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Cracks at Structural Holes

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INTRODUCTION

The application of fracture mechanics to fatigue-crack propagation and residual strength has seen much progress in the last decade. Yet, the complex geometries occurring in engineering structures pose many problems that have yet to be solved. One of these problems is the interaction of a crack and a hole. Cracks usually start in regions of stress concentration, which occur despite careful detail design. Hardly any structure can be conceived that does not contain holes, such as fastener holes, and other structural holes (e.g., access holes). Since a hole is a source of stress concentration, and since there are so many holes involved in any one structure, it may be anticipated that cracks in service will often start at holes. A review of USAF aircraft structural failures [1] revealed that, indeed, around 30 percent of the crack origins were bolt or rivet holes.

The most elementary problem of a through-the-thickness crack emanating from a hole can be treated now with some success. However, cracks at holes usually start out as corner cracks or as surface flaws from the hole wall. This problem is more difficult to analyze. Further complications are due to the presence of a fastener in the hole, interference, load transfer to the underlying structure, and residual stresses. There has been some useful work done on each of these subjects, but a general and satisfactory methodology is not yet available. Many of the problems are associated with the determination of reliable values for the stress-intensity factor. Others are due to uncertainties in flaw development, anisotropy, and fracture and fatigue criteria.

Another series of problems arises when considering the behavior of cracks approaching holes. Here, one is mainly concerned about the crack stopping capabilities of the hole, both as a delay for fatigue cracking and as an arrest of a fast running unstable crack. Again, complications occur due to the presence of fasteners, load transfer, and residual stresses.

This report is intended to give a review of the state of the art of dealing with cracks at holes in engineering structures. The problem of the interaction of cracks and holes is considered in its broadest sense. An attempt is made to establish the usefulness of existing analysis methods and their limitations for practical application. Some problems can be dealt with only in a speculative way, because detailed information does not exist. They are discussed in order to reveal where the problem areas are. A final section is devoted to a factual survey of problems that would be worthwhile solving through future research and development.

THROUGH CRACKS EMANATING FROM HOLES

The Stress-Intensity Factor

On the basis of the work by Bowie [2], the stress-intensity factor for a through crack at a hole in an infinite plate (Figure 1) is given by

$$K=\sigma\sqrt{\pi a}\quad f_B\left(\frac{a}{D}\right) \tag{1}$$

where a is the size of the crack as measured from the edge of the hole, and D is the hole diameter. The function $f_B\,(a/D)$ can be given in tabular or graphical form as f_{BI} for a single crack and f_{B2} for the symmetric case with two cracks. Grandt[3] has recently developed a least squares fit to f_B of the form

$$f_B\,(a/D)=\frac{C_1}{C_2+a/D}+C_3, \tag{2}$$

where C_1, C_2, C_3, have values as given in Figure 1.

If the crack is not too small with respect to the hole size, the hole may be considered part of the crack. The total defect size is then given by the physical crack length plus the hole diameter (Figure 1). The stress intensity is simply

$$K=\sigma\sqrt{\pi a_{eff}}\;. \tag{3}$$

By developing Equation (3) as

$$K=\sigma\sqrt{\pi a_{eff}}=\sigma\sqrt{\pi a}\sqrt{\frac{D}{2a}+\frac{1}{2}}=\sigma\sqrt{\pi a}\;f_{E1}\,(a/D) \tag{4}$$

for the asymmetric case, and

$$K=\sigma\sqrt{\pi a_{eff}}=\sigma\sqrt{\pi a}\sqrt{\frac{D}{2a}+1}=\sigma\sqrt{\pi a}\ f_{E2}(a/D) \qquad (5)$$

for the symmetric case, it follows that f_{BI} and f_{B2} in Equation (1) are replaced by f_{EI} and f_{E2}. A comparison of these functions is made in Figure 2. It appears that the differences between the exact functions and the engineering functions are small, if $a/D > 0.1$. In view of the accuracy of fracture mechanics analysis and the scatter in raw data, the simple Equation (3) can be used in many applications.

For the practical case of finite panels, the Isida (and Feddersen) width correction can be applied to Equations (1) and (3) as was shown by the finite-element calculations by Owen and Griffiths[4]. Results for a finite-size strip were obtained also by Cartwright and Ratcliffe[5], who conducted compliance measurements.

By the establishment of the stress-intensity factor, it should be possible to apply fracture mechanics principles to calculate fatigue-crack growth rates and residual strength of cracks at holes. There are only few test data available to support this. They are discussed in the following sections.

Fatigue-Crack Propagation

Fatigue through-cracks emanating from holes were studied by Rau and Burck (6). They used specimens of Udimet 700, containing small holes (0.007 - 0.020 inch diameter). In their analysis, they used the Bowie solution with an appropriate width correction. Since the object of their study was initiation rather than propagation, the only set of da/dn data they presented is the one shown here in Figure 3.

Due to the smallness of the holes, the crack size is soon on the order of the hole diameter. Hence, the effect of the hole can only be found at low ΔK values (i.e., up to 20 ksi $\sqrt{\text{in.}}$ at the applied ΔS of 95 ksi). In this region the data are close to the reference curve, indicating that the Bowie analysis works well for the prediction of crack growth from small holes in Udimet 700.

The test data [7] for 2024-T3 aluminum sheet collected in Figures 4, 5, and 6 allow a comparison of the Bowie analysis with the engineering analysis. Figure 4 presents the crack-growth curves for the symmetric case of cracks at both sides of the hole. The curve for a standard central crack is also given for comparison. The figure shows that crack growth from holes is very similar to the growth of a central crack, the differences being of the order of magnitude of the usual scatter in crack growth. This means that the hole can very well be considered part of the crack if the amount of crack extension covered is on the order of one or a few times the hole diameter, depending upon the hole size.

The da/dn data of the specimens in Figure 4 are plotted in Figure 5, using the Bowie analysis. Using Equation (5) would not have made much difference, as can be concluded also from Figure 4. According to Figures 4 and 5, the cracks emanating from holes grow slightly faster initially than normal central cracks at the same ΔK. This may be due [7] to the fact that crack closure is less effective due to the presence of the hole.

Test data[7] for the asymmetric case are presented in Figure 6. The ΔK values were corrected for crack eccentricity, using the Isida[8] correction. The crack-growth rates are consistently somewhat higher than for one tip of a central crack at the same ΔK, although most of the discrepancies are within the usual scatter band. One might expect that the difference between the symmetric central crack and the case considered in Figure 6 is in the ΔK history. For the central crack growing at two tips, the increase of ΔK per cycle is about $\sqrt{2}$ times as large as for the single crack at the hole. However, this difference in history cannot account for the discrepancies: drilling a hole at one tip of a central crack[7] immediately reduced the total growth rate by a factor of two, the da/dn for the one crack tip remaining the same; further crack growth followed the standard da/dn-ΔK curve. Apparently, the discrepancy between the test data and the reference curve in Figure 6 is due to other reasons presently not understood.

According to Figure 4 and similar data for single-edge cracks emanating from semicircular cutouts[7], it can be concluded that the growth of through cracks from holes in 2024-T3 aluminum can be treated by means of the Bowie ΔK. Since a relatively large part of the crack-growth life is spent while the crack is still small compared to the hole, predictive calculations often should make use of the Bowie solution. The prediction of crack growth can then be very accurate as shown by Crews and White[9]. Their predicted crack-growth curves (based on Bowie and on center crack basic data) are compared with actual test results in Figure 7. If crack growth covers one to several hole diameters, the Bowie analysis need not be used. Then the hole can simply be taken as part of the crack, and $2a_{eff}$ (Figure 1) as the total effective crack size.

A generalization of the available evidence does not seem justified. However, it is tentatively stated that the Bowie ΔK values are applicable for the prediction of cyclic growth of through cracks emanating from holes.

Residual Strength

As in the case of fatigue-crack growth, only limited data are available on the residual strength of through cracks at holes. No data are known to exist for the case of plane strain. Plane-stress tests were reported(10) on 300 mm (12 in.) wide panels of 7075-T6 aluminum alloy sheet with a fracture toughness of 204 $kg/mm^{3/2}$ for the relevant range of crack sizes.

The results of cracks at one side of the hole are presented in Figure 8; the results for the symmetric case are given in Figure 9. On the basis of K_c=204 $kg/mm^{3/2}$, the residual strength of the cracks at holes was predicted by using the Bowie analysis (dashed lines) and also by using Equation (3) (solid lines). For the longer cracks, the Bowie analysis predicts a somewhat lower residual strength (see also Figure 2). Taking into account the usual scatter in residual strength, the test data can be considered to confirm both predicted lines fairly well.

In the case of residual strength analysis, particularly in plane stress, the critical crack size will usually be on the order of the hole diameter or larger (of course, depending upon hole size). Therefore, the simple engineering solution, which considers the hole part of the crack, will give a useful value for residual strength or critical crack size. This statement can probably be generalized to other materials as well, provided panel sizes are sufficient to obtain true K_c values (11, 12).

Loaded Holes

A few attempts were made(3, 5, 12, 13) to analyze the case of a loaded hole. A simple approximate analysis (12, 13) based on the superposition principle is presented in Figure 10. According to the figure, the stress-intensity factor for a loaded hole is given by

$$K_A = \frac{K_B + K_D}{2} \quad . \tag{6}$$

The Bowie solution of Equation(1) can be taken for K_B. The expression for K_D is well known to be $K_D = P/\sqrt{\pi a}$. By taking a finite size correction, $F(a_{eff}/W)$, and by noting that $P=\sigma W$, it follows that

$$\frac{K}{\sigma\sqrt{\pi a_{eff}}} = \left\{\frac{1}{2} f_B\left(\frac{a_{eff}}{D}\right) + \frac{W}{2\pi a_{eff}}\right\} F\left(\frac{a_{eff}}{W}\right). \tag{7}$$

For the case where the crack tip is well away from the hole $f_B = 1$ (f_B is expressed here in terms of a_{eff}; i.e., $f_B(a/D)$ has to be reworked to give $f_B(a_{eff}/D)$).

Figure 11 allows a comparison of Equation (7) with the results of the compliance measurements made by Cartwright and Ratcliffe(5). The stress intensity first rises sharply and then decreases, since the second term in Equation (7) is a decreasing function of a_{eff}. This is in agreement with the results of the compliance measurements. It is also confirmed by the analysis of Grandt(3). If the cracks grow longer, K increases again as a result of the finite size correction.

Test results to check the applicability of the analyses are not available. The only data that bear some resemblance to this case are those by Figge and Newman(14), who tested center cracked panels subjected to splitting forces at the crack center. Their test data were in good agreement with those of remotely loaded center cracks at the same ΔK. These results show that there is probably little effect of ΔK history. Therefore, it is tentatively assumed that the proposed analysis methods may be satisfactory for the treatment of cracks at loaded holes.

Pin loading creates minor shear stresses along the crack line. Consequently, there will be combined K_I and a K_{II} loading modes. The compliance measurements can only determine G and cannot uncouple K_I and K_{II}. But as pointed out by Cartwright and Ratcliffe, the error in equating $K_I = \sqrt{EG}$ is less than 1 percent. Grandt(3) accounted for this by taking the crack perpendicular to the maximum principal stress. The crack is then at an angle of 81 degrees (instead of 90 degrees) to the loading axis.

Closure

The case of through cracks at open holes can be treated satisfactorily. There are test data available to show that K analysis methods for cracks at open holes can be used in a fracture-mechanics analysis of crack growth and fracture.

If the cracks are small with respect to the hole diameter, the Bowie stress-intensity factor has to be used. It can be applied for longer cracks as well, but then it is easier to use the engineering approach which considers the hole as a part of the crack.

Through cracks at loaded holes can be dealt with in the way discussed in the previous section, but the analysis method still lacks substantiation by test data. Moreover, this case is further complicated by the possible effect of the fastener to be discussed later.

Corner Cracks at Holes

Stress Intensity for the Asymmetric Case

A corner crack at a hole is an important case in the fracture safety control of structures. Recently, the USAF has adopted new damage tolerance criteria placing great emphasis on corner cracks emanating from holes. A rigorous solution for flawed holes does not exist, since this configuration requires a complicated three-dimentional stress analysis. However, stress-intensity estimates have been reported[13, 15-17] employing elliptical crack solutions and correction factors to account for the hole. For some configurations, stress-intensity factors were determined experimentally[18, 19]. A number of these solutions are described in subsequent paragraphs.

A straightforward engineering solution was applied by Smith[15]. He used the standard elliptical flaw solution and applied the Bowie correction factor, as if it were a through crack,

$$K = \frac{\sigma}{\phi}\sqrt{\pi\frac{a^2}{c}}\, f_B\left(\frac{c}{D}\right) , \tag{8}$$

where ϕ is the well-known elliptical integral applicable to elliptical cracks, c is defined as in Figure 12, and f_B is the Bowie function given in Figure 2, but with the abscissa given as c/D instead of a/D. For the case of a quarter-circular flaw with a = c, Equation (8) reduces to

$$K = \frac{2\sigma}{\pi}\sqrt{\pi a}\, f_B\left(\frac{a}{D}\right) , \tag{9}$$

The equation is limited to cases where $a/B < 0.5$, B being the thickness, unless a back-free surface correction would be applied.

Hall and Finger[16] derived an empirical expression on the basis of failing stresses of specimens with flawed holes, assuming the specimens failed when K reached the standard K_{Ic}. They arrived at

$$K = 0.87\,\sigma\sqrt{\pi c_e}\; f_B\left(\frac{c_e}{D}\right). \tag{10}$$

In this equation, c_e represents an effective crack size, which has to be found from the empirical curves in Figure 13. It incorporates the influence of both flaw shape and back-free surface, but it is limited to $a/c < 1$. The Bowie function, f_B, is also based on the effective crack size, c_e.

Liu[17] considered a quarter-circular flaw, such that the flaw shape parameter Φ equals $\pi/2$. He arbitrarily based the Bowie function on an effective crack, $a_e = \frac{1}{2} a\sqrt{2}$. His equation then is

$$K = \alpha_b \alpha_f \frac{\sigma}{\Phi}\sqrt{\pi a}\, f_B\left(\frac{a_e}{D}\right). \tag{11}$$

A corner flaw has two free surfaces, which can be accounted for by a free surface correction of 1.26. Since the edge crack surface correction is already included in the Bowie function, Liu took the free surface correction $\alpha_f = 1.26/1.12 = 1.12$. Taking the back-free surface correction, α_b, equal to unity and noting that $\Phi = \pi/2$, the final equation is

$$K = \frac{2.24\sigma}{\pi}\sqrt{\pi a}\, f_B\left(\frac{a_e}{D}\right),$$

with

$$a_e = \frac{1}{2}\sqrt{2}\; a\ . \tag{12}$$

An entirely different approach[13] is based on the observation that in the case of a through crack the hole may be considered part of the crack, as shown previously. This was assumed to be applicable to a corner crack also. The corner crack is treated as part of an elliptical crack, the other end of which is positioned at the opposite edge of the hole, as shown in Figure 14. The assumed effective crack has semiaxes a_e and c_e. Its stress intensity is

$$K = \alpha_f \frac{\sigma}{\Phi}\sqrt{\pi a_e}\left(\frac{a_e^2}{c_e^2}\cos^2\varphi + \sin^2\varphi\right)^{1/4} . \tag{13}$$

The expression between brackets has to be added since the stress intensity has to be determined at point A. Because of the extra deformation possibilities of the hole-part of the crack, the free surface correction is taken as $\alpha_f = 1.2$. The axes a_e and c_e can simply be expressed as functions of a and c, leading to

$$K = 1.2\,\frac{\sigma}{\Phi}\sqrt{\pi a}\left\{\frac{a^2(D+c)^2(D-c)^2(Dc)^{-1} + 4a^2(D+c)^2}{4Dc\,[4a^2 - (D-c)^2]}\right\}^{1/4} . \tag{14}$$

The elliptical integral Φ has to be based on $a_e/2c_e = a/2\sqrt{Dc}$.

Another way to account for the hole is by using the stress concentration to correct the nominal stress[13]. The crack is treated as a corner crack. The stress σ is replaced by $k\sigma$, where k is the local stress concentration factor for the undisturbed stress field at an uncracked hole,

$$k = 1 + \frac{1}{2}\left(\frac{D}{2r}\right)^2 + \frac{3}{2}\left(\frac{D}{2r}\right)^4 . \tag{15}$$

The dimension r is the distance from the center of the hole.

The stress intensity at the edge of the hole then is given by

$$K_{HOLE} = 3\,\frac{\sigma}{\phi}\sqrt{\pi a}\ , \tag{16}$$

and the stress intensity at the surface by

$$K_{sF}=\frac{\sigma}{\phi}\sqrt{\pi\frac{a^2}{c}}\left[1+\frac{1}{2}\,\frac{D^2}{(D+2c)^2}+\frac{3}{2}\,\frac{D^4}{(D+2c)^4}\right]. \quad (17)$$

Very recently Hall and Engstrom[20] reported on an extensive test program on cracks at holes. Also, they presented a new analysis method for elliptical cracks emanating from holes. They used the solution for a pressurized elliptical crack with a pressure distribution in the form of a polynomial. They fitted the polynomial roughly to the stress distribution around an uncracked hole in a plate under tension. Then they solved the problem of an elliptical crack (without a hole) with the calculated pressure distribution. The result is (see Figure 15 for notations),

$$K=\frac{\sigma}{\phi}\sqrt{\pi a}\left[\cos^2\beta+\frac{a^2}{c^2}\sin^2\beta\right]^{1/4}F\left(\frac{c}{D},\beta\right). \quad (18)$$

The function $F(c/D, \beta)$ is given in graphical form in Figure 16. It is also slightly dependent on a/c, but the variations are within 6 or 7 percent as compared with the case of a/c=0.6 for which Figure 16 holds.

Hall and Engstrom checked their procedure by applying it to a through crack and found it applicable. They also showed that the case of an elliptical crack reduces to the Bowie solution for a/c approaching infinity. The stress intensity factor is then $K=\sigma\sqrt{\pi c}\; F(c/D, 90^o)$, implying that values of $F(c/D, 90^o$ in Figure 16 should be equal to the Bowie function f_B. This is indeed the case.

The solution of Equation (18) was made suitable for corner cracks by applying free-surface correction factors and an extra correction factor for the case of a single corner crack. The result for a single corner crack is

$$K=\alpha_f\alpha_b\,\frac{\sigma}{\phi}\,\sqrt{\pi a}\left[\cos^2\beta+\frac{a^2}{c^2}\sin^2\beta\right]^{1/4}F\left(\frac{c}{D},\beta\right)\sqrt{\frac{D+\pi ac/4B}{D+2\pi ac/4B}} \quad (19)$$

Comparison of Solutions

Wanhill[21] recently compared three of the then known solutions. One of his basic figures is reproduced here as Figure 17, and completed with the other solutions described above. Since one of the methods is limited to quarter-circular cracks, the comparison is based on the case that a = c. Also included is Bowie's solution for a through crack.

Figure 17 is limited to the case that $a/B < 0.5$, such that back-free surface corrections can be neglected. This introduces a difficulty with the Hall and Finger equation in that the value of a_e is strongly dependent on the a/B ratio for $a/B < 0.5$. In view of this, a range of a/B of 0.1 - 0.4 was taken for the Hall and Finger relation, which corresponds with a range of c_e/c of 0.15 (extrapolated) to 0.7 (Figure 13).

Another difficulty arises because the Hall and Engstrom analysis essentially considers the variation of K along the crack front. Therefore the K values are given for $\beta = 0^o$ (edge of the hole), $\beta = 20^o$, and for $\beta = 90^o$ (surface). As explained in the previous section, the case of $\beta = 90^o$ represents the condition that $F(c/D, \beta) = F_B$ (Bowie), and hence, the line for $\beta = 90^o$ coincides with Smith's solution.

It should be noted that the variation of K can also be included in some of the other solutions, particularly in the ones by Smith and Broek. The latter assumed that the highest K (at the edge of the hole) would be of significance for the fracture problem. For the equation by Smith it is rather the intersection of the crack with the plate surface that is represented in Figure 17. By applying the Bowie function to other locations at the crack front, the calculated K would be higher and comparable to those obtained by the Hall and Engstrom approach. The relations proposed by Hall and Finger and by Liu consider the critical point to be somewhere between the edge of the hole and the surface (reflected by a_e).

Hall and Engstrom applied their analysis to a limited series of fracture toughness specimens. They calculated the stress intensity at fracture as a function of crack front angle β. They found that the stress intensity at fracture was higher than K_{Ic} for $0 < \beta < 20^o$, and lower than K_{Ic} for $\beta > 20^o$. Therefore, they concluded that $\beta = 20^o$ is the critical point. In the region of $\beta = 20^o$ the gradient of K is not large. Hence, the conclusion on what is the critical point becomes very sensitive to the K_{Ic} value chosen as representative.

A comparison of the various methods can now be made. The line for $\beta = 20^o$ of the Hall-Engstrom analysis is higher than the other solutions. The line for $\beta = 90^o$ coincides with that of Smith's approach. Thus, the line for $\beta \approx 30^o$ - 40^o will come close to the other solutions. Then the K values predicted by all solutions approach each other for flaw sizes larger than the hole diameter. The experimental data shown in Figure 17 were obtained from photoelastic measurements. They are at least on the same order of magnitude as the predictions. It is noteworthy that Liu's solution predicts K values for small flaws almost as high as for through cracks. For these small flaws Broek's equation predicts the lowest values.

Almost all analysis methods gave good results when applied to certain sets of fracture data. Equation (10) by Hall and Finger matched their data within 10 percent. Liu applied his Equation (12) to the same data and found fair agreements. The data covered fairly large values of the ratio a/D. Also the data by Hall and Engstrom were for large a/D. Their results are collected in Table 1 and analyzed by means of the Hall and Finger equation under the assumption that the flaws were quarter-circular. The results are remarkably good. Since a/B for these data was rather large, the data fall near the upper boundary in Figure 17. This is not too close to the line for $\beta = 20^o$, considered critical by Hall and Engstrom, but it would be close to a line for $\beta = 30^o$.

Test data for small a/D were obtained by Broek, and showed fair agreement with Equation (14). The low range of a/D is technically important, since the larger part of the fatigue-crack-growth life is spent there. Small differences in K may thus affect the propagation life significantly. Broek's data are presented in Table 2, together with the calculated K_{Ic} values according to Equations (10) and (14). Predictions by means of Equation (14) are closer to the standard K_{Ic} value, but it should be noted that a number of specimens may have been of inadequate thickness. However, Grandt and Hinnericks[18] also found stress intensities considerably less than predicted by Equations (10) and (12). Their values are based on fatigue-crack-growth rates of corner cracks, which were related to K through the da/dn - ΔK relation measured on compact tension and edge-cracked specimens.

Liu's approach is limited to quarter-circular cracks. The equation of Hall and Finger is valid only if $a < c$. The other approaches have no built-in limitations. However, the discrepancies between them are large enough to state that at least all but one must have limited applicability. The approach of Hall and Engstrom is promising, because it is a first attempt to a general analysis of the problem.

Not only is further analysis required, also more and systematic test data should be made available to allow a better appreciation of existing and forthcoming analysis techniques. The data presently available cover too small a range of a/D and a/c ratios to permit conclusive statements regarding the applicability of the analysis methods.

Other Crack Shapes

Although single corner cracks may be the most frequently observed flaws at holes, other crack geometries do occur (Figure 18). One of the analysis methods discussed in the previous sections was intended to apply to these other crack configurations. The approach of Hall and Engstrom[20] treats the general case of elliptical flaws at holes in an infinite solid. Then there remains the problem of defining correction factors for plates of finite thickness (and finite width). This can be done by means of empirical fitting, but some correction factors may be obtained by systematic finite element analysis, or alternatively, photoelastic measurements.

After the single corner flaw, the symmetric case of two corner flaws of equal size is probably the most easy to analyze. Application of the Hall and Engstrom analysis to this case would simply result in Equation (19) with deletion of the last factor with the square root. Some data provided by Hall and Engstrom are reproduced in Figure 19. The figure shows the variation of K along the crack front at the onset of fracture for this flaw shape. If the analysis is assumed correct, it follows from Figure 19 that fracture occurred when the material at $\beta = 20^o$ was subjected to a K equal to K_{Ic}.

Now the difficulty involved in the method becomes apparent. In order to be able to predict the residual strength of a given configuration, one has to know which K to use. If one chose to assume that K at $\beta = 20^o$ is the significant quantity, failure would be predicted at point A for the given K_{Ic}. Actual test data vary between P and Q. If any of the other configurations of Figure 18 were to be analyzed by the same method, the significant value of β for that particular case would have to be known. It is obvious from Figure 19 that a different choice of β would affect the outcome of the prediction. Not only the stress intensity factor varies along the crack front, also the fracture toughness may be different in different directions. Materials with greater anisotropy than 4340 steel may exhibit another critical β, if K_{Ic} in the direction of that β is significantly lower than in other directions. In order to make the method useful for engineering applications, test programs are required to establish the fracture condition in terms of the angle, β. The tests would have to cover different configurations, and do so for a wide range of the geometrical parameters B, D, a, and c. Of course, any other analysis procedure would be faced with the same problem. The approaches discussed in the previous sections either assumed $\beta = 0$ or 90^o to be critical, or they empirically established an effective crack size which implicitly accounts for the correct β.

The data in Figure 19 can be analyzed easily by considering the hole as part of the crack. The defect then would be a surface flaw of approximately semielliptical shape, with major axis $2\bar{c} = 2c+D$ and minor axis $\bar{a} \approx a$. The flaw shape parameter, ϕ, is to be based on $\bar{a}/2\bar{c}$. Since these are shallow flaws, the backfree surface correction is fairly large and cannot be neglected. Applying this correction, assuming $\sigma/\sigma_{ys} \approx 0.5$ for the determination of the flaw shape parameter, and taking K_{Ic}=75 ksi $\sqrt{in.}$, the fracture stresses, σ, of the specimens in Figure 19 are predicted as 82, 94, 79, 114, 100, 68 ksi. The actual fracture stresses are listed in the same order in Figure 19. The estimates are unconservative by only 6 to 12 percent. Thus, this simple procedure may be suitable for a quick appraisal of the order of magnitude of the failure stress.

Other configurations may also include other loading conditions. The most prominent of these is the case of a loaded hole. Although some few test data are available, the analysis of the problem is hardly touched upon in the literature. In the case of large holes in lugs where the point of load application is relatively far from the crack plane, the analysis of the open hole may suffice[13]. For the general case, however, a complete analysis has still to be provided. It is likely that the problem of a wedge loaded hole with elliptical cracks needs to be solved first. Then the superposition procedure of Figure 10 may be applicable.

Fatigue-Crack Propagation

Fatigue-crack propagation of elliptical flaws is a problem for which a generally accepted analysis method is not yet available. The complication of the presence of a hole seems only minor. More than in the case of fracture, the variation of K along the crack front is of concern for fatigue-crack propagation.

A semielliptical surface flaw has its highest stress intensity at the end of the minor axis, the stress intensity at the surface being lower by a factor $\sqrt{a/c}$. Suppose that fatigue-crack growth in all directions is governed by the same relation between da/dn and ΔK. The crack will then grow faster inward than along the surface, thus increasing its ratio a/c. When $a \approx c$, the stress intensity is essentially constant along the crack front. Consequently da/dn will be the same at any crack tip element and the crack remains semicircular.

This tendency for cracks to become semicircular was observed by Mukherjee and Burns[22] in plexiglas sheet, a material not showing directional effects. Irrespective of the initial c/a ratio, the cracks changed shape until $c/a \approx 0.96$. Similar results were obtained by Corn[23] for an aluminum alloy, two steels and two titanium alloys. Marked deviations from this behavior occurred[23] in the case of bending, when the crack depth approached midthickness. Deviations may also occur when the crack-growth properties in the thickness direction differ from those in width direction. Finally, there is an increasing effect of the back-free surface when the crack moves further inward, resulting in an extra variation of K along the crack front.

There exists some evidence[20, 22] that cyclic growth of surface flaws can be predicted on the basis of standard da/dn - ΔK data. Provisions have to be made that the gradual change of crack shape and the directional fatigue properties are properly accounted for. An example[20] of the applicability of standard data is given in Figure 20. The crack depth propagation rate is in good agreement with the baseline data. Crack length growth rates are higher than the baseline data, but the crack still tended to become semicircular

If standard fracture mechanics approaches apply to surface flaws, there is a basis to assume that they apply to elliptical flaws at holes as well. Due to the larger variation of K along the crack front (Figure 16), the change of shape must be expected to be more pronounced than in the case of surface flaws. Therefore it is unlikely that crack growth can be reliably predicted if a flaw of constant shape is assumed. It is probably even insufficient to consider both the growth of c and a; one or two intermediate positions may be required. Experimental data are now becoming available (e.g., Reference 20) allowing an analysis of this problem. The next step will have to be the introduction of retardation models into the integration procedure.

Once the scene is set for a reliable prediction of crack growth, there remains one technical problem. This concerns the assumption of initial flaw shapes. Depending upon the assumed damage, machining practice, fastener type, etc., an endless variation of initial flaw shapes can occur. For a surface flaw, the crack-propagation life until critical size is reached depends more on flaw shape than upon initial flaw size and fracture toughness[24]. This is illustrated in Figure 21. The same probably holds for flaws at holes.

It might be argued that the flaw shape giving the shortest life should be prescribed. Most likely this would call for too frequent inspections or for inefficient weight penalties. As in all damage tolerance requirements, a certain risk of premature failure will have to be accepted. Therefore, the most unlikely initial flaw shapes may have to be disregarded. Establishment of a prescription for one or more initial flaw shapes would require an analysis of many configurations along the lines discussed above.

Closure

Several analysis methods have been proposed to deal with the problem of corner cracks at holes. Most of these gave satisfactory results when applied to limited sets of data. A promising attempt for a more general solution of the problem was made by Hall and Engstrom, but this method still contains some uncertainties as to its application (what is the significant β for the K at fracture). A further analysis of this method seems worthwhile if test data are made available covering a wide range of the relevant parameters. For the time being, a fracture mechanics approach must be based on one of the other analysis techniques. If one is aware of the limitations of these procedures, uncertainties can be accounted for by safety factors of reasonable magnitude.

THE EFFECT OF FASTENERS

When considering a crack emanating from a fastener hole, the influence of the fastener has to be taken into account. If the fastener is a loose fit in an otherwise untreated hole, and when there is no load transfer, it is likely to have little effect on the behavior of a crack emanating from the hole. In general, however, the fastener has a tight (interference) fit. In many cases it does transfer some load. Moreover, the holes are often cold worked to improve fatigue resistance. All these things have an effect on cracking behavior, since they induce a redistribution of local stresses to the effect that the stress intensity is different from that at a cracked open hole.

Some data[25] regarding the effect of fasteners are presented in Figure 22. They show the large beneficial effect of interference and cold working. In the case of load transfer, the crack-propagation rates were significantly higher[25]. Large interference leads to slower growth rates. Equal amounts of growth of a corner crack at an unloaded taperlok bolt in 2219-T851 aluminum took 29, 21, and 12 kilocycles at interferences of 0.0060, 0.0038, and 0.0024, respectively[20]. In the case of the open hole, the same crack growth occurred in only 6 kilocycles.

These data indicate some trends, but they cannot be generalized. Other stress levels, other fastener systems, and load transfer may change the picture considerably. So many parameters are involved that systematic test data are hard to find, if at all available. Investigations to the effect of fasteners all tend to include too many of these parameters, to an extent that even elaborate test programs often fail to give generalizable results. Another shortcoming of the tests is inherent in the production of specimens. In order to obtain the required starter crack, the specimens are precracked before the interference fit fastener is installed or before the hole is cold worked. Both procedures are liable to build additional residual stresses into the crack tip area. A different stress system would exist at the crack tip if it had grown after fastener installation or hole expansion. Conceivably, also, crack-growth behavior would be different.

Application of fracture mechanics principles to cracks at filled fastener holes requires knowledge of the effect of interference, cold work, and load transfer on the stress-intensity factor. A promising attempt to attack this problem was made by Grandt[3]. He calculated stress intensity factors for cold worked and interference fit holes by solving the problem of a cracked hole with an internal pressure distribution equal to the hoop stress surrounding an uncracked fastener hole.

Figures 23 and 24 show the observed trends. Since the shape of the curves depends upon the applied stress, the calculation has to be repeated for different stresses. Consequently, the results cannot be presented nondimensionally. The results in Figure 23 may be slightly misleading, because the hoop stress will be partly released when the bolt gets more clearance as the crack grows (decreasing stiffness). This effect was not accounted for in Grandt's solution.

It appears from Figures 23 and 24 that both an interference fit and cold work significantly affect the stress intensity. Mandrelizing is more effective, since it gives a larger reduction of the stress intensity over a wider range of a/D values. It is particularly this range that is of importance for fatigue-crack growth, since the larger part of the life is spent while the cracks are still small. This is also reflected by the data in Figure 22.

For large a/D the stress intensity of the interference fit becomes larger than that of an open hole (compare the Bowie solution and interference fit curves for σ = 17.5 ksi in Figure 23). As explained above, the difference may be smaller in reality as the interference decreases due to the lower stiffness resulting from the larger crack. Yet, this phenomenon is considered typical for an interference fit. It also constitutes the essential difference between an interference fit and a mandrelized hole, as discussed in the following paragraph.

During mandrelizing the rim of the hole is plastically expanded. After removal of the mandrel the surrounding elastic material is allowed to contract, and thus it exerts compressive stresses to the rim. The plastic expansion of the rim does occur upon installation of an interference fastener. But the fastener stays in place, and hence, no contraction of the surrounding elastic material occurs. As a matter of fact, there exist tensile stresses around the hole, instead of compressive stresses. This is confirmed by the positive stress intensity of significant magnitude that remains at σ = 0 (Figure 23).

As a result, the interference fit shows less resistance to stress corrosion than a cold worked hole, since there is always an active K, even at zero stress. Stress corrosion testing of various fastener systems[25] revealed not a single crack at mandrelized holes after 1000 hours exposure. Holes with interference fit fasteners started to crack after 80 hours, the longest life to first crack being 360 hours. When interference fit fasteners were installed in the mandrelized holes, cracks still initiated after 1000 hours.

From a practical point of view it seems that mandrelizing is more effective than interference fasteners, especially when stress corrosion can play a role. A combination of the two may not seem logical, but it is liable to prevent fretting damage and give a longer crack-free life. Mandrelizing is a process that can be controlled reasonably well. When applying interference fasteners alone, there are chances that some bolts can be improperly installed. This should be accounted for in damage tolerance specifications and calculations.

HOLES IN REINFORCED STRUCTURES

The analysis of cracks at holes in reinforced or built-up structures should include the problems listed below.

(a) Due to the presence of a cracked hole, load will be transmitted from the cracked material into the underlying reinforcements. Usually, this will not affect the fastener in the cracked hole; the load transfer occurs through the adjacent fasteners, which may not carry any load in the absence of the crack. The result is twofold. In the first place, the cracked element experiences a lower stress, to the effect that growth rates are reduced. However, the load transfer through adjacent fasteners may induce other cracks. These cracks may occur in the same element, which leads to multiple parallel cracks. Also, they may occur in the underlying reinforcements. In case that load transfer occurs through the fastener in the cracked hole (lap joints, stringer run outs), the cracking tends to reduce the load transfer. This reduces the stresses at the cracked fastener at the expense of higher stresses at adjacent fasteners, which again may develop multiple cracks. A rigorous damage tolerance analysis might have to consider these possibilities.

(b) An extreme case of load transfer to reinforcing elements occurs in stiffened panels if the cracks grow long. A skin crack across a stringer leads to extremely high growth rates in the stringer once it cracks. Cracks extending to the next stringer induce a high load transfer also, leading to low fatigue endurance of that stringer.

(c) Lap joints, stringer-skin combinations, load-bearing splices all contain eccentricities. The resulting bending stresses may have to be accounted for in damage tolerance calculations.

It is almost needless to mention that present analysis procedures are insufficiently developed to involve all these problems. However, the powerful modern stress analysis techniques (e.g., finite elements) are basically capable of solving the problems. In principle, they all are a matter of superposition of K solutions, and therefore, they may be simpler than the basic analysis of a corner crack at a hole.

The question may be raised whether it is practical to deal with these detailed problems. At present it is certainly premature in view of the following reasons:

(a) The analysis of a cracked hole is still not satisfactory.

(b) The scatter in raw data makes predictions inaccurate anyway.

(c) There is still no reliable methodology to account for load interaction and retardation.

(d) There are additional unknowns in the load history, temperature history, and the effect of environment.

Therefore, a general analysis of the listed problems may suffice. It would provide an appreciation of the relative significance of each of them. Then they could be dealt with in an approximate way, without the necessity of costly detailed analysis of each particular structural geometry.

The case of multiple cracks at holes was mentioned several times. This problem was analyzed by Burck and Rau[26]. They determined stress-intensity factors for single and multiple cracks at linear arrays of holes, either perpendicular or parallel to the load path. The result is shown in Figure 25(a). Multiple colinear cracks soon attain a high stress intensity. The single crack in this configuration would only reach a high K when approaching the neighboring hole (see also the section on arrest capabilities of holes). If multiple cracks are aligned in the loading direction, there is an important shadow effect giving a significant reduction of K.

On the basis of Figure 25(a), Burck and Rau predicted crack-growth lives for wrought Udimet 700. Their results are given in Figure 25(b). Due to the presence of multiple holes, the lifetime of single cracks appears to be influenced by a factor of 0.5-3 as compared with a single crack at a single hole. Multiple cracks show an even larger difference in growth lives. The case of multiple cracks in an array parallel to the load axis is unstable. If one of the cracks becomes longer than the others, its K increases, while K of the other cracks decreases. The effect is larger for longer cracks, so that the array is likely to promote one crack to grow to failure. For colinear cracks, the K for all cracks increases if any one crack becomes larger.

Built-up structures contain large structural holes, such as access holes, and window holes. Such holes are reinforced to ensure proper load transmittal and low stress concentrations. Cracks often develop in these areas, either in the skin or in one of the reinforcements. Dure to their complicated structural geometry, these areas require a detailed analysis along the lines normally used for stiffened structures (e.g., References 12, 27-27).

ARREST CAPABILITIES OF HOLES

Fatigue Cracks Approaching Holes

Fastener holes usually occur in rows. A crack initiated at one of them may interact with other holes in the crack path. If a fatigue crack runs into a hole, it may be arrested there for a considerable time. Therefore, holes are often considered as useful crack stoppers. Unfortunately, it turns out that this is seldom true.

Isida[30] has determined stress intensity factors for cracks approaching holes. If the crack tip is in the vicinity of the hole, the stress intensity tends to infinity. This can be observed also in Figure 25(a). Consequently, the fatigue crack must run into the hole at an extremely fast rate. If the crack reaches the hole, the defect size is suddenly increased by the hole diameter. When the crack reinitiates at the other side, there is a much larger crack with an inherently higher growth rate. These two effects appear to offset the gain in life from the dormant period necessary for reinitiation.

This is confirmed by the test data[31] shown in Figure 26. Irrespective of the size and spacing of the holes, the crack-propagation curve is practically identical to the reference curve, the differences being on the order of the normal scatter. Crack-growth rates as a function of ΔK (on the basis of Isida's solution) perfectly satisfy the reference curve[31]. Hence, the case can be treated with normal fracture mechanics procedures (that do not include the dormant period). In the USAF damage tolerance requirements[38], the dormant period is completely neglected. The requirements assume the existence of an 0.005 inch crack at the other side of the hole when a crack runs into a hole. According to Figure 26, this may be a little overconservative.

Probably, the beneficial effect of the hole is much larger in the case of mandrelized holes. Crack growth into the hole is not likely to be affected much by the expansion, but the residual compressive stresses will certainly lengthen the reinitiation period. There are no test data available to prove this point. It is confirmed indirectly by tests on expanded stopholes. However, these holes were drilled at the crack tip, rather than at some distance ahead of the crack tip. These test data will be discussed in Section 8.2 on stop drilling.

Arrest of fatigue cracks can be attained in three different ways:

(a) Reduction of stress concentration

(b) Introduction of residual compressive stresses

(c) Reduction of stress-intensity factor

Reduction of the stress concentration occurs when the crack runs into a hole. As shown previously, this may not be beneficial unless there are also residual stresses as a result of mandrelizing. Reduction of the stress-intensity factor occurs when the crack approaches a reinforcement element (e.g., a stringer). The result is that the crack-growth rates are drastically reduced, although a total arrest may not occur. Since stringers are usually attached to the skin by means of fasteners; total arrest can occur if the crack runs into a fastener hole.

Without further analysis it cannot be foreseen whether it is preferable that the crack runs into a fastener hole or passes between two holes. The stringer takes load from the skin and thus reduces the stress-intensity factor.

The stringer is more effective in doing so when the fasteners are closer to the crack path; the stiff stringer element between the two nearest fasteners tends to keep the crack closed. If the crack passes between holes, the nearest fasteners are twice as close to the crack as in the case where the crack runs into a fastener hole. Therefore, the latter case provides a smaller reduction of K (Figure 27). Since the beneficial effect of the hole itself is small (Figure 26), conceivably, the best result is obtained if the crack passes between fasteners. However, cracks cannot be forced one way or the other in real structural situations. Therefore, a damage tolerance analysis should consider both cases.

Of course, the previous reasoning will be violated if the holes are mandrelized. Also, the load transfer to the stringer may induce fatigue failure of the latter. This may imply that it is preferable to have the crack run into a hole, a case where there is less load transfer to the stringer. The point is that each particualr geometry (as for stronger geometry, stiffening ratio, fastener size and spacing) requires a completely new analysis. Systematic test data on the subject will become available in the near future[e.g., 32].

Arrest of Fast-Running Cracks

The capability of holes to arrest post-instability crack growth is a matter of great interest. The problem is a complicated one because it has to be treated on the basis of dynamic stress intensity and elastic energy release rates, while there may also be a contribution of kinetic energy. A qualitative analysis of dynamic crack arrest can be made in principle[12], and this could be extended to give a qualitative formulation of the effect of holes. From an investigation by Kobayashi, et al.[33, 34], it can be concluded that the arrest power of small holes is probably poor. Therefore, the arrest capability of holes in general is probably not of great technical importance. Since the discussion could not be more than speculative, it will be omitted.

A particular case of arrest at holes occurs in stiffened panels, where the arrest may be essential to the fail-safe strength. A few remarks on this subject seem in place. They lead to the conclusion that holes are not too significant for arrest. As discussed in the previous section, there is a larger reduction of K if the crack passes between rivets. Which case is preferable depends upon the strength of stringers and fasteners as well as upon the crack resistance of the skin.

The problem is outlined in Figure 28[12, 29] for a particular panel configuration. Formal analysis of this panel provides the residual strength diagram of Figure 28(a) for a crack passing between fasteners, and the diagram of Figure 28(b) for a crack running into a hole. Due to the larger skin stress reduction in Case A, the skin crack-propagation curve is much higher than in Case B. The failure criterion is stringer failure at Point H at a stress of 31.8 kg/mm^2. Any smaller crack starts propagation at a stress in accordance with Curve f, but it is arrested at the stringer. The stress can be raised to Point H where stringer failure triggers panel failure. This is confirmed by test data[29].

In Case B, arrest will occur in the same way, but the final fracture criterion is skin crack propagation at Point K at stress of 29 kg/mm^2, followed by stringer failure at H. However, there may be a beneficial effect of the rivet hole. Suppose the crack is arrested in a hole at R. The reduction of stress concentration implies that further crack growth requires a higher stress than given by Curve f. This stress will be somewhere between R and L depending upon the hole size. If this stress is as low as S, the crack propagates to T and the behavior is the same as before with no change in strength. If crack growth is postponed until U, there will be no further crack arrest and stringer failure occurs at V.

The fastener hole may be so large that crack growth is postponed formally to W. This is insignificant, since stringer failure will occur at L, which results in total failure. The highest attainable benefit is from K to L, which results in total failure. The highest attainable benefit is from K to L. Comparison with Case A shows that this would be approximately the same level as for a crack passing between holes. This reasoning is fairly well confirmed by test data.

The level of final failure is decisive for the possibility of arrest of a post-instability crack, also if dynamic effects play a role. Thus, it seems that only minor improvements can be expected from holes. However, each panel configuration requires a new analysis; there is no general rule. The behavior is dependent on the size of the hole to a certain extent (up to Point L). It is unlikely that mandrelizing or interference fasteners would make any difference as far as fail safe stress is concerned. It has to be noted, however, that further fatigue cracking may occur from the hole. The beneficial effect of the hole is then annihilated and the residual strength is determined by Point H. The use of mandrelized holes or interference fasteners then is that they may postpone such further fatigue cracking, but not necessarily increase the fail safe strength, Point H.

RETARDATION OF CRACKS AT HOLES

There is ample evidence[15, 20, 35] that load interaction effects and retardation do occur if through cracks and corner cracks at holes are subjected to variable amplitude loading. Smith[15] has actually predicted crack growth of corner cracks at holes under spectrum loading on the basis of the Willenborg[36] intergration model. This prediction showed a fair agreement with available test data.

Apart from the questionable soundness of present-day integration models, there may be some concern as to the similarity of the retardation effect in the case of through cracks and in the case of elliptical flaws (at holes). Due to the large variation of K along the crack front for elliptical flaws, the size of the plastic zone will vary also[37]. Consequently, residual stresses, crack closure and retardation may vary as well. It is unlikely that retardation at the surface and at the edge of the hole (and intermediate positions) can be treated independently; there is probably a strong interaction.

None of the formulae to calculate plastic zone sizes appeared to give satisfactory results when applied to surface flaws[37]. Since the presently available retardation models are based on plastic zone size, they may not be directly applicable to surface flaws and to corner cracks at holes. A critical analysis of spectrum test and overload test data on cracks at holes[15, 20] may provide more insight into this problem.

BEHAVIOR IN SERVICE

Inspection

In the case of through cracks at holes in built-up sheet structures, critical crack sizes are usually fairly large. This means that inspection for cracks may be relatively easy. Complications are mainly due to accessibility, multilayer reinforcements, and thickness changes. The case of corner cracks (and other elliptical cracks) at holes in thicker structure is more difficult. Critical crack sizes are often small (e.g., on the order of a few tenths of an inch). Safety then depends upon the possibility of detecting extremely small flaws. This is not the place to discuss inspection techniques and therefore only a few general remarks will be made.

Damage tolerance of a structure can be improved in a number of ways:

(a) Increase of fracture toughness

(b) Improvement of cyclic crack-growth properties

(c) Decrease of crack detection limit

(d) Provisions for crack arrest

The latter possibility applies primarily to structures permitting relatively large cracks, as, e.g., a stiffened panel (Figure 28). It can be disregarded in a discussion of the criticality of small corner cracks.

A diagrammatic crack-growth curve is shown in Figure 29. The minimum detectable flaw size is a_d; the critical flaw size, a_c. The period n_d is available for crack detection. Selection of a material with a higher toughness may increase the critical crack size to $\overline{a_c}$. This provides an additional period, $\overline{n}$, for crack detection, assuming approximately the same crack-growth curve for the tougher material. Apparently the gain is only small. Also, the necessity to find small cracks remains, because the cracks are small during the greater part of $n_d + \overline{n}$. When the cracks are large in size, their detection becomes very urgent. Selection of a material exhibiting lower cyclic growth rates is obviously more effective.

Reduction of the minimum detectable flaw size from a_d to $a_d{}^*$ provides an extra period, n^* for crack detection, $n^* >> \overline{n}$. Apparently, there is much more to be gained by improving inspection techniques. New USAF damage tolerance requirements[38] are based on an initial flaw size of 0.01 to 0.05 inch (depending on the configuration). A minimum guaranteed lifetime is then prescribed. Obviously, this implies the necessity to detect small cracks. If it could be proven that smaller cracks could be reliably detected, it would be easier to comply with the damage tolerance requirement for nonredundant structures.

There are some data available from the literature providing an appreciation of the success in finding flaws at a fastener hole. Some interesting observations were made by Knorr[39]. In cases where the fastener could be taken out of the hole, eddy current techniques appeared to be most successful. The probability of crack detection was investigated by letting 9 inspectors examine 200 bolt holes, 80 of which were cracked. The result is reproduced in Figure 30.

Consider the possibility of detecting a quarter-circular corner crack with 0.05 inch radius at a hole. The crack area would be on the order of 1.2 mm^2. If it were requested that 95 percent of these cracks were to be detected, there would only be 25 percent probability of accomplishing this goal. Cracks would have to be about 3 mm^2 in area (0.08 inch radius) to ensure a near to 100 percent probability of detection of 95 percent of all cracks of this size.

The situation is much worse for ultrasonic inspection. Knorr[39] describes a special ultrasonic technique, called the caroussel method to find corner cracks at countersunk fastener holes with the fasteners installed. Only 10 percent of the cracks of 3 mm^2 could be found with 99.5 percent probability.

The problem of detecting small cracks at fastener holes is getting more and more attention. Hopefully, improved techniques will be developed that can be effectively applied in service circumstances, and that have the power to indicate small cracks at fasteners.

Stripping, Stop Holes, and Repairs

Once a crack is detected, corrective action has to be taken. In the case of a small crack at a fastener hole, usually the fastener is removed, the hole reamed and mandrelized, and an oversize fastener installed. This procedure is fully satisfactory if the crack is completely removed. However, there is no guarantee for complete removal of the crack. The inspection techniques do not allow a good appraisal of the crack size. Therefore, there is no information on how much oversize the hole has to be drilled. Also, an inspection after oversize drilling does not ensure there is no part of the crack left (see previous section). Mandrelizing then can be used to introduce residual stresses at the tip of a remaining crack, thus slowing down its further propagation.

Partial removal of the crack can also be satisfactory. Suppose a 0.04-inch crack at a 0.40-inch-diameter hole would be reduced to a 0.02-inch crack by drilling a 0.44-inch hole (i.e., 10 percent oversize). This would decrease the a/D ratio from 0.1 to 0.05. Consequently, the stress-intensity factor would be drastically reduced (Figure 17). Of course the crack would no longer be quarter-circular; its dimensions would be greater along the edge of the hole than along the surface. Therefore the reduction of K may not be as great due to the shape effect.

This principle can also be applied in cases where crack detection is impossible. A certain initial crack size (below the detection limit) is assumed to exist. The propagation life to critical crack size is calculated. It is also calculated to what size the crack will have grown when half the life is expired. The hole is drilled oversize when the half life is consumed, irrespective of whether a crack is detected of not. From the calculated possible crack size and the amount of oversize drilling, it can be determined what size of crack can still be present. Then the calculation is repeated for this crack size and the time for the next oversize drill can be established. This periodic stripping[11,12] can be applied in cases where damage tolerance cannot be guaranteed otherwise. Mandrelizing may be applied to account for inaccuracies in the calculations. It should strictly be used as an extra safety and should not be accounted for in the calculations.

In redundant structures, long cracks usually can be tolerated and their detection is less critical. The discovery of such a crack does require action, but sometimes a provisory action may suffice, pending a more elaborate repair at a convenient time. Provisory repairs often consist of drilling holes to stop cracks (stop holes).

On the basis of Figure 26, it may be expected that a stop hole in itself is not likely to be very effective. This was confirmed by many stop drills during tests on 15 full-scale wing center sections(40). It was also shown by means of coupon tests by DeRijk and Otter(41) and by Van Leeuwen, et al.(42). As is shown in Figure 31, the reduction of the stress concentration has little effect. However, the situation can be greatly improved if the holes are expanded by cold deformation (Figure 32). The stop holes were mandrelized by means of a split cylinder which could be made to expand by means of a wedge. The direction of the parting plane had a significant influence on the crack stopping effectiveness.

Other methods of introducing residual stresses to reduce crack growth were investigated by Eggwirtz(43) and by Van Leeuwen, et al.(42). They pressed steel balls into the material, leaving a "Brinell" dimple at the crack tip. Eggwirtz reports the development of auxiliary equipment enabling application to aircraft parts where access to the structure is limited.

A final repair of the crack often consists of layered strips across the cracked region. A gradual load transfer should be endured by staggering the strips, otherwise new cracks will develop soon. Periodic inspection of repairs is certainly necessary(40).

GENERAL OBSERVATIONS, REQUIRED RESEARCH, AND CONCLUSIONS

The problem of cracks at holes has many aspects, most of which were dealt with only superficially in this report. The obvious reason is that so many parameters are involved that a rigorous treatment, if at all possible at this stage, would require several hundreds of pages. However, the main conclusion to be drawn from this study is that at present a more elaborate text is not justified.

Certain achievements have been made, but many of the basic problems have not yet been solved. In addition, what little analysis that was done is insufficiently supported by test data. Almost any reported test program involved too many test parameters to be of much significance as a substantiation of analysis methods.

In the following paragraphs a brief inventory will be made of the knowns and unknowns of the problems, as they appeared from the present study. Some suggestions are made for fruitful research and further development of this area.

(a) Several procedures are available to calculate stress intensity factors for two-dimensional cases. The most elementary two-dimensional case is rather well solved and confirmed by test data. More complicated two-dimentional cases have been explored, such as fastener-filled holes, interference fasteners, mandrelized holes, and cracks growing into holes. Procedures are to be further developed and refined. Systematic test programs are required to check their applicability.

Very little has been done on cases where there is load transfer through the fasteners, either as a result of primary loading or as a result of cracking. It would be worthwhile to carry out a prametric analysis, supported by a limited test program.

(b) Three-dimensional cases are still the most difficult. No solutions are available for general application. In principle, the three-dimentional case can be solved by means of finite element analysis. There seems to be reluctance to initiate this work. This is mainly because many different flaw geometries would have to be considered and the program would be very costly. Yet, a cleverly planned finite element program could be used for a parametric study involving a/c, a/B, and a/D. This would at least show the relative significance of these parameters and point the way to further work. It could lead to a set of master curves covering the problem area. A test program would be required to show their usefulness.

(c) Most emphasis has been on determining stress intensity factors. However, one of the main problems of elliptical cracks is how the flaw develops and changes shape. All available information is either incomplete or speculative. Yet, it must be possible to obtain some general clues as to the development of flaws. This would require a fairly large test program, carefully laid out to generate the information that is really wanted. The parameters involved should cover wide ranges. In a later stage, it should be extended to explore the effect of retardation on crack shape and vice versa.

(d) The arrest capability of a hole is probably overestimated. Qualitative considerations and limited experiments lead to the belief that arrest of a fatigue crack at a hole is balanced by an increase of K if the hole is approached, and by the increased defect size if the hole becomes part of the crack. Arrest of cracks at holes does occur in redundant structures, but there may be cases where it is more favorable if the crack passes between holes. The situation may change if the holes are cold worked.