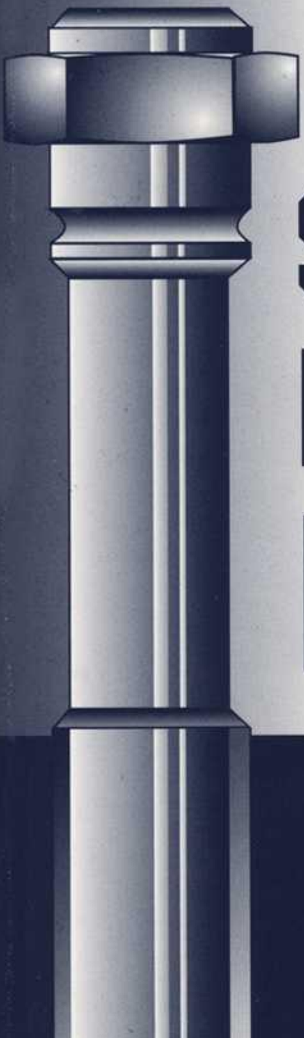

STRUCTURAL INTEGRITY OF FASTENERS

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Structural Integrity of Fasteners

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Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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Foreword

The Symposium on Structural Integrity of Fasteners was held in Miami, Florida on 16–19 Nov. 1992. The symposium was sponsored by the American Society for Testing and Materials through Committee E08 on Fatigue and Fracture. Members of Subcommittee E08.04 on Structural Applications and specifically the Task Group on Fracture Mechanics of Fasteners selected papers for the program. Organizational assistance from Dorothy Savini and Shannon Wainwright was most helpful. Pir M. Toor of Bettis Laboratory, Reactor Technology, West Mifflin, Pennsylvania served as technical program chairman. Those who served as session chairmen were J. L. Rudd, Air Force Wright Laboratory, Dayton, Ohio; H. S. Reenszynder, Bethlehem Steel Corporation, Bethlehem, Pennsylvania; G. T. Embley, Knoll Laboratory, Schenectady, New York; Alan Liu, Rockville International, California; and R. E. Johnson, US-NRC, Washington, DC.

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious effort of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM Committee E08, I acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

Pir M. Toor
Technical Program Chairman

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Pir M. Toor

An Overview of Structural Integrity of Fasteners

Introduction

Threaded members are important structural elements and influence significantly the strength and endurance of the whole structure. Further, because of high demands to structural reliability during the design and analysis of threaded members, there usually arises the tasks of achieving static strength and durability under variable internal and external loads on the stages of crack initiation and propagation.

Indeed, bolts have unique material requirements among the structural elements of an engineering component. Mechanical loads require the use of threads, and functional requirements demand low resistance to sliding motion between thread contact surfaces. Additionally, fabrication and processing operations can introduce unfavorable material properties, residual stresses, and undetected flaws. Also, actual service conditions can be quite different from those postulated for normal design consideration. Hence, bolts used in any system must have certain mechanical properties that are stipulated by specifications.

In spite of the fact that design procedures specify minimum yield strength levels, minimum tensile properties, and resistance to stress corrosion cracking, there are documented cases of stud cracking. Indeed, fracture evaluation of defects (cracks) occurring in the threaded portions of studs and bolts is a recurring problem in structures. Currently there is no explicit procedure for fracture analysis of bolting applications. Fracture analyses have been conducted according to specific industry need. Due to the complex stress state at the root of a thread, the procedure is complicated and time consuming. Hence, a more realistic and uniform fracture procedure for analysis of threaded members is needed.

The principal parameters required for fracture mechanics analysis are:

1. Stress state in the region of interest.
2. Initial flaw shape that may exist.
3. Initial flaw size that may exist.
4. Fracture toughness for the bolt material.
5. Crack growth rate data for the material.
6. Design factor.

The above parameters are discussed in detail in the sections that follow.

Fracture Phenomenon

Brittle Fracture

Brittle fracture generally occurs without prior plastic deformation. The fracture surface associated with this type of failure is flat (cleavage) with no shear lips. This type of failure typically occurs very quickly.

Usually, brittle fracture occurs in a component that has an existing crack in a tensile stress field. Fracture toughness is the material property that measures the fracture resistance of a given material and is affected by temperature.

Small initial flaws become large under cyclic loading (a fatigue process) and reach a critical size, eventually resulting in brittle fracture. In the case of fasteners, the most likely place to initiate brittle fracture are the regions of high stress concentration or stress gradient. These locations are thread root radius, thread to shank fillet, and head to shank fillet.

Ductile Fracture

Ductile fracture is generally accompanied by large amounts of plastic deformation. The transition from brittle fracture to ductile fracture generally occurs with changes in service conditions, for example, the state of stress, temperature, and the strain rate.

Ductile fracture can result in either complete separation of the component into two or more fragments or in simply a reduction in functional or load-carrying capability of the component due to gross yielding. Brittle and ductile fracture morphologies are generally distinct in that the former is frequently cleavage and flat and the latter is dimple rupture accompanied by included ("slant") fracture surfaces adjacent to the component surface. These inclined surfaces are sometimes referred to as "shear lips." This type of fracture involves both crack initiation and crack propagation.

This type of fracture becomes complex when the component contains notches or grooves. The triaxial state of stress at these locations restricts the plastic flow in the components at these discontinuities. Hence the resulting fractured surfaces would show similar shear lips and will look more like a fibrous or cleavage-type surface. Such fractures tend to appear more like a brittle fracture.

The most likely location for ductile failure is the minimum sectional area. This is the region where gross yielding of the region can occur. In the case of a fastener, it is not likely that ductile failure will occur at the thread root because here the plastic flow will be restricted as mentioned in the previous paragraph.

Corrosion Fatigue

Most structural components are subjected to fluctuating load and invariably operate in various environments. This type of behavior of metals in various environments is of primary importance. Corrosion fatigue behavior of a given environment-material system refers to the characteristics of the material under fluctuating loads in the presence of a particular environment.

Load Relaxation

This is a time-dependent phenomenon causing a decrease in stress in a component that is held to a certain fixed deformation. The load relaxation is a creep-related process characterized by the change of elastic strain to plastic strain resulting in stress reduction. In the case of threaded members (bolts, studs), preload will be reduced gradually with time. This process is a function of the temperature involved and the initial load.

In order to avoid joint failure, it is necessary to account for loss of preload due to stress relaxation in the initial design.

Stress relaxation can occur if the following conditions exist:

1. Material that is susceptible to stress relaxation.
2. High service temperature during operation.
3. Component having irradiation exposure.

Loss of preload can be minimized or eliminated by taking proper account of these factors into design.

Parameters Influencing Fracture

Introduction

There are many parameters that influence the fracture behavior of bolts. For low and intermediate strength steels, temperature-induced changes in metal grain ductility are known to introduce fracture state transition. Fracture-state transition temperature for most steels covers a wide range. Therefore, material characterization from a linear elastic fracture mechanics point of view is necessary. An appropriate material must be selected to meet structural requirements at the specified lowest service temperature for the section size of interest.

The role of environment has received a great deal of attention in most engineering designs. If environment effects are significant, then environment becomes an important reference for material characterization and analysis in the brittle fracture criterion. In addition to temperature and environment influence, the influence of loading condition is also an important factor in a design to resist fracture.

Indeed, a detailed study of fracture state, service temperature and environment effect, and loading condition and strength levels must be performed to evolve a fracture-resistant design.

Material Characterization

All engineering materials contain imperfections. Subsequent manufacturing and processing operations may produce additional cracks, inclusions, and other deficiencies. Such flaws can range in size from the microscopic to the very large. Surprisingly, large cracks often do not represent as serious a threat to structural integrity because they are more easily detected. Undetected smaller cracks, however, can grow to critical size as a result of service loading and environmental conditions. In ductile materials, once a crack has grown to critical size, it can result in catastrophic failure of the component.

In view of the above phenomena, ductile materials should be used for fabrication of critical parts. Although these materials have a greater tolerance for flaws, they also have a lower strength. Ductile materials, therefore, offer an alternative for the problem of material fracture, but this advantage is paid for by heavier, bulkier, and less efficient designs.

Most often, materials used in design are such that when service conditions are considered, they typically fail in a brittle manner. Under these conditions, stresses very near a flaw exceed the strength of the material even though the average design stresses in a part are very low. Therefore, the safe design of a component demands thorough understanding of the behavior of a material in the presence of flaws. In other words, the integrity of the material must be assessed for its intended use.

The plain-strain fracture toughness, K_{Ic}, quantitatively relates the critical crack size to applied load and geometry of a component. This material property is used to estimate minimum component loads, to compare candidate materials, and to assist in new alloy development. Therefore, the material's integrity must be established for its intended use.

Temperature Effect

Temperature is another important parameter that can cause brittle fracture. Ferritic steels and some titanium alloys have a temperature below which they become brittle. Materials that are ductile at room temperature become brittle at temperatures below the ductile brittle temperature transition range. In this low temperature range, these materials have very low energy absorption capability.

In addition, heat treatment and cold working of materials are processes used to increase a material's ductile strength properties, but such processes can also result in a drastic drop in fracture toughness.

Therefore, comprehensive investigation must be made to understand the influence of the temperature range at which the component will operate. The true limiting factor in the temperature application is the estimate of the lowest service temperature.

Environment

Many materials experience accelerated crack initiation and propagation under the joint action of a corrosive environment. For certain materials, the presence of corrosive environment can greatly reduce fracture toughness. In the presence of a corrosive environment, the metal surface affected fails to develop a protective oxide or corrosive oxide film and hence corrosion pits are formed.

Corrrosion control often starts with material selection. To establish material performance that can be expected in service, it is necessary to compare candidate materials with other materials for which long-term service experience is available. This is generally achieved by accelerated laboratory tests as these tests generally represent an extreme condition. Generally, crack propagation tests of precracked fracture mechanics specimens in aggressive environments are used. These types of tests give information to obtain: (1) a limiting stress intensity factor, K_{ISCC}, below which crack initiation and growth will not occur, and (2) the rate of environmental crack growth at higher stress intensity factor values.

The information obtained from these environmental tests is then used to select a material suitable for the intended service application. Also, limitations are determined on stress, temperature, and other parameters affecting the fracture strength of the material.

Loading Condition

Tensile Loads—If the bolt is perfectly symmetrical, the faces of the head and nut are exactly perpendicular to the axis of the threads, joint surfaces are flat and parallel, and loading the bolt by a hydraulic tensioner will produce a pure tension condition. Finite element analysis of bolts has shown that the tensile stress is zero at the free end of the bolt and that it rises uniformly through the head to the stress level found in the body. A similar pattern is observed in the threaded end, but the average stress in the threaded section is higher than the average stress in the body because the cross-sectional area is less in the threads. However, in real structure, consideration should be given to the effects of misalignments and non-perpendicularities, methods of applying preload, and variation in the coefficient of friction. For most practical applications, there is no uniform stress level, even in the body. This has a variety of implications when we are computing such things as stress levels, preloads, spring constants, etc.

In general, there is a concentration of the load at the first engage thread. The first three engaged threads carry most of the load in any case. This means that most of the nut is not doing its share of the work. This situation can be improved by tapering the threads or altering the pitch on either nut or bolt to have more uniformity in load distribution. The most popular way is to use a nut that is partially in tension.

A bolt is always put into service tension when it is properly tightened. Subsequent external loads usually do not modify this basic tension load very much if the joint is properly designed. However, it is important to estimate the magnitude of other types of loads that can be imposed on a bolt in use. These are considered in the following sections.

Bending—Because joint and nut surfaces are never exactly perpendicular to the thread axis, a bolt almost never stretches uniformly when it is tightened; instead, it bends to some degree. Thermal loading conditions produce stresses in fasteners when there is either a thermal gradient through the different components clamped in the joint or there are materials with different coefficients of thermal expansion subjected to a uniform temperature condition.

Thermal differential between the fastener and the clamped components will produce tensile stress in the fastener. This stress is in addition to the initial assembly preload tensile stress. In addition, if there are non-perpendicularities and non-parallelisms between the various parts, bending stresses will be produced. The bending condition takes the form of a transverse stress gradient that is additive to the bolt tensile stress for elastic behavior. For this type of thermal bending condition to exist it is necessary that the head not rotate to relieve the bending movement. The bending stresses vary linearly across the bolt diameter and achieve their highest magnitudes at the surfaces. Lateral deflections and end rotations also cause bending stresses in bolts.

Torsional Shear Stress—When fasteners are preloaded by torque, a torsional shear stress is induced throughout the various cross sections of the fastener. The value of the torsional shear stress varies with respect to the radial distance from the center line of the fastener. It is a function of the frictional constraints between the threads of the nut and the threads of the bolt, as well as between the clamping surfaces of bolt heads and nuts and their respective contact surfaces. An average value of the shear stress due to preloading by torquing is normally used for stress calculations.

Cyclic Loading

Generally, threaded members do not experience direct cyclic loading. However, pressure and thermal loading, which are cyclic in nature, can introduce cyclic load conditions through the joint components. Due to both linear motions and rotation in the joints, loads are of tension and bending type. Cyclic loads can cause fastener failure by crack propagation of an initial flaw that may be present in the material as well as initiation and subsequent propagation of a crack from an initially unflawed region of material.

Combined Loading

In the preceding sections, the causes and effects of individual loading conditions (tensile, bending, and torsion) were discussed. However, in real situations, these loads interact and have a combined effect on the integrity of the component. Therefore, any realistic analysis must account for all the loads acting on a component in a combined manner. Tensile, bending, and torsional loads acting on a circular cyclic containing an external circumferential notch are shown in Fig. 2.

Stress Relaxation

Stress relaxation is a time-dependent phenomenon in which stress decreases in a structural component that is restrained to a fixed deformation. It is a creep-related phenomenon in which elastic strain changes to plastic strain, resulting in stress reduction.

The stress relaxation process is a function of initial stress level and applied temperature. For worst case combination of temperature, stress level, and material, preload can be reduced significantly in threaded joints. For brittle fracture evaluation, it is necessary to account for loss of preload due to stress relaxation.

Types of Flaws

Introduction

In order to apply fracture mechanics, it is assumed that a crack or flaw exists in the structure in a threaded member; the most likely location at which the crack will initiate is the highly stressed region of thread root. It is generally recognized that the first engaged thread in a bolt/stud is usually the location of the highest stress. Fracture analysis procedure also requires definition of the shape and size of the assumed crack or flaw. The initial size of the flaw is usually controlled by the inspection capability, and the shape is governed by structural configuration and state of stress. Realistically, the shape of a flaw is established from either laboratory specimens or in-service failure observations and the size is established from the nondestructive examination (NDE) capabilities. However, from the design verification point of view, simplicity of basic assumptions are important considerations. At the root of a thread, the flaw shape is usually assumed as either a circumferential flaw or a part-through edge crack as shown in the following sections.

The initial size and shape of a flaw in the evaluation of structural integrity plays an important role. The stress intensity factor solutions are different for various types of crack configurations, and under similar stress fields structures can have different strengths. Therefore, it is important that before developing a brittle fracture procedure, the size and shape of the flaw used in the analysis be established. In this paper four types of flaw configurations will be discussed. A bolt under tensile load is shown in Fig. 1. The stress intensity solutions in the literature are calculated assuming a single groove in a cylindrical bar under complex load conditions as shown in Fig. 2.

Semi-Circular Surface Defect Model

The geometry for this defect shape is given in Fig. 3. The stress intensity factor solution is obtained by line-averaging the axial stress component over the crack depth. The stress intensity factor solution for this case is given below.

$$K_I = 1.22\,\bar{\sigma}\,\frac{\sqrt{\pi a}}{\phi} \tag{1}$$

where

K_I = the stress intensity factor,
$\bar{\sigma}$ = the average stress over defect,
a = the initial flaw size, and
ϕ = the complete elliptic integral of the second kind;
ϕ is $\pi/2$ for a semi-circular flaw.

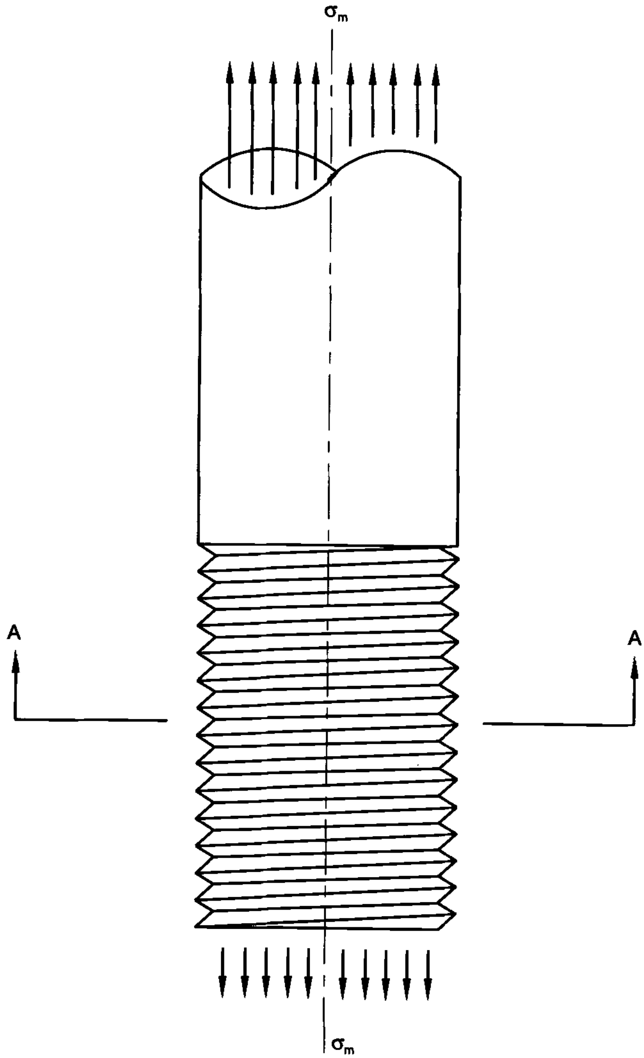


FIG. 1—*Bolt under tension load.*

Single Edge Notch Model

This model is illustrated in Fig. 4. Assessment of cracked solid cylinder was carried out by Johnson [*1*], and an edge crack model was developed. This model is also used by PVRC AD Hoc Group on Toughness Requirement. The stress intensity solution for this model is given as

$$K_I = \sigma \sqrt{\pi a}\, F\,(a/D_m) \quad (2)$$

where

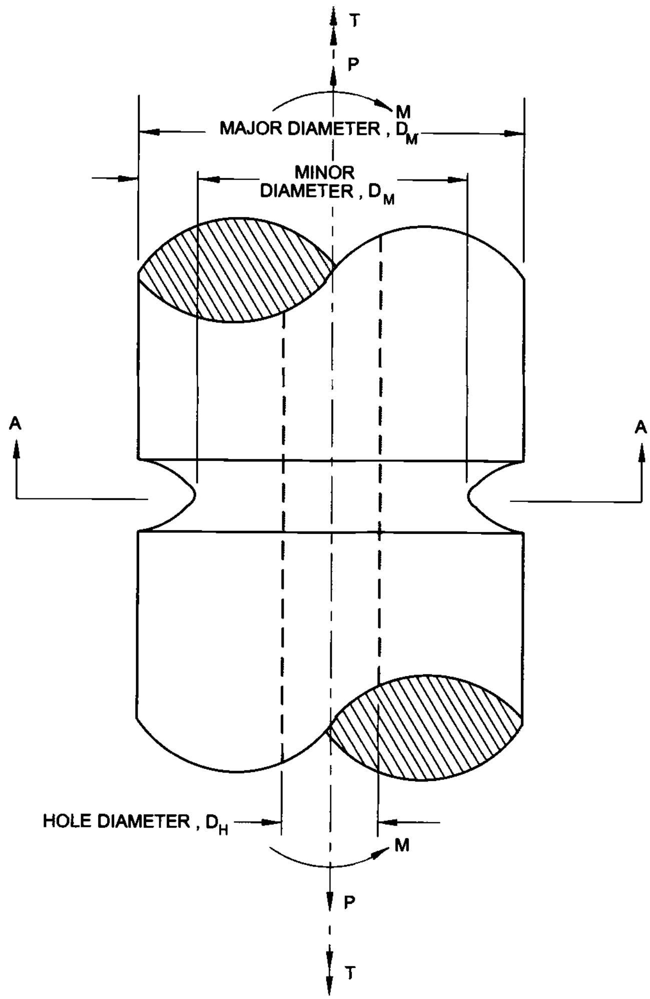


FIG. 2—*Circular cylinder containing external circumferential notch under combined loading.*

$F(a/D_m) = 1.12 - 0.231\ (a/D_m) + 10.55\ (a/D_m)^2 - 21.72\ (a/D_m)^3 + 30.39\ (a/D_m)^4$, and
σ = gross stress.

For application in the thread region:

$a = a_i + a_n$,
a_i = initial flaw size,
a_n = thread depth, and
D_m = major diameter of the threaded region.

Circumferential Crack Model

This model is shown in Fig. 5. Harris [2] has given a solution for stress intensity factor for this type of model as

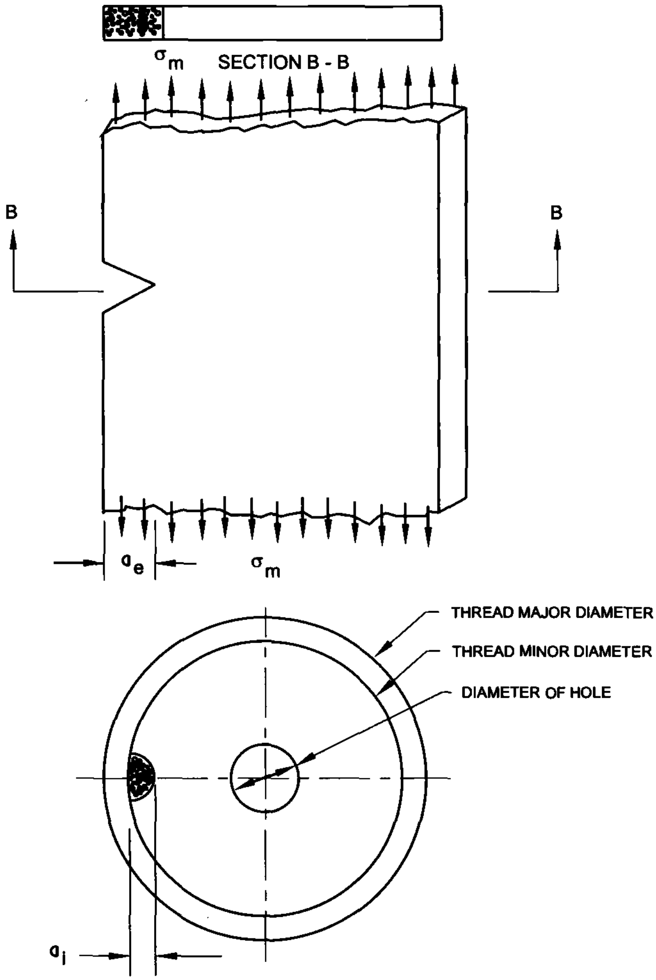


FIG. 3—*Single-edge cracked plate in tension representing an asymmetric crack configuration in a circular cylinder.*

$$K_I = \sigma_m M_m \sqrt{\pi a} \quad (3)$$

where

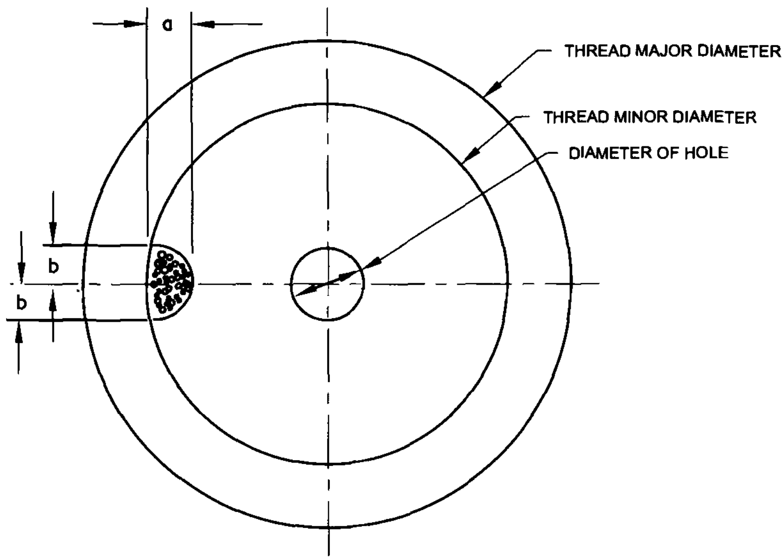
σ_m = gross membrane stress,

$$\sigma_m = \frac{4P}{\pi(D_m^2 - D_h^2)}$$

M_m = geometric correction factor.

$$M_m = \frac{1 - (D_h/D_m)^2}{[(1 - 2a/D_m)^2 - (D_h/D_m)^2]\left[0.8 + \dfrac{2a/D_m}{1 - 2a/D_m}\left(4 + \dfrac{1.1\ D_h/D_m}{1 - D_h/D_m - 2a/D_m}\right)\right]^{1/2}} \quad (4)$$

where



SECTION A - A ON FIGURE 2

FIG. 4—*Semi-circular crack configuration.*

a = total crack length initial crack length plus thread depth,
D_m = major diameter,
D_h = diameter of the hole, and
P = tensile load.

This model is more valid and versatile as it accounts for the presence of a central hole.

The above solution is applicable only to the membrane case. A suggested limit of applicability of this solution is $D_h/D_m \leq 0.5$.

Sickle Shape Model

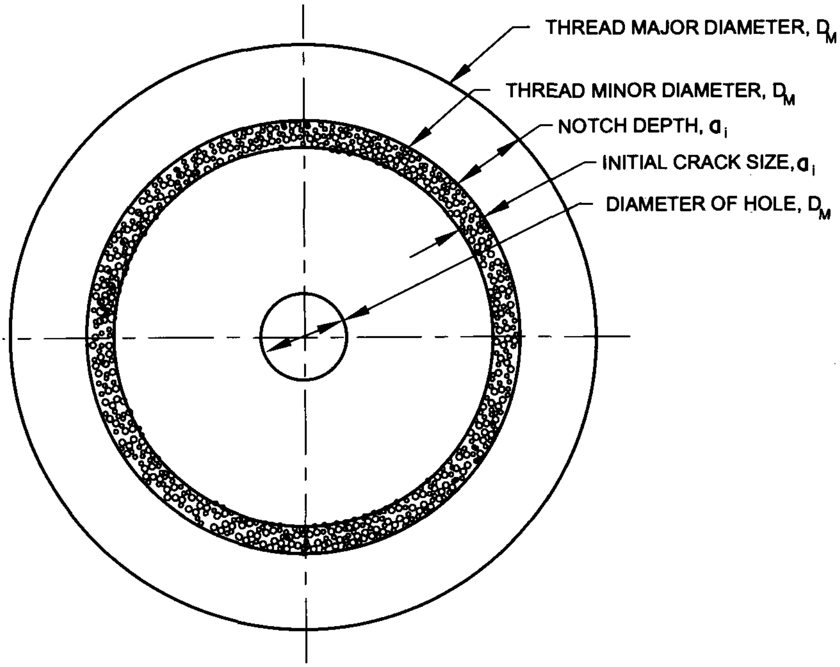
In notched cylinders, a sickle-shaped crack often develops that may cover the whole circumference of the bolt (Fig. 6). Mattheck et al. [*3*] have developed a solution for the stress intensity factor for this type of model at the deepest point, A, as

$$K = \int_0^a b(x, a)\ \sigma(x)dx \tag{5}$$

where $b(x, a)$ is the weight function that is obtained from the stress intensity factor, $K_r(a)$, and the corresponding crack opening displacement, $u_r(x, a)$, for a reference load case

$$b(x, a) = \frac{H}{K_r(a)} \cdot \frac{\partial u_r(x, a)}{\partial a} \tag{6}$$

where



SECTION A - A OF FIGURE 2

FIG. 5—*Circumferential crack configuration.*

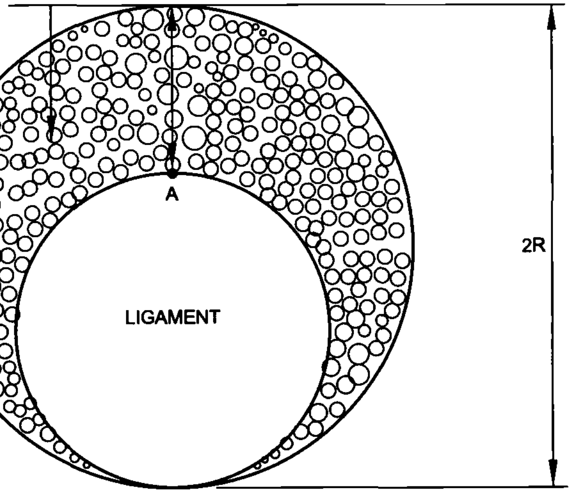


FIG. 6—*Sickle-shaped crack fully surrounding the cylinder circumference.*

$H = \left(\frac{E}{1 - \nu^2}\right)$ for plane strain, and
$H = E$ for plane stress.

$$K_r = \sigma_0 \sqrt{\pi a}\, F_r(a/R) \tag{7}$$

where σ_0 is the tensile stress.

and

$$F_r(a/r) = 1.1215 + 0.1644\,(a/R) + 5.1396\,(a/R)^2 - 15.932\,(a/R)^3 + 24.746\,(a/R)^4 - 10.986\,(a/R)^5 \tag{8}$$

The crack opening displacement $U_r(x, a)$ as a function of x and a is calculated assuming the following relationship.

$$u(x, a) = u_{max}(a) = (1 - x/z)^{1/2} \tag{9}$$

u_{max} is calculated by 3-D finite element analysis at $x = 0$ under a tensile stress, and the normalized displacement expression is given as

$$\frac{u_{max}E}{(1 - \nu^2)\sigma_0 R} = = \sum_{i=1}^{4} C_i(a/R)^I \tag{10}$$

with $C_i = 0.1965$, $C_2 = 22.515$, $C_3 = -44.317$, and $C_4 = 39.088$.

From the above equations, K_r is obtained as

$$K_r = \sigma_0 \sqrt{\pi a}\, F_r(a/R) \tag{11}$$

where $F(r)$ is given

$$F(r) = 1.1215 + 0.1644\,(a/R) + 5.1396\,(a/R)^2 - 15.932\,(a/R)^3 + 24.746\,(a/R)^4 - 10.986\,(a/R)^5 \tag{12}$$

The weight functions for the special cases of linear stress distribution $\sigma_0(1 - x/a)$ and quadratic stress distribution $\sigma_0(1 - x/a)^2$ are given as

$$F_{lin}(a) = 0.4446 + 1.1086\,(a/R) - 3.4582\,(a/R)^2 + 5.396\,(a/R)^3 + 0.2057\,(a/R)^4 - 1.4844\,(a/R)^5 \tag{13}$$

$$F_{qua} = 0.6048 + 1.2542\,(a/R) - 3.4095\,(a/R)^2 + 4.6189\,(a/R)^3 + 2.4984\,(a/R)^4 - 2.6806\,(a/R)^5 \tag{14}$$

These equations are valid and applicable for $0 \leq a/R \leq 1$. The superposition method can be used to determine the stress intensity factors.

Empirical Approach to Stress Intensity Factors

An empirical approach to determine the stress intensity factor has been proposed by James and Mills [*4*]. They developed a function based on the analytical and experimental data for straight front crack, semi-circular crack front, and threads for tension and bending load conditions. They agreed that there are regimes of a/D where each of the solutions is applicable. The stress intensity factor subjected to tension is given as:

$$K = \sigma(\pi a)^{1/2}\, F(a/D) \tag{15}$$

where

$$F(a/D) = A_e^B(a/D) + C + D(a/D) + E(a/D)^2 + F(a/D)^3 + G(a/D)^4 \tag{16}$$

where

$$A = 2.043,\ B = 31.332,\ C = 0.6507,\ D = 0.5367,\ E = 3.0469,\ F = -19.504,\ G = 45.647$$

The authors claim the above equation is reasonably accurate for $a/D > 0.004$. A similar solution is proposed for loads subjected to bending. An additional discussion on this approach is given by A. F. Liu and R. C. Cipolla in this volume (STP 1236).

Loading Rate Effect

In general, fracture toughness of structural materials, particularly steels, decreases with loading rate. For a given temperature, the fracture toughness measured in an impact test, K_{id}, generally is lower than the fracture toughness measured in a static test, K_{ic}. In other words, it shows that at a constant temperature, fracture toughness tests conducted at higher loading rates generally result in lower toughness values.

The loading rate effect is significant for materials that exhibit strain rate effects, such as structural steels having yield strengths less than about 140 ksi. The loading rate at a given temperature can affect the notch toughness significantly for such materials. Ideally, the fracture toughness values should be determined at loading rates that are experienced by the actual structure. Variation of loading rate throughout the structure will affect the allowable stress through its dependence on plane strain fracture toughness, K_{ic}.

Thus, the actual service loading rate will have a significant influence on any fracture criterion specified, either static or dynamic.

Crack Growth Equation

The use of the concept of fracture mechanics in the design and analysis of structures assumes the existence of initial flaws or cracks. These cracks under repeated service loading conditions propagate and become unstable (fast-fracture) when a critical crack length is reached. The rate of crack propagation depends on many factors, such as: (1) material, (2) environment, (3) service load history, (4) crack geometry, (5) local structural configuration. It is known from Ref *5* that for a particular material the crack growth rate, da/dN, can be described as a function of the stress intensity factor range, ΔK. At present there is a large number of crack growth equations. The Forman crack growth equation, Ref *6*, as described below is widely used in the industry.

$$da/dN = \frac{c(\Delta K)^n}{(1 - R)K_c - \Delta K} \tag{17}$$

where da/dN is the rate of crack growth, c and n are material constants, ΔK is the stress intensity factor range, R is the stress ratio defined as minimum stress divided by maximum stress, and K_c is the critical stress intensity factor.

The stress intensity factor range ΔK is defined as

$$\Delta K = \Delta\sigma \sqrt{\pi a} \cdot F(a/D) \tag{18}$$

where $\Delta\sigma$ is the stress range, a is the half crack length, and $F(a/D)$ is the product of various geometric and boundary condition correction factors.

The values of c and n (material constants) are calculated from constant amplitude test data by the following technique derived from the Forman equation.

$$\log[(1 - R)K_c - \Delta K] + \log(da/dN) = \log c + n \log \Delta K \tag{19}$$

For any two points, which represent a segment of the crack growth rate curve, two simultaneous equations are solved for c and n.

Design Safety Factor

A safety factor is required in a brittle fracture analysis procedure to account for possible variability due to unknowns and inaccuracies at various stages. A decision has to be made not only on the magnitude of the safety factor but also on how and when it should be applied. There are various possibilities that exist and that should be considered before a final decision is made. These possibilities are:

1. Safety factors on fatigue stresses.
2. Safety factors on basic data.
3. Safety factor on initial crack size.
4. Safety factor on final life (cycles).
5. Safety factor on failure load.

Acknowledgment

The work reported in this paper was done over a number of years by the author as the chairman of ASTM Task Group E08.04.07 on Fracture Mechanics of Fasteners. I would like to thank the task group members for their many lively discussions on the structural integrity of fasteners. The author also wants to thank Westinghouse-Bettis Laboratory for its continuous support, which has made it possible for the author to participate in ASTM committee activities. The views expressed are entirely those of the author and do not reflect the views of the ASTM or the Westinghouse-Bettis Laboratory.

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Introduction

In 1986, ASTM Committee E24 concluded that there was enough interest to establish a Task Group (E24.06.04) under Subcommittee E24.06, the Application of Fracture Mechanics. The scope included providing analysis procedure, test methods, and criteria for structural integrity evaluation of fasteners. Two study groups were created under this task group, one engaged in assimilating references on fatigue and fracture mechanics application and the second to compile stress intensity factors applicable to fasteners. (In 1993, E24 merged with Committee E09 to form Committee E08 on Fatigue and Fracture.)

The symposium on Structural Integrity of Fasteners, held in Miami, Florida, on 18 Nov. 1992, was conceived a year previously at the ASTM Committee Week in Dallas, Texas. At this meeting, a workshop on fatigue and fracture of fasteners was held. Participants showed an interest in a one-day symposium on structural integrity of fasteners.

The quest for more efficient structures has prompted the development of improved materials, stress analysis, and fabrication and inspection techniques. Higher allowable stress usually results from the use of these improved techniques. Higher stresses are generally acceptable from the standpoint of static stresses; however, when these stresses are cyclic in nature, crack initiation may occur. Generally speaking, for fasteners, testing is used to predict crack initiation.

In order to review the latest developments in dealing with fatigue and fracture behavior of fasteners, the Miami symposium was held. The symposium was specifically concerned with fatigue (crack initiation), fracture (of crack growth) failure, and evaluation and criteria for structural integrity of fasteners. The symposium consisted of four sessions. This volume, which resulted from the symposium, contains the text of the papers presented plus the text of other submitted papers.

Many people contributed time and energy to make the symposium a success. Special thanks are due to: (a) *the speakers*, for the time and effort spent in preparing their presentation and final manuscripts; (b) *the session chairmen*, for their effort in keeping the sessions moving in a timely manner; and (c) *the reviewers*, for their careful editing of the manuscripts.

The papers in this volume are state-of-the-art on fatigue and fracture mechanics for fasteners. These papers are useful for engineers, scientists, and researchers whose interests lie in the structural integrity of fasteners.

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