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A CRACK OPENING DISPLACEMENT APPROACH TO CRACK PATCHING,(U)

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STRUCTURES NOTE 455

# A CRACK OPENING DISPLACEMENT APPROACH TO CRACK PATCHING


by

R. JONES and R. J. CALLINAN



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# A CRACK OPENING DISPLACEMENT APPROACH TO CRACK PATCHING

by

R. JONES ~~and~~ R. J. CALLINAN

*SUMMARY*

*The results of a numerical investigation into crack patching indicate that a modified form of the crack opening displacement approach may be useful in estimating the effect that fibre composite patches have on cracks in thin sheets.*

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16. *ABSTRACT*

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CONTENTS

## NOTATION

| | |
|---|---|
| $\sigma$ | Applied tensile stress. |
| $G_{12}$, $G_{13}$, $G_{23}$ | Shear moduli of the patch. |
| $E_1$, $E_2$ | Young's moduli of the patch. |
| $\gamma_{12}$ | Poissons ratio of the patch. |
| $t_a$ | Thickness of adhesive layer. |
| $t_s$ | Thickness of sheet. |
| $t_0$ | Thickness of the patch. |
| $K_{1p}$ | Stress intensity factor for the patched crack. |
| $K_{1u}$ | Stress intensity factor for the unpatched crack. |
| $a$ | Crack half length. |
| $\alpha$ | Characteristic length. |
| $v_p$ | Opening of the patched crack. |
| $v_u$ | Opening of the unpatched crack. |
| $\epsilon_{py}$ | Strain in the patch in the $y$ direction. |
| $v_{pa}$ | Displacement in the patch in the $y$ direction. |

## 1. INTRODUCTION

This paper forms part of a detailed investigation into the repair of aircraft structural components, using bonded composite overlays, currently underway at the Aeronautical Research Laboratories, Australia [1–6]. To date a large number of cracked components have been successfully repaired in this fashion; these include wing skins, wing planks, and wheels (see Ref. [2]). The present paper is concerned with an observed correlation between the reduction of the opening of a patched crack, at any point along the crack, and the reduction in the stress intensity factor due to patching. This correlation raises the possibility of using crack opening displacement measurements as a measure of patch efficiency.

## 2. CORRELATION

Let us begin by considering a thin rectangular sheet of dimensions 508 mm × 635 mm × $t_s$ mm, where the thickness $t_s$ will be allowed to vary, subjected to a uniform tensile stress $\sigma$. The sheet contains a central crack 38·1 mm long which is patched by a boron epoxy laminate covering the entire length of the crack. The laminate is uniaxial, the fibres lying perpendicular to the length of the crack. The lateral dimensions of the patch are 152·4 mm × 50·8 mm × $t_p$ where $t_p$ is the thickness of the patch and will be allowed to vary (see Fig. 1).

The patch is bonded to the sheet with an epoxy resin of thickness $t_a$. The Young's modulus of the sheet is 71·02 GPa while the Poisson's ratio is 0·32. The moduli of the laminate are

$$E_1 = 208 \cdot 1 \text{ GPa} \qquad G_{12} = G_{13} = 7 \cdot 24 \text{ GPa}$$

$$E_1/E_2 = 8 \cdot 18 \qquad G_{23} = 4 \cdot 94 \text{ GPa}$$

$$\gamma_{12} = 0 \cdot 1677$$

where the 1-axis is in the fibre direction;
the 2-axis is parallel to the crack;
the 3-axis is in the thickness direction.

This problem was analysed using the finite element methal and uses the advanced crack tip element developed by the authors in [3] and the adhesive element, which allows for transverse shear deformation in the sheet and the patch, described in [4]. Various types of patches were considered including constant thickness patches applied to one or both sides of the sheet and stepped thickness patches (see Fig. 2).

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5. M. J. Davis.—Stress Intensity Reduction by Strategic Reinforcement, Proc. 1977 Conference Australian Fracture Group, pp. 90–101, (1977).

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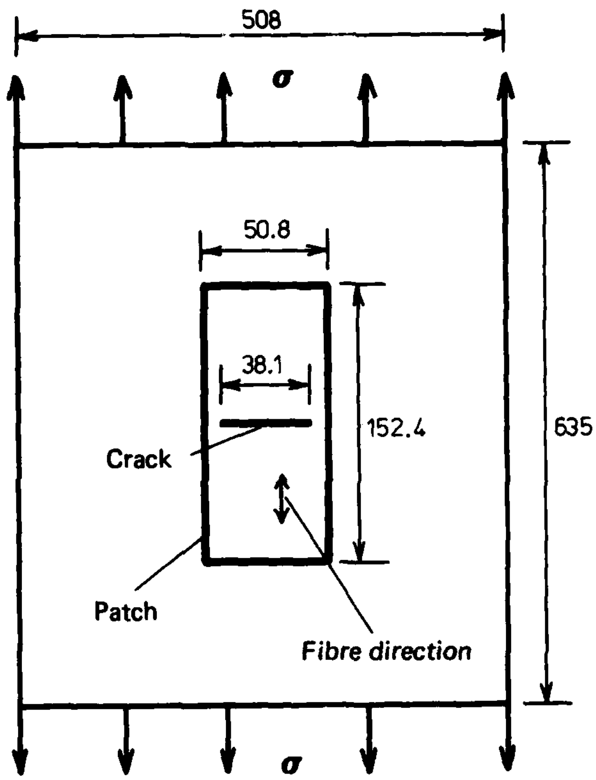
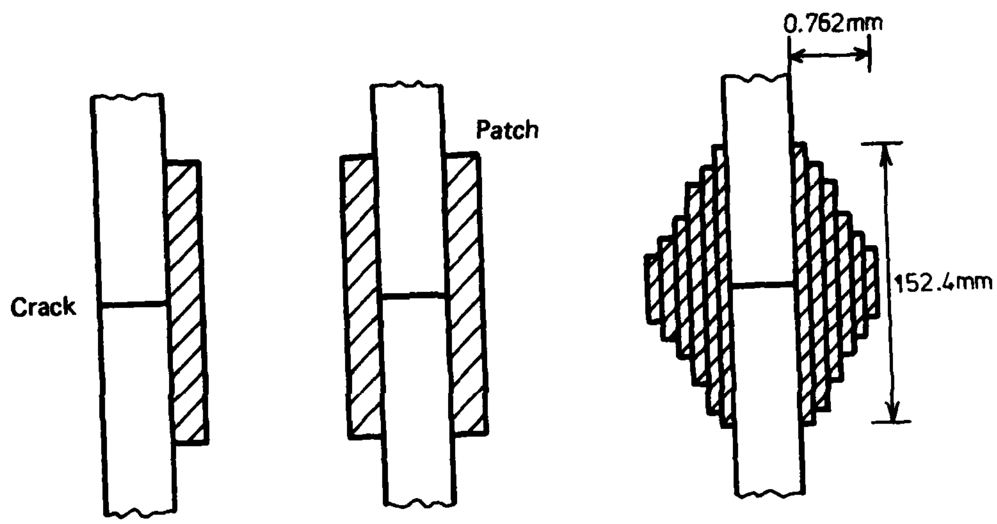



**FIG 1 PATCHED TENSION PANEL (dimensions in mm)**

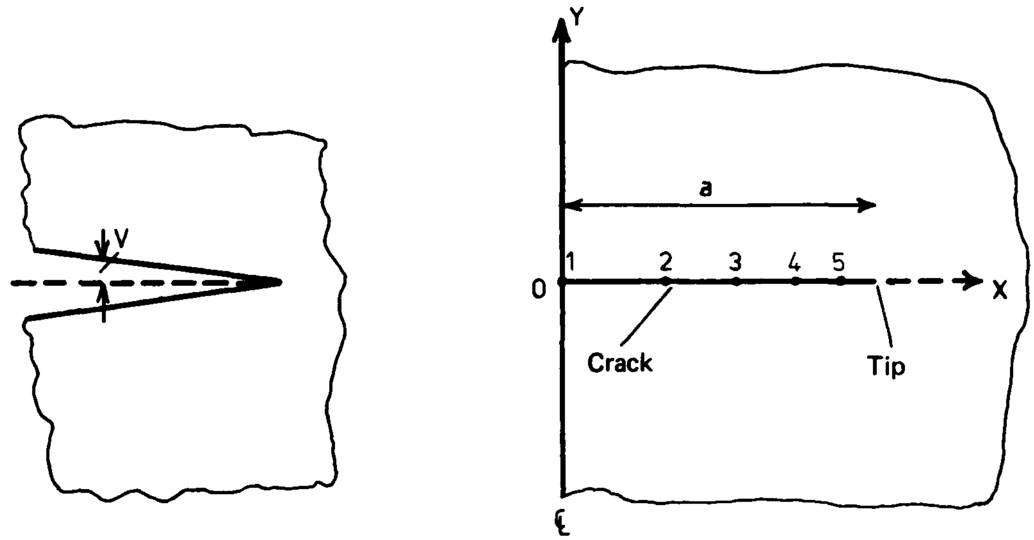



a) Constant thickness patch (one sided)

b) Constant thickness patch (two sided)

c) Stepped thickness patch (two sided) equal steps

FIG 2 PATCH GEOMETRY




(a) Crack opening displacement

(b) Points of evaluation of the patch efficiency

FIG 3.

The point of interest in the present investigation is the correlation between the calculated values of the stress intensity factor for a patched crack and the opening up of the crack at various points along its length. This correlation is studied by evaluating on the one hand the non-dimensionalized reduction in the stress intensity factor given by,

$$1 - K_{1p}/K_{1u}$$

where $K_{1p}$ is the stress intensity factor for the patched crack and $K_{1u}$ is the stress intensity factor for the unpatched crack. On the other hand we also evaluate, at various points along the crack, a quantity which we term the "patch efficiency" and which we define by

$$\text{patch efficiency} = 1 - v_p/v_u \qquad (1)$$

where $v_p$ is the displacement of a point on the patched crack and $v_u$ is the displacement of the corresponding point on the unpatched crack. These displacements are in the direction perpendicular to the length of the crack i.e., the crack opening displacements. With this notation the unpatched crack yields a patch efficiency of zero, whilst a patch efficiency of unity occurs when the patched crack does not open up during loading.

In all cases studied the patch efficiency was evaluated at the five points along the crack shown in Figure 3*b*. The coordinates of points 1–5 are (0, 0), ($a$/3, 0), (2$a$/3, 0), (0·76$a$, 0), (0·86$a$, 0) respectively where $a$ is the half crack length. It should be mentioned that it is a well established result in linear elastic fracture mechanics that the crack opening displacement, in the case of unpatched cracks, very close to a crack tip (such as point 5) is directly proportional to the stress intensity factor.

In Table 1 we see the effect that increasing the thickness of the patch has upon both the calculated values of the patch efficiency and the reduction in the stress intensity factor; these results are all for constant thickness patches.

**TABLE 1**
**Correlation for Constant Thickness Patches**
($t_a$ = 0·1016 mm, $t_s$ = 2·29 mm)

| Patch Thickness (mm) on one side only | Patch efficiency at points: | | | | | $1-K_{1p}/K_{1u}$ |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Reinforced on each side of the sheet | | | | | | |
| 0·762 | 0·90 | 0·88 | 0·88 | 0·88 | 0·88 | 0·88 |
| 0·508 | 0·88 | 0·86 | 0·86 | 0·86 | 0·87 | 0·87 |
| ·3 81 | 0·86 | 0·85 | 0·84 | 0·85 | 0·86 | 0·86 |
| ·2 54 | 0·84 | 0·82 | 0·81 | 0·82 | 0·85 | 0·85 |
| 1 27 | 0·78 | 0·76 | 0·76 | 0·77 | 0·79 | 0·79 |
| Reinforced on one side only | | | | | | |
| 1·016 mm | 0·81 | 0·80 | 0·79 | 0·79 | 0·81 | 0·81 |
| 0·762 | 0·79 | 0·78 | 0·77 | 0·77 | 0·79 | 0·79 |
| 0·508 | 0·77 | 0·75 | 0·74 | 0·74 | 0·76 | 0·76 |
| 0·254 | 0·71 | 0·69 | 0·68 | 0·69 | 0·73 | 0·73 |
| 0·127 | 0·63 | 0·61 | 0·61 | 0·62 | 0·66 | 0·66 |

Here we see that, to a reasonable approximation the patch efficiency is constant along the entire length of the crack. This constant value agrees closely with the reduction in the stress intensity factor due to patching.

Whereas in Table 1 the thickness of the sheet was held constant at $t_s$ = 2·29 mm and the patch thickness was varied, in Table 2 the thickness of the sheet was allowed to vary. Here the patch is the step thickness patch shown in Figure 2(*c*) which is of the same plan form as the previous patches; this patch comprises six layers of boron on each side of the sheet.

**TABLE 2**
**Correlation for Step Thickness Patches**
($t_a = 0{\cdot}1016$ mm)

| Sheet Thickness (mm) | Patch efficiency at points | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | $1-K_{1p}/K_{1u}$ |
| 5·08 | 0·78 | 0·77 | 0·76 | 0·76 | 0·78 | 0·78 |
| 3·81 | 0·84 | 0·83 | 0·81 | 0·82 | 0·83 | 0·83 |
| 2·29 | 0·91 | 0·90 | 0·89 | 0·89 | 0·89 | 0·89 |
| 1·27 | 0·95 | 0·95 | 0·94 | 0·94 | 0·94 | 0·94 |
| 0·64 | 0·98 | 0·97 | 0·97 | 0·97 | 0·97 | 0·97 |

Again we see that the patch efficiency is virtually constant along the entire length of the crack and agrees closely with the reduction in stress intensity.

So far we have only considered an adhesive thickness of 0·1016 mm, which is commercially available; another thickness which is also available is 0·2032 mm. Table 3 shows the effect that this twofold increase in adhesive thickness has upon the patch efficiency for the stepped patch considered above and for a sheet thickness of 2·29 mm.

**TABLE 3**
**Further Correlation for Step Thickness Patches**
($t_s = 2{\cdot}29$ mm)

| Patch efficiency at points | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | $1-K_{1p}/K_{1u}$ |
| 0·88 | 0·89 | 0·88 | 0·88 | 0·88 | 0·88 |

Yet again we see that the patch efficiency is effectively constant along the entire crack length, and coincides with the reduction in the stress intensity factor.

We thus see that, in this limited study, the patch efficiency is a good estimate of the reduction in the stress field at the tip of a crack. Furthermore, computing the patch efficiency at the centre of the crack, or at a point removed from the tip, removes the necessity of having special crack tip elements and yet still allows an estimate to be made of the reduction in the stress intensity factor due to patching.

## 3. PATCH EFFICIENCY MEASUREMENT TECHNIQUES

The concept of patch efficiency may also be a useful experimental tool since the opening of the crack may easily be measured when the crack is unpatched and may be derived as follows, from strain gauge measurements on the patch when the crack is patched.

Let us consider a panel with a centrally located crack, of length $2a$. Define a system of $x$, $y$ coordinates with origin at the centre of the crack and with the $y$ axis perpendicular to the crack. Then in the case of mode 1 fracture the displacement, in the $y$ direction, at any point $(x, \alpha)$ in the patch is given by

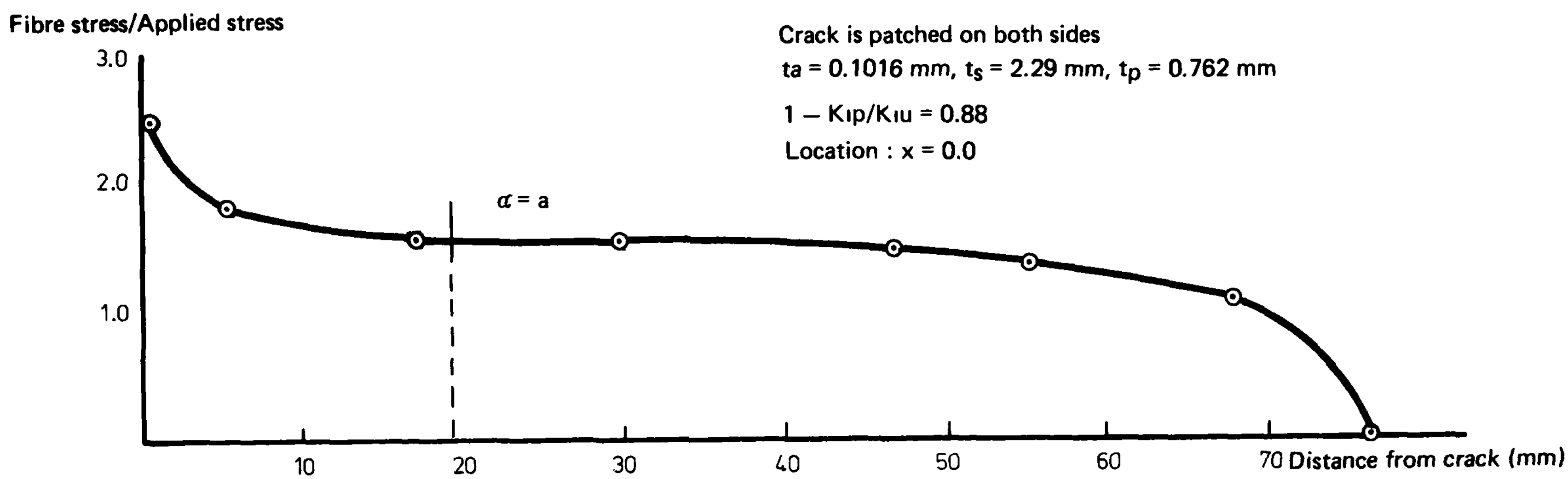



FIG 4(a). VARIATION OF FIBRE STRESS ALONG PATCH CENTER LINE

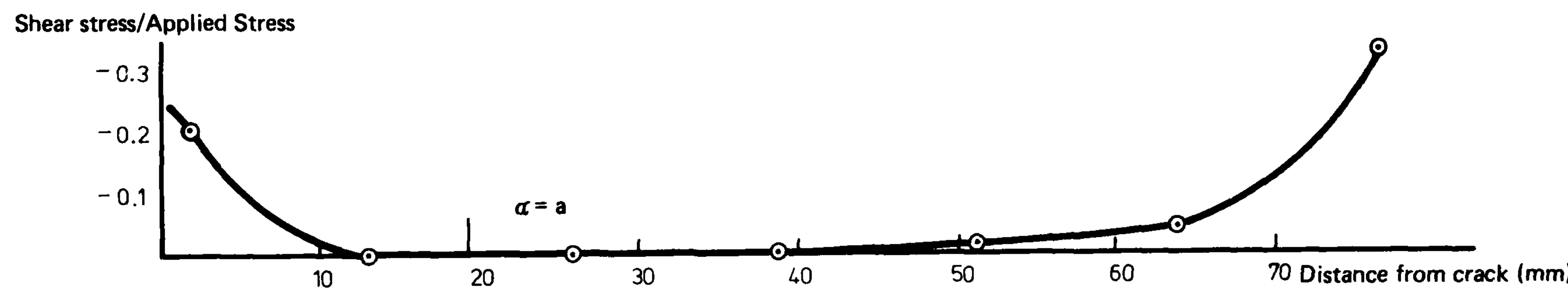



FIG 4(b). VARIATION OF SHEAR STRESS ALONG PATCH CENTER LINE

$$v_{pa}(x, \alpha) = \int_0^{\alpha} \epsilon_{py}\, dy \tag{2}$$

where $\epsilon_{py}$ is the strain in the patch in the $y$ direction. The effect that the crack has upon the strain $\epsilon_{py}$ in the patch is discussed in detail in Reference [7] and is shown in Figure 4 for the full thickness patch, of Figure 2($a$), which has $t_a = 0{\cdot}1016$ mm, $t_s = 2{\cdot}29$ mm and $t_p = 0{\cdot}762$ mm. From these references and from Figure 4 we see that we can choose a value for $\alpha$, which is less than the crack length, such that at $y = \alpha$ the shear stress in the adhesive and the derivative of the extensional strain in the patch i.e. $d\epsilon_{py}/dy$ are both effectively zero.

Since, at this point, the shear stress is zero the movement, in the $y$ direction, in the sheet, which we will denote by $v_s(x, \alpha)$, is exactly equal to the movement in the patch, i.e.

$$\begin{aligned} v_s(x, \alpha) &= v_{pa}(x, \alpha) \\ &= \int_0^{\alpha} \epsilon_{py}\, dy \end{aligned} \tag{3}$$

Expanding $v_s(x, \alpha)$ by means of Taylor's theorem we see that

$$v_s(x, o) = v_s(x, \alpha) - \alpha\left(\frac{\partial v_s}{\partial y}\right)_{y=\alpha} + o(\alpha^2) \tag{4}$$

However we have chosen $\alpha$ such that at $y = \alpha$ $v_s = v_{pa}$ and as a result

$$\begin{aligned} \left(\frac{\partial v_s}{\partial y}\right)_{y=\alpha} &= \left(\frac{\partial v_{pa}}{\partial y}\right)_{y=\alpha} \\ &= \epsilon_{py}(x, \alpha) \end{aligned} \tag{5}$$

(i.e. strain in the patch = strain in the sheet)
Consequently substituting for $\partial v_s/\partial_y$, as given by equation (5), into equation (4) and rearranging terms we see that

$$v_s(x, o) = v_s(x, \alpha) - \alpha\epsilon_{py}(x, \alpha) \tag{6}$$

where the terms of order $\alpha^2$ and higher have been omitted since at $x = \alpha$ the derivatives of $\epsilon_{py}$ with respect to $y$ are zero.

Recalling that $v_s(x, \alpha) = \int_0^{\alpha} \epsilon_{py}\, dy$ we finally obtain the relationship

$$v_s(x, o) = \int_0^{\alpha} \epsilon_{py}(x, \alpha)\, dy - \alpha\epsilon_{py}(x, \alpha) \tag{7}$$

Since $v_s(x, o)$ is the opening of the crack we see that the opening of the crack at any point $x$ along its length may be directly calculated once the strain in the patch is known.

As can be seen from Reference [4] (Figs 5, 6 ,7 and 8) as $x$ approaches the value of $a$, i.e. near the crack tip, the value of $\alpha$ necessary to satisfy the requirements of zero shear stress etc. reduces significantly. For example whereas from Figure 4, where $x = 0$, the minimum allowable value of $\alpha$ is approximately $\alpha = a$ (the half crack length) from Figure 8 of Reference [4], for the case $x = a$, the minimum allowable value is approximately $a/3$.

## 4. CONCLUSION

A limited numerical study has shown that there is a very good correlation between the patch efficiency and the reduction in the stress intensity factor due to patching. We have also

7. R. Jones and R. J. Callinan.—A Design Study in Crack Patching. A.R.L. Structures Report 376, 1979.

seen that the patch efficiency can be obtained from a knowledge of the crack opening displacements of the unpatched crack and from strain gauge measurements on the patch. This approach may have some advantages over the present method for experimentally estimating the reduction in the stress intensity factor which is based on the increase in fatigue life due to patching. Indeed, since this reduction is often dramatic, the fatigue life is generally increased by at least an order of magnitude and quite often no crack growth is recorded.

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| R. J. Callinan | 29 |
| B. C. Hoskin | 30 |
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| Sandia Group Research Organisation | 153 |
| American Institute of Aeronautics and Astronautics | 154 |
| Applied Mechanics Review | 155 |
| The John Crerar Library | 156 |
| The Chemical Abstracts Service | 157 |
| Bell Helicopter Textron | 158 |
| Boeing Commercial Airplane Co.: | |
| Head Office, Mr. R. Watson | 159 |
| Industrial Production Division | 160 |
| Cessna Aircraft Co., Executive Engineer | 161 |
| Lockheed Missiles and Space Company | 162 |
| Lockheed California Company | 163 |
| Lockheed Georgia Company | 164 |
| McDonnell Douglas Corporation, Director | 165 |
| Metals Abstracts, Editor | 166 |
| Calspan Corporation (Formerly Cornell Aero Labs.) | 167 |

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| United Technologies Corporation: Pratt and Whitney Aircraft Group | | 168 |
| Battelle Memorial Institute, Library | | 169 |
| **Universities and Colleges** | | |
| Florida | Aero. Engineering Dept. | 170 |
| Stanford | Department of Aeronautics Library | 171 |
| Brooklyn Inst. of Polytech. | Polytech. Aeronautical Labs. Library | 172 |
| California Inst. of Technology | Guggenheim Aeronautical Labs. Library | 173 |
| Massachusetts Inst. of Technology | Library | 174 |
| Spares | | 175–184 |