NASA INDUSTRIAL APPLICATIONS STUDY

Industrial Review
for
DETERMINATION OF FRACTURE TOUGHNESS PARAMETER OF LARGE METAL STRUCTURES

Dr. A.M. Wahl

10 December 1964

Contract NASw 952

Presented to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Office of Technology Utilization
Washington, D.C.

by

WESTINGHOUSE ELECTRIC CORPORATION
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FIGURE

INTRODUCTION

A tremendous amount of research is now being conducted on the subject of fracture mechanics and fracture toughness. This involves the determination of the fracture or bursting strength of large structures or machine components which may have small cracks or defects present. Such structures of interest to industry include, for example, large turbine or generator rotors, turbine disks, pressure vessels of various types, large blowers and fans, large oil tanks, and railway axles. Small cracks may be present in such structures or may develop after a time from fatigue or repeated loading after which the structure may fail catastrophically, often with large losses of life and property. For this reason, the problem of predicting the fracture strength of such a structure becomes tremendously important, but at the same time it may be extremely difficult.

One approach to this problem which is coming into wide use is the fracture mechanics approach as discussed in reference 1[*]. In this approach, the elastic stress is calculated in the immediate neighborhood of a crack in a structure. This stress is characterized by a parameter K called the "stress intensity factor." This parameter depends on the shape of the structure and on the load; however, it is not the same as a stress concentration factor. It is postulated that at some critical value of K for a given material (denoted by K_c) rapid crack propagation and complete or catastrophic failure will occur. This value of K_c is frequently called fracture toughness.[1] Usually the lowest values of K_c are obtained for relatively thick specimens (where plane strain conditions occur) and these values are called K_{Ic}. In most practical structures, we are concerned with the plane strain fracture toughness K_{Ic} values.

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* References are listed at the end of this review

Using this fracture mechanics approach, the problem of predicting the bursting or fracture strength of a structure reduces to: (1) calculating the K-value for the actual structure under operating conditions, and (2) determining the K_{Ic}-value for the given material by use of a suitable test specimen. The contribution of NASA Technical Note D-2395[2] is largely in the latter phase.

CONTRIBUTIONS OF NASA TECHNICAL NOTES D-2395 AND D-2206

Normally, stress intensity factors, K_c, for any material are found by tension tests on specimens having sharp notches or cracks. These specimens may be flat bars with cracks on two opposite sides or round bars containing deep notches. The formulas for calculating K-values for such specimens are well known; however, to find the plane strain values (K_{Ic}) for many materials, it is necessary to go to extremely large size specimens, which unfortunately require extremely high load capacity tensile testing machines. Such machines are not normally available.

To avoid such high load requirements, tensile specimens made of flat plates with a notch on one side (the single-edge-notch tension specimen) are now being used. Such specimens require much lower capacity testing machines; however, the determination of the critical stress intensity factors, K_c or K_{Ic}, from such specimens has been rather uncertain since no formulas were available for calculating K-values for such specimens.

The contribution of TN D-2395[2] consists of the development of a method for finding the K-factors for such single-edge-notch tension specimens, as well as for other shapes of specimens. These K-factors are found as a function of ratio of notch depth to width of specimen, and also the ratio of specimen length to width. Technically, the method utilizes a boundary value calculation procedure applied to the well-known Williams stress function. It turns out that the first matrix coefficient is proportional to the stress intensity factor K. Thus, the method is useful for finding K-values for specimens of different geometrical proportions.

The theoretical results of TN D-2395 were checked by an experimental compliance procedure in TN D-2396.[3] This offers further proof of the validity of the method.

The procedure developed in TN D-2395 should be of value in the further development of fracture mechanics since the method may well be applied not only to the single-edge-notch tension specimen but also to other shapes of specimen which have further possibilities, as discussed later. Thus, the method should be valuable to industry in general, since it would contribute toward better estimates of bursting strength or fracture strength of structures, pressure vessels, or machine components.

In TN D-2206,[4] a practical method was developed for analyzing plastic deformations in biaxial stress fields or plate type structures. This method appears promising for analyzing plastic strains in test specimens such as the single-edge-notch tension specimen considered in reference 2. (See further discussion of this in a later paragraph.)

POTENTIAL APPLICATION OF METHOD DEVELOPED IN TECHNICAL NOTE D-2395

Recently, a shape of specimen developed by Manjoine [5] has been utilized for determining plane strain fracture toughness K_{Ic}-values. This specimen has advantages of small size and a high degree of constraint. (See figure 1 which indicates schematically the method of load application.) Commonly used dimensions are AB = 0.5 inch and BC = 1.6 inches. These advantages are important in experiments involving neutron irradiation where it is desired to determine fracture toughness of large pressure vessels utilized in nuclear power plants. However, the question arises as to how to calculate the K-values for different ratios of crack length to width, a/w, and of different ratios of v/w.

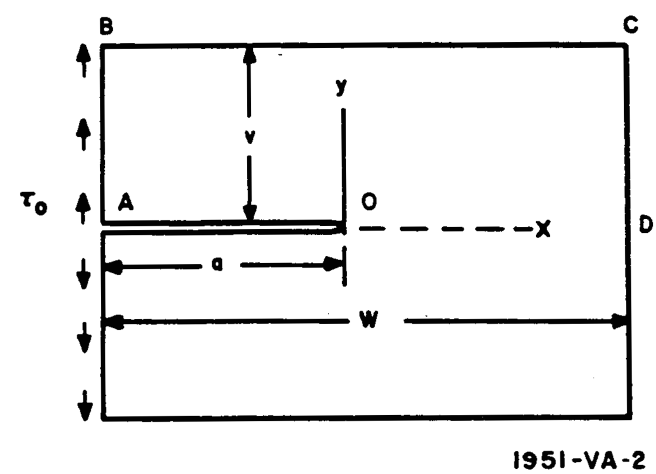

Figure 1. Manjoine Specimen Schematic

The method developed in TN D-2395[2] is valuable in that it may be applied to the specimen of figure 1, which is loaded differently from the single-edge-notch tension specimen of reference 2. As indicated in reference 5, this specimen is actually loaded by a pin on the upper half and through a bolt threaded into the lower half. It is expected that the schematic loading of figure 1 will be sufficiently close for an analytical approach.

In applying the method of reference 2 to the specimen of figure 1, a uniform shear stress and zero normal stress are assumed along the edge AB as shown. Zero shear and normal stresses are also assumed along edges BC and CD. Using the same stress function as assumed in reference 2 and utilizing the boundary conditions of figure 1, the values of stress intensity factor K may be found for various ratios of v/w and a/w. This would provide useful information on the effects of varying dimensions in this specimen.

POTENTIAL FURTHER DEVELOPMENTS

The method of TN D-2395 should also be of value in estimating the size of the plastic region near the crack tip 0 of figure 1. It is believed that the size of this plastic zone should be kept small compared to the thickness of the specimen (perpendicular to the x-y plane of figure 1) in order for this approach (utilizing the K_{Ic}-factors) to be valid.

Technically, the plastic zone size could be estimated approximately as follows utilizing the stresses calculated using the method of TN D-2395.[1] In this case, the assumption is made that the axial strain is zero, and from this condition the axial stresses could be calculated at any point using known elasticity equations. These stress components could be combined to give an equivalent stress using the maximum shear or octahedral shear strength theory. Knowing this stress and the yield stress of the material, the size of the plastic zone could be estimated. This would be useful in obtaining an idea of the required specimen thickness.

The same general method might be applied to obtain an idea of the plastic zone size for the single-edge-notch tension specimen discussed in reference 2.

The method for analyzing plastic stresses and strains given in TN D-2206[4] also appears to be of potential value in evaluating the results obtained from fracture tests on various shapes of specimen such as the single-edge-notch tension specimen of reference 2 or the shape shown in figure 1. The use of such a method would be of particular value in evaluating cases where the plastic zone size is relatively large. This would be a contribution to the further development of fracture mechanics. It appears that the method could be applied not only to the test specimens considered in references 2 and 5, but also to other cases commonly used such as the double-edge-notch-tension specimen.

In TN D-2206, the equations were given for a plane stress condition so that they apply strictly only to thin plates; however, it is believed that these equations may be modified to apply to plane strain conditions which are of great practical interest to industry.

One further development which would be of value is to utilize the stress and strain distributions obtained using the method of TN D-2395 as a starting point for the iteration method of TN D-2206. This may be helpful in reducing the number of iterations required to obtain a solution for a given loading.

Actual tests on different materials to correlate the results obtained on specimens of different geometries should also be made as a check on the analytical results.

CONCLUSIONS

The subject of fracture mechanics is a rapidly developing field which is of great practical importance to a number of industries, particularly where large structures or machine components subject to high stresses are concerned. Such industries include the electrical, heavy machinery, oil, steel, and chemical industries. Among the structures involved the following may be mentioned: turbine and generator rotors, turbine disks, large blowers and fans, pressure vessels of various types, and oil tanks. It is important to design such structures so that catastrophic failure will not occur and at present the fracture mechanics approach is most widely used.

The contribution of NASA TN D-2395 is valuable to industry in that it provides a practical method of calculating the fracture toughness parameter for a variety of test specimen shapes. These can later be applied to the calculation of fracture strengths in a variety of shapes of actual structures or machine components.

The contribution of NASA TN D-2206 consists in the development of a method for analyzing plastic strains in plate type structures. This general method appears to be valuable for the further development of the fracture mechanics approach, particularly for cases where considerable plastic flow may occur before fracture.

REFERENCES

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