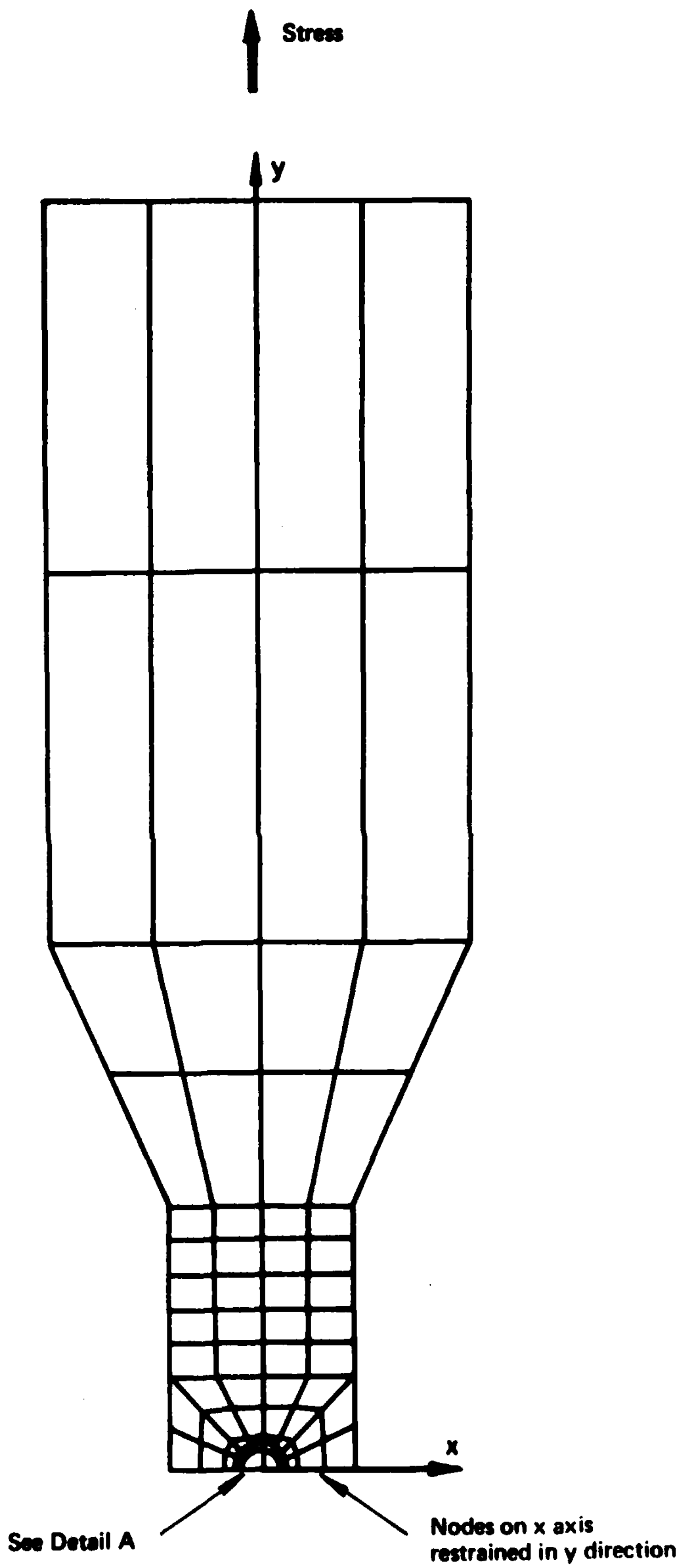


FIG. 6(a) FINITE ELEMENT FOR SPECIMEN NO 2 CRACKED ON ONE SIDE WITH BONDED RIVET

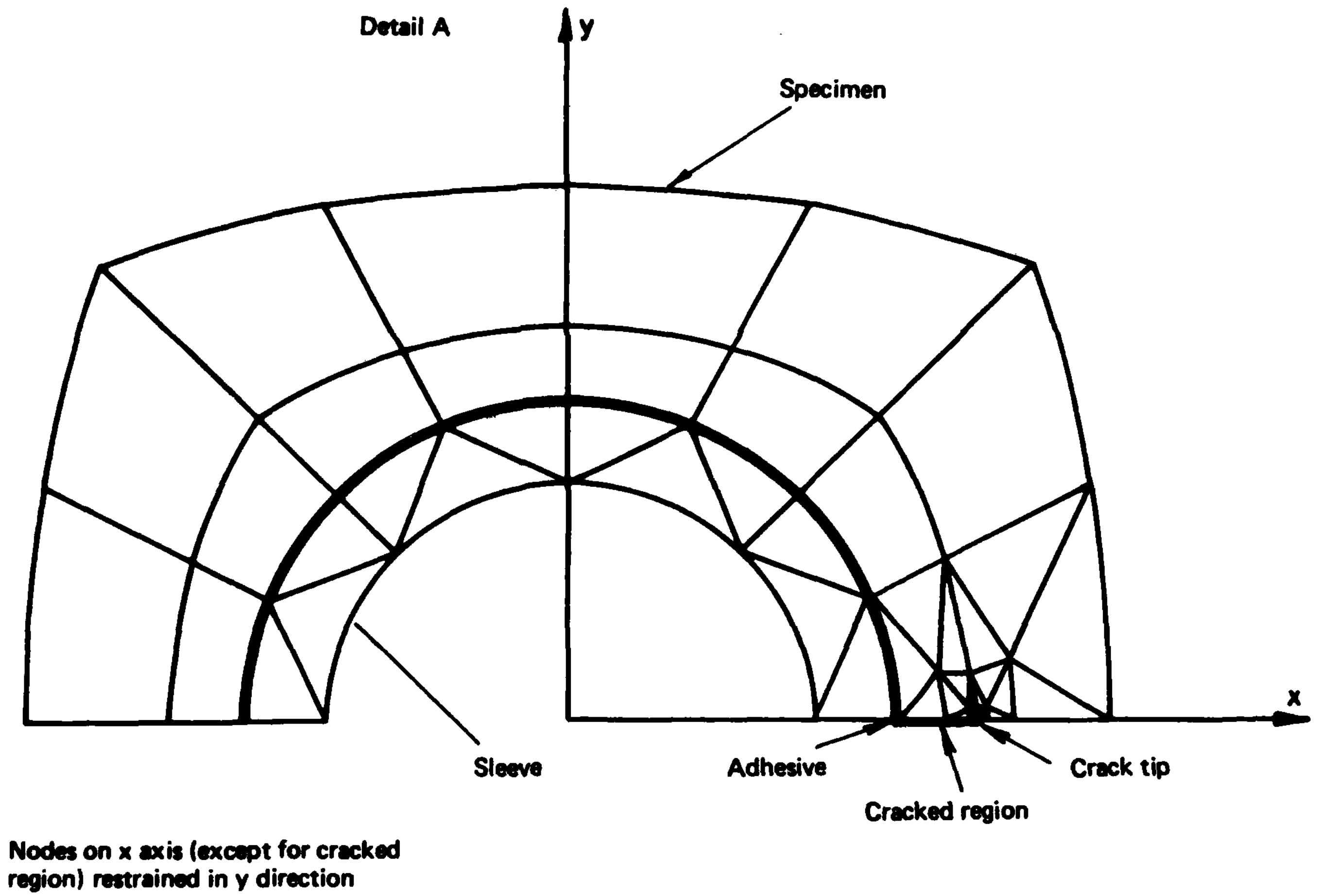


FIG. 6(b) FINITE ELEMENT MESH FOR SPECIMEN NO 2 CRACKED ON ONE SIDE WITH BONDED SLEEVE

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Stress analysis	Fatigue life	12010
Inserts		
Adhesive bonding		

16. Abstract

Recent experimental work has shown that adhesively bonded inserts can significantly increase the fatigue life of fastener holes. This paper concentrates on developing an understanding of the mechanisms which give rise to the observed increase in life. Cracked as well as uncracked fastener holes are considered. It is shown that both the stress concentration factors, and the stress intensity factors are significantly reduced by the use of either bonded rivets or bonded sleeves. It is also shown that the stress intensity factor, for a cracked hole repaired by a bonded insert, can be obtained by analogy with readily available solutions.

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