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A NOTE ON THE CRACKED PLATES REINFORCED BY A LINE STIFFENER

O. S. Yahsi and F. Erdogan

LEHIGH UNIVERSITY
Bethlehem, Pennsylvania 18015

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A NOTE ON THE CRACKED PLATES REINFORCED BY A LINE STIFFENER(*)

O.S. Yahsi and F. Erdogan
Lehigh University, Bethlehem, PA 18015

1. Introduction

In this note the problem of a cracked plate reinforced by a line stiffener is reconsidered. The original solution of the problem was given in [1]. A variation of the problem with debonding between the plate and the stiffener near the cracked region was considered in [2]. However, the special case of the problem in which the crack tip terminates at the stiffener does not appear to have been studied. In practice the solution may be necessary in order to assess the crack arrest effectiveness of the stiffener. In this note the problem described in Figure 1 is reformulated, the asymptotic stress state near the crack tip terminating at the stiffener is examined, and numerical results are given for various stiffness constants.

2. The Integral Equation

Consider the plane elasticity problem shown in Figure 1. It is assumed that the elastic plane is reinforced by a stiffener which is embedded into the medium. Let the thickness of the stiffener in y-direction be sufficiently small so that its in-plane bending stiffness may be neglected. Hence, the stiffener may be approximated by a membrane. The Airy stress function for the stiffened elastic plane may be expressed as follows:

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$$\phi(x,y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}[R_1(\alpha)+xR_2(\alpha)]e^{-|\alpha|x}\, e^{-i\alpha y}\, d\alpha$$

$$+ \frac{2}{\pi}\int_0^{\infty}[S_1(\beta) + yS_2(\beta)]e^{-\beta y} \cos\beta x \, d\beta\ , \quad y > 0,$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty}[R_1(\alpha) + xR_2(\alpha)]e^{-|\alpha|x}\, e^{-i\alpha y}\, d\alpha$$

$$+ \frac{2}{\pi}\int_0^{\infty}[S_3(\beta) + yS_4(\beta)]e^{\beta y} \cos\beta x \, d\beta\ , \quad y < 0, \tag{1}$$

where R_1, R_2 and $S_1,\ldots,S_4$ are unknown functions. From Figure 1 one may note that if the loading is symmetric, x=0 is a plane of symmetry (which is assumed in (1)) and the six unknowns of the problem may be determined from the following continuity, equilibrium and boundary conditions:

$$u(x,+0) - u(x,-0) = 0\ , \quad 0 \le x < \infty\ , \tag{2}$$

$$v(x,+0) - v(x,-0) = 0\ , \quad 0 \le x < \infty\ , \tag{3}$$

$$\sigma_{yy}(x,+0) - \sigma_{yy}(x,-0) = 0\ , \quad 0 \le x < \infty\ , \tag{4}$$

$$\frac{1}{E}[\sigma_{xy}(x,+0) - \sigma_{xy}(x,-0)] = -\gamma\frac{\partial^2 u}{\partial x^2}\ , \quad 0 \le x < \infty\ , \tag{5}$$

$$\sigma_{xy}(0,y) = 0\ , \quad -\infty < y < \infty\ , \tag{6}$$

$$\left.\begin{aligned} \sigma_{xx}(0,y) &= f(y)\ , \quad -d < y < -b\ , \\ u(0,y) &= 0\ , \quad -\infty < y < -d\ , \quad -b < y < \infty\ . \end{aligned}\right\} \tag{7a,b}$$

Equation (5) is obtained from the equilibrium of the stiffener (of length dx) in x direction by observing that the strain in the stiffener is $\partial u/\partial x$. The stiffness constant γ is, therefore, given by

$$\gamma = E_s A_s / E \tag{8}$$

where E_s is the Young's modulus and A_s is the cross-sectional area of the stiffener corresponding to the unit plate thickness and E is the Young's modulus of the plane. Using the expressions

$$\sigma_{xx} = \partial^2\phi/\partial y^2 , \quad \sigma_{yy} = \partial^2\phi/\partial x^2 , \quad \sigma_{xy} = -\partial^2\phi/\partial x\partial y \tag{9}$$

and the Hooke's Law, five of the unknowns in (1) may be eliminated by the homogeneous conditions (2)-(6) and the sixth may be determined from the mixed boundary conditions (7).

Defining a new unknown function

$$\frac{\partial}{\partial y} u(x,+0) = g(y) , \quad -\infty < y < \infty \tag{10}$$

and from (7b) observing that $g(y) = 0$ for $-\infty < y < -d$ and $-b < y < \infty$, after some simple manipulations, (7a) may be reduced to

$$\frac{1}{\pi}\int_{-d}^{-b} \frac{g(t)dt}{t-y} + \frac{1}{\pi}\int_{-d}^{-b} k(y,t)g(t)dt = \frac{2}{E} f(y), \quad -d < y < -b , \tag{11}$$

where

$$k(y,t) = 2\gamma \int_0^\infty \frac{\beta e^{(t+y)\beta}}{\gamma\beta(1+\nu)(3-\nu)+4} (1 + \frac{1+\nu}{2} t\beta)[3+\nu+(1+\nu)y\beta]d\beta . \tag{12}$$

If the crack is embedded in the left-hand plane (i.e., if $-d < -b < 0$), then the kernel $k(y,t)$ is bounded for all values of y and t in the closed interval $[-d,-b]$. However, if the crack tip terminates at the stiffener (i.e., if b=0, or c=a, Figure 1), then it may be shown that $k(y,t)$ becomes unbounded as y and t go to the end point b=0 simultaneously. The singular part of $k(y,t)$ may easily be separated by examining the behavior of the integrand in (12) for $\beta\to\infty$. Thus, it can be shown that

$$k(y,t) = k_s(y,t) + k_f(y,t) , \tag{13}$$

$$k_s(y,t) = -\frac{(3+\nu)(1-\nu)}{(1+\nu)(3-\nu)}\frac{1}{t+y} - \frac{3(1+\nu)}{3-\nu}\frac{y}{(t+y)^2} + \frac{2(1+\nu)}{3-\nu}\frac{y^2}{(t+y)^2} , \quad (14)$$

$$k_f(y,t) = -\frac{8}{3-\nu}\int_0^\infty\left(\frac{3+\nu}{1+\nu} + y\beta\right)e^{(t+y)\beta}\frac{[1+t\beta(1+\nu)/2]}{\gamma(1+\nu)(3-\nu)\beta+4}\,d\beta . \quad (15)$$

In the limiting case of b=0, $k_s(y,t)$ and the Cauchy kernel in (11) constitute a generalized Cauchy kernel.

From (7b) and the definition (10) it is seen that the integral equation (11) must be solved under the following single-valuedness condition:

$$\int_{-d}^{-b} g(t)dt = 0 . \quad (16)$$

It should be noted that equations (11)-(15) are obtained under generalized plane stress assumption. For plane strain E and ν should be replaced by $E/(1-\nu^2)$ and $\nu/(1-\nu)$, respectively.

For $-b < 0$ the solution of (11) may be obtained by introducing the following dimensionless quantities:

$$\eta = \frac{2}{d-b}\left(y + \frac{d+b}{2}\right) , \quad \tau = \frac{2}{d-b}\left(t + \frac{d+b}{2}\right) ,$$

$$G(\tau) = g(t) , \quad (-1 < (\eta,\tau) < 1) , \quad (17)$$

and by using a standard Gauss-Chebyshev integration procedure [3]. In this case the unknown function $G(\tau)$ is of the following form

$$G(\tau) = h(\tau)/\sqrt{1-\tau^2} , \quad (18)$$

where $h(\tau)$ is a bounded function. After determining $h(\tau)$, the Mode I stress intensity factors at the crack tips may be defined by and calculated from

$$k_1(-b) = \lim_{y\to -b} \sqrt{2(y+b)}\,\sigma_{xx}(0,y)\ , \quad (y>-b)\ ,$$
$$= -\frac{E}{2} \lim_{y\to -b} \sqrt{2(-b-y)}\,\frac{\partial}{\partial y} u(+0,y)\ , \quad (y<-b)\ ,$$
$$= -\frac{E}{2} \sqrt{(d-b)/2}\; h(1)\ ; \tag{19}$$

$$k_1(-d) = \lim_{y\to -d} \sqrt{2(-y-d)}\,\sigma_{xx}(0,y)\ , \quad (y<-d)\ ,$$
$$= \frac{E}{2} \lim_{y\to -d} \sqrt{2(y+d)}\,\frac{\partial}{\partial y} u(+0,y)\ , \quad (y>-d)\ ,$$
$$= \frac{E}{2} \sqrt{(d-b)/2}\; h(-1)\ . \tag{20}$$

In the case of b=0, because of the kernel k_s given by (14) the solution of the integral equation (11) has no longer square root singularities. By introducing the new normalized quantities

$$\eta = \frac{2}{d}\,y+1\ , \quad \tau = \frac{2}{d}\,t+1\ , \quad G(\tau) = g(t)\ , \quad -1 < (\eta,\tau) < 1\ , \tag{21}$$

assuming $G(\tau)$ of the form

$$G(\tau) = h(\tau)(1-\tau)^{\alpha}(1+\tau)^{\beta}\ , \quad (-1 < \mathrm{Re}(\alpha,\beta) < 0)\ , \tag{22}$$

and by following the function theoretic method outlined, for example, in [3] the characteristic equations of the problem giving α and β may be obtained as follows:

$$\cot\pi\beta = 0\ , \tag{23}$$
$$\cos\pi\alpha + \frac{1+\nu}{3-\nu}(\alpha^2+2\alpha) - \frac{(3+\nu)(1-\nu)}{(3-\nu)(1+\nu)} = 0\ . \tag{24}$$

Equation (23) gives the expected result of $\beta = -1/2$ whereas (24) shows that α depends on the Poisson's ratio of the plane only. Again note that (24) is obtained for plane stress; for the plane strain case ν should be replaced by $\nu/(1-\nu)$. With α and β known, (11) may be solved by using a Gauss-Jacobi integration formula [3].

3. Asymptotic Stress Field

For the plane with a crack terminating at the stiffener in order to study the initiation of various modes of fracture growth the asymptotic behavior of the stress state around the crack tip $x=0$, $y=0$ has to be investigated. Going back to the basic formulation of the problem various stress components around the crack tip may easily be expressed in terms of bounded integrals with $g(y)$ defined by (10) as the density function. For example, after some relatively simple manipulations the stress $\sigma_{xx}(0,y)$ for $y>0$ may be expressed as

$$\sigma_{xx}(0,y) = \frac{E}{2\pi}\int_{-d}^{0}\left[\frac{4\nu}{(1+\nu)(3-\nu)}\frac{1}{t-y} + \frac{3(1+\nu)}{3-\nu}\frac{y}{(t-y)^2} + \frac{2(1+\nu)}{3-\nu}\frac{y^2}{(t-y)^3}\right]g(t)dt$$
$$+ \frac{Em}{2\pi(3-\nu)}\int_{-d}^{0}\left[m(1+\nu)\frac{yt}{t-y} - (1+\nu)\frac{yt}{(t-y)^2} - \frac{2y}{t-y} + (3+\nu)\frac{t}{t-y}\right]g(t)dt$$
$$+ \frac{Em}{2\pi(3-\nu)}\left(my - \frac{3+\nu}{1+\nu}\right)\int_{-d}^{0}\left(1 - \frac{m(1+\nu)}{2}t\right)e^{-m(t-y)}Ei\left(m(t-y)\right)g(t)dt\ ,$$
$$0<y<\infty\ , \qquad (25)$$

where $Ei(x)$ is the exponential integral and

$$m = \frac{4}{(1+\nu)(3-\nu)\gamma}\ . \qquad (26)$$

If we now observe that (see (21) and (22))

$$g(t) = h(\tau)(1-\tau)^{\alpha}(1+\tau)^{-\frac{1}{2}} = G(t)(-t)^{\alpha}(t+d)^{-\frac{1}{2}}, \quad (0>\alpha>-1) \qquad (27)$$

and define the sectionally holomorphic function

$$F(z) = \frac{1}{\pi}\int_{-d}^{0} \frac{g(t)}{t-z}\,dt \ , \tag{28}$$

we obtain the asymptotic behavior of F(z) near the end point z=0 as follows:

$$F(z) = \frac{G(0)}{\sqrt{d}}\,\frac{z^{\alpha}}{\sin\pi\alpha} + F_o(z) \tag{29}$$

where $F_o(z)$ is bounded near z=0. From (28) it is seen that at $z = y>0$ F(z) is holomorphic and

$$F(y) = \frac{1}{\pi}\int_{-d}^{0} \frac{g(t)}{t-y}\,dt = \frac{G(0)}{\sqrt{d}}\,\frac{y^{\alpha}}{\sin\pi\alpha} + F_o(y) \ . \tag{30}$$

From (25) and (30) it can now be shown that only the terms in the first integral in (25) contribute to the stress singularity and by using (30) these terms may be expressed as

$$\frac{1}{\pi}\int_{-d}^{0} \frac{y}{(t-y)^2}\,g(t)dt = y\,\frac{d}{dy}\,F(y) = \alpha\,\frac{G(0)}{\sqrt{d}}\,\frac{y^{\alpha}}{\sin\pi\alpha} + F_1(y) \ , \tag{31}$$

$$\frac{1}{\pi}\int_{-d}^{0} \frac{y^2}{(t-y)^3}\,g(t)dt = \frac{y^2}{2}\,\frac{d^2}{dy^2}\,F(y) = \frac{\alpha(\alpha-1)}{2}\,\frac{G(0)}{\sqrt{d}}\,\frac{y^{\alpha}}{\sin\pi\alpha} + F_2(y) \ , \tag{32}$$

where F_1 and F_2 are bounded near y=0.

By substituting from (30)-(32) into (25), the leading term of σ_{xx} near y=0 is then found to be

$$\sigma_{xx}(0,y) \cong \frac{G(0)E}{2\sqrt{d}\,\sin\pi\alpha}\left[\frac{4\nu}{(1+\nu)(3-\nu)} + \frac{1+\nu}{3-\nu}\,\alpha(\alpha+2)\right]y^{\alpha} \ , \quad y>0 \ , \tag{33}$$

where G(0) is given in terms of the bounded function $h(\tau)$ as (see (27))

$$G(0) = (2/d)^{\alpha-\frac{1}{2}}\,h(1) \ . \tag{34}$$

Similarly, other critical stress components and their asymptotic values near the crack tip x=0, y=0 may be determined as follows:

$$\sigma_{yy}(0,y) = \frac{E}{2\pi(3-\nu)}\int_{-d}^{0}\left\{\frac{4}{1+\nu}\frac{1}{t-y} - \frac{(1+\nu)y}{(t-y)^2} - \frac{2(1+\nu)y^2}{(t-y)^3} - \frac{m(1+\nu)ty}{(t-y)^2}\right.$$

$$- \frac{m(1-\nu)t}{t-y} - \frac{m^2(1-\nu)yt}{t-y} - 2m\left(\frac{1-\nu}{1+\nu} + ym\right)\left(1 - \frac{1+\nu}{2}mt\right) *$$

$$\left. * \, e^{-m(t-y)} \, Ei(m(t-y))\right\} g(t)dt \,, \quad 0 < y < \infty \,, \tag{35}$$

$$\sigma_{yy}(0,y) \cong \frac{G(0)E}{2\sqrt{d}\,\sin\pi\alpha}\left[\frac{4}{(1+\nu)(3-\nu)} - \frac{1+\nu}{3-\nu}\alpha^2\right]y^\alpha, \quad y>0 \,, \tag{36}$$

$$\sigma_{yy}(x,-0) = \frac{2E}{\pi(3-\nu)}\int_{-d}^{0}\left\{\frac{t}{t^2+x^2} - \frac{tx^2}{(t^2+x^2)^2} - \frac{m(1-\nu)}{4}\left[\frac{t^2}{t^2+x^2}\right.\right.$$

$$\left.\left. + \left(mt - \frac{2}{1+\nu}\right)\int_0^\infty \frac{e^{\beta t}\cos\beta x}{\beta+m}\,d\beta\right]\right\} g(t)dt \,, \quad 0 < x < \infty \,, \tag{37}$$

$$\sigma_{yy}(x,-0) \cong \frac{EG(0)}{2\sqrt{d}\,\sin\frac{\pi\alpha}{2}}\,\frac{2+\alpha}{3-\nu}\,x^\alpha \,, \quad x>0 \,, \tag{38}$$

$$\sigma_{xy}(x,-0) = \frac{E}{2\pi(3-\nu)}\int_{-d}^{0}\left\{\frac{7+2\nu-\nu^2}{1+\nu}\,\frac{x}{x^2+t^2} - \frac{2(5-\nu)xt^2}{(x^2+t^2)^2} - \frac{2mxt}{t^2+x^2}\right.$$

$$\left. + \left[2m^2t - 4m(1+\nu)\right]\int_0^\infty \frac{e^{\beta t}\sin\beta x}{\beta+m}\,d\beta\right\} g(t)dt \,, \quad 0 < x < \infty \,, \tag{39}$$

$$\sigma_{xy}(x,-0) \cong \frac{EG(0)}{4\sqrt{d}}\left[\frac{(5-\nu)\alpha}{(3-\nu)\sin\frac{\pi\alpha}{2}} + \frac{7+2\nu-\nu^2}{(3-\nu)(1+\nu)\cos\frac{\pi\alpha}{2}}\right]x^\alpha \,, \quad x>0 \,. \tag{40}$$

From the asymptotic expressions (33), (36), (38) and (40) it is seen that stress components near the crack tip has the form

$$\sigma_{ij} \cong \frac{G(0)E}{\sqrt{d}}\,r^\alpha f_{ij}(\nu) = Eh(1)2^{\alpha-\frac{1}{2}}(r/d)^\alpha f_{ij}(\nu) \,, \quad (i,j = x,y) \,, \tag{41}$$

where r is a small distance from the crack tip, and f_{ij} are known functions and $-1 < \mathrm{Re}(\alpha) < 0$. Thus, the calculated quantity h(1) is the measure of the stress singularity near the crack tip. For b=0 in the numerical analysis, in addition to $k_1(-d)$ defined by (20), the following "stress intensity factor" is defined and tabulated (Figure 1)

$$\begin{aligned} k_1(0) &= \lim_{y \to +0} \sqrt{2}\, y^{-\alpha}\, \sigma_{xx}(0,y) \\ &= \frac{Eh(1)}{2a^{\alpha}\sin\pi\alpha}\left[\frac{4\nu}{(1+\nu)(3-\nu)} + \frac{1+\nu}{3-\nu}(\alpha^2+2\alpha)\right], \quad a = \frac{d}{2}. \end{aligned} \tag{42}$$

We note that for any external load leading to the opening of the crack $G(0) < 0$. Since α is also negative, from (33), (36), (38) and (40) it follows that near the crack tip we have $\sigma_{xx}(0,y) > 0$, $\sigma_{yy}(0,y) > 0$, $\sigma_{xx}(x,-0) > 0$, and $\sigma_{xy}(x,-0) < 0$, which are the intuitively expected results.

The power of singularity α defined by (27) and calculated from (24) is given in Table 1. The stress intensity factors calculated for constant crack surface pressure $\sigma_{xx}(0,y) = -\sigma_0$, $(-d<y<-b)$, $\nu = 0.3$, generalized plane stress, various crack locations, and various values of the stiffness constant γ are given in Table 2. Note that, as expected, the stress intensity factors decrease as γ increases and as the crack moves closer to the stiffener.

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Table 1. Variation of the power α of the stress singularity with Poisson's ratio.

ν	α	
	Plane Stress	Plane Strain
0	0	0
0.1	-0.1026	-0.1096
0.2	-0.1547	-0.1743
0.3	-0.1913	-0.2267
0.4	-0.2197	-0.2739
0.5	-0.2429	-0.3196

Table 2. The calculated stress intensity factors: $k'(-b) = k_1(-b)/\sigma_0\sqrt{a}$ $k'(-d) = k_1(-d)/\sigma_0\sqrt{a}$, $k'(0) = k_1(0)/\sigma_0 a^{-\alpha}$, $a = (d-b)/2$, $c = (d+b)/2$, $\gamma = E_s A_s/E$, $\nu = 0.3$, $\alpha = -0.1913$, the case of generalized plane stress.

	k'(0)	k'(-b)				k'(-d)				
γ/a \ c/a	1	1.1	1.5	2.0	10	1	1.1	1.5	2.0	10
0.1	1.197	0.952	0.993	0.998	1.000	0.988	0.994	0.998	0.999	1.000
0.2	1.008	0.919	0.988	0.996	1.000	0.981	0.989	0.996	0.998	1.000
0.25	0.953	0.905	0.985	0.995	1.000	0.977	0.986	0.995	0.998	1.000
0.3	0.911	0.894	0.983	0.995	1.000	0.975	0.984	0.994	0.997	1.000
0.4	0.850	0.874	0.978	0.993	1.000	0.970	0.981	0.993	0.997	1.000
0.5	0.806	0.858	0.974	0.991	1.000	0.966	0.977	0.992	0.996	1.000
0.6	0.774	0.844	0.971	0.990	1.000	0.962	0.974	0.990	0.995	1.000
0.7	0.748	0.833	0.967	0.989	1.000	0.959	0.972	0.989	0.995	1.000
0.8	0.726	0.823	0.964	0.988	1.000	0.956	0.969	0.988	0.994	1.000
1.0	0.694	0.806	0.959	0.986	1.000	0.951	0.965	0.985	0.993	1.000
1.25	0.664	0.790	0.953	0.983	1.000	0.946	0.960	0.983	0.992	1.000
1.5	0.643	0.777	0.948	0.981	1.000	0.941	0.957	0.981	0.991	1.000
1.75	0.626	0.766	0.944	0.979	1.000	0.938	0.953	0.979	0.990	1.000
2	0.613	0.757	0.941	0.978	1.000	0.935	0.951	0.978	0.989	1.000
2.5	0.593	0.744	0.933	0.975	1.000	0.930	0.946	0.975	0.987	1.000
3	0.578	0.733	0.930	0.973	1.000	0.925	0.942	0.972	0.986	1.000
3.5	0.567	0.725	0.926	0.971	1.000	0.923	0.939	0.971	0.985	1.000
4	0.558	0.718	0.922	0.969	1.000	0.919	0.936	0.969	0.984	1.000
5	0.545	0.708	0.917	0.966	1.000	0.915	0.932	0.966	0.982	1.000
7	0.529	0.695	0.909	0.962	1.000	0.909	0.926	0.962	0.980	1.000
10	0.516	0.683	0.902	0.958	0.999	0.904	0.921	0.958	0.977	0.999

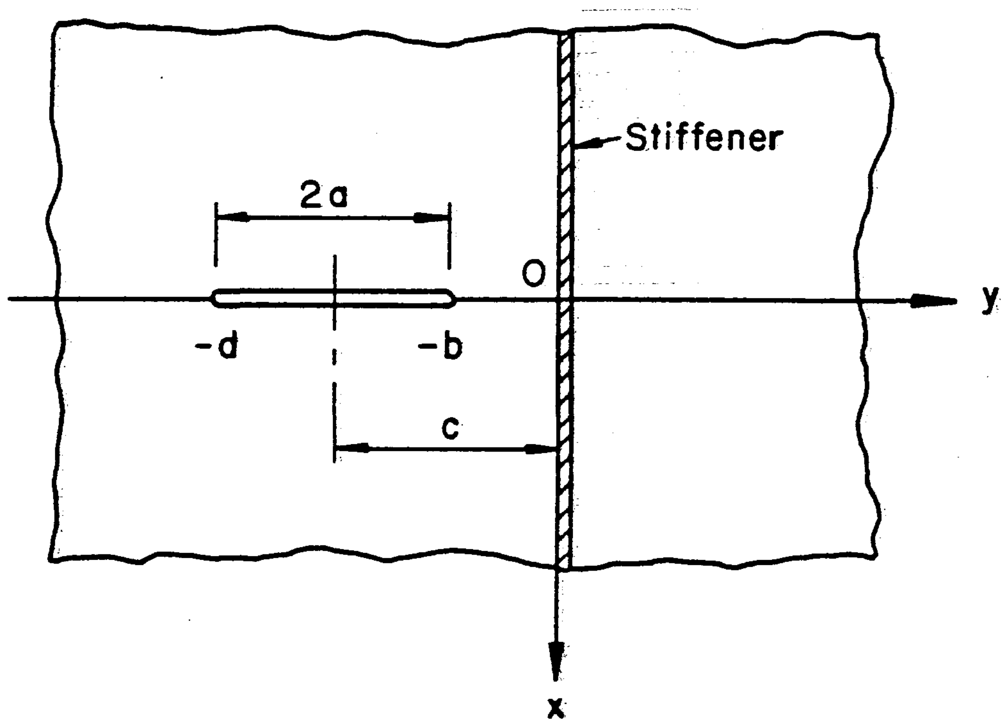

Figure 1. The geometry of a stiffened plate containing a crack.

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16. Abstract

In this note the problem of a cracked plate reinforced by a line stiffener is reconsidered. The original solution of this problem has been given in the literature. Also, a variation of the problem with debonding between the plate and the stiffener near the cracked region has been reported in the literature. However, the special case of the problem in which the crack tip terminates at the stiffener does not appear to have been studied. In practice, the solution may be necessary in order to assess the crack arrest effectiveness of the stiffener. In this note the problem of a stiffened plate with a crack is reformulated, the asymptotic stress state near the crack tip terminating at the stiffener is examined, and numerical results are given for various stiffness constants.

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