UCRL--53254

DE82 014955

Design Guidance for Fracture-Critical Components at Lawrence Livermore National Laboratory

R. D. Streit

Manuscript date: March 3, 1982

DISCLAIMER

This document contains information that is the property of the University of California and is loaned to you by the University of California. It is not to be distributed outside the University of California. It is not to be used for any purpose other than that for which it was loaned to you. It is not to be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or by any information storage and retrieval system, without the prior written permission of the University of California. The University of California makes no warranty, expressed or implied, for the use of the information contained herein. The University of California is not responsible for any errors or for any consequences arising from the use of the information contained herein.

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$5.00 per copy • (Microfiche \$3.50)

PREFACE

The purpose of this document is to define the areas in which various fracture-safe design approaches must be applied. Various decisions had to be made concerning the consequences involved if fracture of a component should occur. In general, there are no clear cut lines of distinction between consequences. Thus, it is important for designers and engineers to assess the consequences of failure of a structure being analyzed in a way compatible with this document. It is useful to put oneself in the position of the user and ask, "How safe do I feel?" Then, based on the answer to this question, decide what level of safety in design is appropriate.

The cost of a failure and relative safety levels chosen are based on what I have observed over the last few years at this Laboratory. As conditions change (either technological, economic, etc.) this document should be changed to reflect the current philosophy. As such, it is important that the users provide constructive input on the use of this guidance to the author, so that it can be properly updated as necessary.

A handwritten signature in dark ink, appearing to read "R. D. Streit", is positioned above a horizontal line.

R. D. Streit

CONTENTS

Preface	ii
Abstract	1
Introduction	1
Scope	2
Hazards	2
Definitions and Nomenclature	3
Elements of Fracture Control	3
Fracture Mechanics Design	3
Basis of Fracture Control Plan	7
Fracture Control Guidance	9
Category I	9
Category II	9
Category III	9
Category IV	10
Category V	10
Category T	10
Factors Important for Fracture Control	11
Fracture Control Summary	12
Acknowledgments	13
References	14

Design Guidance for Fracture-Critical Components at Lawrence Livermore National Laboratory

ABSTRACT

Fracture is an important design consideration for components whose sudden and catastrophic failure could result in a serious accident. Elements of fracture control and fracture mechanics design methods are reviewed. Design requirements, which are based on the consequences of fracture of a given component, are subsequently developed. Five categories of consequences are defined. Category I is the lowest risk, and relatively lenient design requirements are employed. Category V has the highest potential for injury, release of hazardous material, and damage. Correspondingly, the design requirements for these components are the most stringent. Environmental, loading, and material factors that can affect fracture safety are also discussed.

INTRODUCTION

Because of the sudden and often catastrophic nature of brittle fracture, it is important to consider fracture mechanics in the design of all components whose failure could result in personnel injury, release of hazardous or radioactive material, or loss of time and money. The primary cause of such failures is the growth of small flaws due to loading and environment until such size that the structure becomes unstable and failure occurs. Accordingly, there are three basic elements to fracture control: (1) loading, (2) crack size and geometry, and (3) resistance to crack propagation in the appropriate environment.

Understanding all factors that affect fracture in a complex structure is not possible. Thus, a fracture control plan is employed to systematically consider the primary fracture elements in the design, fabrication and use of fracture critical components.¹⁻³ The responsible engineer must correctly identify the input to the fracture control evaluation and assess all conditions (e.g., dynamic loading, corrosive environments, brittle welds, etc.) that may prove critical to the design integrity. The section on Factors Important for Fracture Control will aid in this evaluation. The Laboratory's Engineering Sciences Division can also provide important technical advice in such circumstances.

For the purpose of this document, fracture critical components are divided into five main categories* based upon their potential consequences should fracture occur. Category I is the lowest risk thus requiring minimal fracture guidance; whereas Category V has the highest potential for personnel injury and damage. Correspondingly, Category V components are designed and tested to the highest standards.

The five categories are as follows:

Category I: Failure has essentially no potential to cause injury and the cost of failure is low (i.e., less than \$5000).

Examples: Small equipment, low pressure piping.

Category II: Failure has essentially no potential to cause injury, but the cost of failure is moderate (i.e., cost to repair is between \$5000 and \$50,000).

Example: Remote operation equipment such as a high volume hydraulic pump.

*Temporary and test equipment are covered by a sixth category, Category T.

Category III: Failure has potential for only minor injury (i.e., only first aid necessary) and cost to repair failure is low to moderate (i.e., cost to repair is less than \$50,000).

Example: Lifting devices (i.e., hooks, fork lift) where personnel are cleared from immediate area.

Category IV: Failure has the potential for moderate injury (i.e., does not require hospitalization) and/or the cost of repairs are high (greater than \$50,000).

Example: Remote operation of a high pressure vessel.

Category V: Failure can result in severe injury and/or the release of hazardous or radioactive material. In this category the cost of failure is usually high; however, the potential for injury or hazardous release is the overriding concern.

Example: Tritium vessel or manned area high pressure vessel.

Only cases in which there is a potential for injury or release of hazardous materials is a fracture control plan required. Other cases are presented as fracture guidance. The engineer is cautioned, however, that the cost of failure due to downtime, replacement cost, and other inconveniences can be high even in noninjury cases.

An ME safety note may be required for designs of some fracture-critical components. The safety note must include a fracture control plan that states how the fracture-safe design criteria are met by the design, material, fabrication, and service conditions. To assess what designs will require a safety note, see the LLNL Health and Safety Manual⁴ and the ME Department's Design Safety Standards.⁵

SCOPE

Many factors influence the design and material requirements of fracture-critical components. It would be impossible to detail a specific fracture control plan to cover the range of laboratory needs. The goal of this document is to provide the designer and engineer with the necessary information and design guidance to assess the role that fracture control will play in the design and fabrication of a given structure. It is the engineer's responsibility to develop or otherwise obtain a fracture control plan that is appropriate for the structure and safety level requirements. This re-

port establishes guidance for such a fracture control plan.

A number of fracture control plans are available from technical societies, industry, and government.¹⁻⁶ Where the scope of these plans is compatible with the component under evaluation, their use is acceptable. In any case, however, it is important to consult with the Engineering Sciences Division to aid in the development of a fracture control plan or to ensure that the critical elements of fracture control are adequately addressed in existing plans.

HAZARDS

A structure that is not fracture-safe can fail by sudden, catastrophic propagation of a crack at nominal stresses as low as a small fraction of the yield strength of the material. Factors affecting fracture safety include material properties, temperature, environment, component geometry, as well as the flaw size and its geometry. The temperature at which some materials have inadequate

resistance to crack propagation can be above normal ambient temperatures. Depending upon the type of structure, energy potential, and proximity to personnel, the hazard can vary considerably. In addition to loss of function of the fracture-critical structure, explosion, flying debris, and loud noise may accompany failure.

DEFINITIONS AND NOMENCLATURE

a,c	flaw dimensions	K_{Ic}, J_{Ic}	plane strain fracture toughness. The two parameters are related by the relation
B	specimen or component thickness		
B_y	specimen or component thickness limitation for plastic yielding		
C_V	Charpy V-notch		$J_{Ic} = (K_{Ic}^2/E')$
DT	dynamic tear	K_{Ia}	crack arrest toughness
E'	elastic modulus adjusted for plane strain; $E/(1 - \nu^2)$, where E is the elastic modulus and ν is Poisson's ratio	K_{Id}	plane strain fracture toughness for dynamic loading
K_I	applied stress intensity	S_u	ultimate tensile strength
		S_y	yield strength

ELEMENTS OF FRACTURE CONTROL

Linear elastic fracture mechanics (LEFM) is a design tool in which the brittle fracture of structures can be predicted through component loading and either real or postulated cracks. By ensuring that the design stress intensity (with an appropriate factor of safety) is less than the material fracture toughness (evaluated for the specific environment and loading), unstable crack propagation can be avoided. This design relationship is analogous to the association of a component's stress state and the material tensile properties. LEFM enables the engineer to evaluate a material's resistance to crack propagation and thus provide a basis by which given materials may be certified for fracture critical applications. In addition to material certification, tests based on fracture concepts (i.e., Charpy and dynamic tear), are often used for screening materials and in the surveillance of material degradation.

Various design philosophies may be employed in fracture-safe design. A few common practices include: designing for an allowable "lifetime" based on fatigue crack-growth predictions; employing fail-safe concepts based on large plastic deformation, multiple load paths or redundant members; providing for leak-before break; and/or developing suitable inspection procedures. Although differing in application, all methods are aimed at ensuring that the crack sizes remain less than the critical size for brittle fracture. Fracture control plans are a useful means of employing the required design philosophies.

FRACTURE MECHANICS DESIGN

Mechanical engineering design generally encompasses structural synthesis, analysis, material selection, and design stress-level evaluation. The engineer uses fracture mechanics as one of his tools by which to choose materials, design stress levels, and allowable crack sizes for inspection or quality control to achieve the goal of a safe design.

The stress-intensity factor is related to the nominal stress, geometry and flaw size by

$$K_I = F(\text{geometry}) \sigma \sqrt{a}$$

where F is a constant that depends only on the geometry of the part and crack, σ is the nominal stress, and a is the crack size. Fracture will occur when the stress level and/or crack length is increased such that

$$K_I \leq K_{Ic}$$

where K_{Ic} is the critical stress-intensity factor for a particular material (including heat-treatment, weldments, etc.) at a given temperature, loading rate, and environment. Under plane strain conditions, the critical stress intensity is replaced by the material's fracture toughness K_{Ic} , dynamic fracture toughness K_{Id} , or crack arrest toughness K_{Ia} , based on the design conditions. Many references are available for fracture toughness data. A

useful compendium of sources is given in Ref. 10. Thus, the three factors that influence fracture control are: (1) allowable design stress level, which is often a function of the "rated-capacity" of the component; (2) flaw size and shape, which can be monitored by quality assurance and inspection techniques; and (3) toughness of the material, which is controlled by selection and processing.

Stress intensity solutions for many useful geometries can be easily found in available handbooks^{11,12} and technical publications. The stress intensity solution for a through-thickness crack of length $2a$ in a large plate (Fig. 1) is

$$K_I = \sigma \sqrt{\pi a}$$

This formulation of the stress intensity is extremely useful for initial estimates of critical crack size, required toughness level, or safe working stress. Correction factors can be found in the literature to account for plate dimensions, non-symmetric loading, or a nonsymmetrically located crack. Similarly, solutions for edge cracks in plates often provide a useful starting point for the fracture analysis of some geometries (Fig. 2).

Many of the cracks found in practice arise from such things as weld defects, arc burns,

corrosion pits, machining marks, or other defects in manufacture. These cracks are generally approximated by the thumbnail crack shown in Fig. 3. Even in thin plates, the leading edge of such a thumbnail crack could be subjected to plane strain constraint, so the corresponding fracture toughness may be low.

For relatively small elliptically shaped flaws ($a < B/2$) and a nominal stress well below yield, the critical flaw size is given by

$$a = \frac{1}{1.21\pi} \left(\frac{K_{Ic}}{\sigma} \right)^2 \quad \text{for a surface flaw, or}$$

$$a = \frac{1}{\pi} \left(\frac{K_{Ic}}{\sigma} \right)^2 \quad \text{for a buried flaw.}$$

In the more general case the flaw depth Q is replaced by a/Q . Q is a flaw shape factor that accounts for the crack aspect ratio a/c , and stress level. It can be evaluated from Fig. 3.

Once the critical stress for crack propagation has been reached, the thumbnail crack will often grow through the plate to become a through-thickness crack. A value often quoted for this subsequent through crack length is $2B$. Whether

FIG. 1. Through-wall crack geometry in a large plate and associated stress intensity solution.

FIG. 2. Edge-notched geometries and associated stress intensity solutions.

the through crack arrests will depend on its length and the value of K_{Ic} for the plate thickness. Thus in thin sheets, with large K_{Ic} , if a small crack is permissible, it may be less restrictive to design against propagation of the through crack. However, if the structure has to contain pressure for long periods, e.g., a gas storage pressure vessel, then propagation of thumbnail cracks may have to be considered. In thick plates, the value of K_{Ic} may be low enough so that once the thumbnail crack grows into a through crack there isn't much chance of stopping it. In this case, design has to be based on thumbnail flaws.

As an example of fracture-critical design, in 1965 a large rocket motor case failed while under

hydrostatic test due to an internal flaw about 0.1 by 1.4 in. The motor dimensions were 260-in. diam, 0.73-in. wall, and 65-ft length. The material's yield strength was $S_y = 250000$ psi. The pressure at failure was 542 psi or 0.5% of proof pressure.

$$\sigma = \frac{pR}{t} = \frac{542 \text{ psi} \times 130 \text{ in.}}{0.73 \text{ in.}} = 97000 \text{ psi}$$

$$\frac{\sigma}{S_y} = 0.39$$

FIG. 3. Buried elliptical and thumbnail cracks and associated stress intensity solutions.

$$a/2c = \frac{0.05 \text{ in.}}{1.4 \text{ in.}} = 0.036 ; Q \sim 1.0$$

$$a = 0.05 \text{ in.} = \frac{1}{\pi} \left(\frac{K_{Ic}}{\sigma} \right)^2 = \frac{1}{\pi} \left(\frac{K_{Ic}}{97000 \text{ psi}} \right)^2$$

$$K_{Ic} = (\pi \times 0.05 \text{ in.})^{1/2} (97000 \text{ psi})$$

$$K_{Ic} \sim 38500 \text{ psi-in.}^{1/2}$$

Larger values of K_{Ic} had been expected for this material. However, subsequent fracture toughness tests showed that the location of the crack tip relative to the weld was an important factor. Also the fracture tests exhibited considerable scatter.

Virtually all designs are the result of numerous compromises and trade-offs with respect to cost, weight, capacity, etc. Often, because of fracture requirements, the design employing the highest yield strength material will not result in either the lightest or the least expensive structure. In general, materials with high yield strength have relatively low fracture toughness as in the example above, and similarly, low yield materials have high toughness. However, as with all generalities, there are exceptions. There are some high strength materials that also have high toughness. These materials are usually quite expensive and not readily available. In some cases their use is limited by either the design environment, service temperature, or both. On the other hand, some materials have both low strength and low toughness. Such materials are generally used in low-stress components which are not fracture critical.

BASIS OF A FRACTURE CONTROL PLAN

A fracture control plan is a specific set of analyses and recommendations developed for a

particular structure to ensure its fracture integrity. As described by Rolfe and Barsom,² a fracture control plan should contain four basic elements:

1. *Identification* of the factors that may contribute to the fracture integrity of a structural member. This would include service conditions and loading (including static, dynamic, and cyclic events), geometric or weld particulars, and required material and fabrication specifications.

2. *Evaluation* of the relative importance of each of the factors identified, in particular stress, toughness, and flaw size limitations (Fig. 4). Assess the contribution of fatigue crack growth and corrosion leading to the critical flaw size and evaluate the influence of residual stresses and/or embrittled regions to the design analysis.

3. *Determination of trade-offs* and compromises relative to the various design alternatives. By considering the influence of tensile stress, flaw size, and material toughness with respect to cost, design life, load rating, and range of design applicability, an optimum design can be chosen. Include analysis of the factor of safety and fatigue life considerations. For example, for the same quality inspection and fabrication (i.e., same critical flaw size) and material toughness (K_{Ic}), a reduction in the design stress may be evaluated as an increase in the factor of safety or an extension of the fatigue life. These design alternatives should be optimized toward the desired goal.

4. *Recommendations* of the specific design considerations to ensure the safety and reliability of the structure against failure. Such recommendations can include rated capacity or design stress level, material and/or fabrication qualification, inspection—both initial and as function of life—and allowable environments.

If employed in an organized and well thought-out manner, the fracture control plan concept provides a very useful tool in ensuring the fracture integrity of engineering structures.

FIG. 4. Schematic showing effect of fracture toughness and plane-strain to plane-stress transition (loss of constraint) on critical flaw size.²

FRACTURE CONTROL GUIDANCE

Relative to the five categories of consequences discussed in the Introduction, the fracture control plan can range from a very simple material justification with no testing to one that specifies extensive analysis and testing. In addition to the five categories defined in the Introduction, a sixth category, Category T, is defined to cover test or temporary equipment and vessels that fall outside the realm of Categories I through V. Use of Category T design requirements will be very limited.

CATEGORY I

Because of the minor consequences resulting from failure in Category I components, the fracture guidance is simply based on "good design." No fracture control plan is required. Sharp corners, high stress risers, brittle welds and heat-affected zones, and cracklike geometries should be avoided where possible. Materials used should be compatible with the intended environments and service temperatures, and the stresses should be maintained at a reasonable level relative to the material tensile behavior. Visual inspection of these components should ensure that no gross material and/or fabrication defects exist.

CATEGORY II

The consequences of failure in Category II components are more serious than Category I due to the increased cost of repair; however, as in Category I components, there is essentially no potential for injury or release of hazardous material if the part fails. Thus, although fracture control is still considered a guidance and not a requirement, the moderate cost of failure makes it worthwhile to establish some fracture-safe assurances.

Fracture control for Category II components is based on having the critical flaw size (including environment, fatigue, temperature, and load rate) sufficiently larger than the detectable flaw size as determined by preservice and in-service inspection. In this case, flaws can be found and repaired before they grow to critical size. Inspection intervals will be set such that a previously undetected flaw cannot grow to critical length prior to the

next scheduled inspection. Fracture toughness testing is not required for components in Category II if data are available in the literature. For components fabricated from structural steels, a minimum fracture toughness of $30 \text{ ksi-in.}^{1/2}$ ($33 \text{ MPa-m}^{1/2}$) can generally be assumed as a worst case under most operating conditions exclusive of embrittling environments. As with Category I components, good design judgment is a critical element to ensure fracture safety.

CATEGORY III

The cost of failure for Category III components are comparable to Category II. However, Category III failures have the potential to cause minor injury. Because of this potential for injury, a fracture control plan is required. Similar to Category II components, fracture control will be based on ensuring that a flaw cannot grow to the critical crack size between inspections even if worst-case operating or accident conditions (e.g., stress, temperature, environment, etc.) are assumed. The maximum allowable flaw size is to be at least as large as the minimum detectable flaw size as determined by preservice and in-service inspection.

The allowable flaw size at a given inspection is determined by calculating what the critical flaw size is (i.e., where $K_I = K_{IK}$) and estimating how much crack growth is possible between inspections (considering fatigue, stress corrosion cracking, and corrosion-enhanced fatigue). The allowable flaw size is defined as one-fourth the critical flaw size minus the amount of crack extension possible between inspections. If such a flaw is found, corrective actions are required.

To be considered a detectable flaw, there must be a reliability of 90% or greater that it will be detected. No flaw less than 0.5 in. (1.27 cm) will be considered detectable in inspection unless detection capability can be demonstrated in in-service conditions. Flaw sizes significantly greater than 0.5 in. (1.27 cm) in depth should be assumed if the part geometry is complex or inspection capability is limited.

Fracture toughness tests or dynamic tear (DT) tests will be conducted for the material and

heat treatment used. Results from DT tests can be used to approximate toughness.¹³ Toughness values obtained from the literature will be acceptable if the material and processing are essentially the same as the specified material. If no data are available and a test is not feasible, a maximum toughness of 25 ksi-in^{1/2} (27.5 MPa-m^{1/2}) can be assumed for structural steel. The maximum toughness allowed for an unqualified steel in Category III is less than that allowed in Category II due to the increased risk of injury.

Other means of fracture-safe assurance may be employed in Category III components providing that the integrity of the system can be verified by analysis, inspection, and/or maintenance. Redundant members, multiple load paths, and fail-safe protection are all viable alternatives.

CATEGORY IV

Because of the high cost of failure and the potential for injury, brittle failure cannot be tolerated. Components in the Category IV classification should be designed such that failure occurs only after significant plastic deformation (i.e., elastic-plastic or fully plastic failure). The critical flaw size for Category IV components, based on linear elastic fracture analysis, must be greater than twice the section thickness under consideration for the worst-case operating or accident stresses (i.e., $a_{cr} \geq 2B$), or, through-thickness yielding must be ensured, i.e., $B \leq B_Y$. To ensure through-thickness yielding in the presence of large sharp cracks in a plate, the thickness B should meet the following requirement:

$$B \leq B_Y = \left(\frac{K_{Ic}}{S_y} \right)^2$$

The fracture toughness and yield strength are based on lowest service temperature and loading rates comparable to the maximum credible accident. Section thickness up to 1.5 times B_Y can be used if stresses significantly lower than yield can be demonstrated or inspection requirements eliminate the potential for brittle fracture.

Material used in Category IV components must be fracture tested using either standard fracture toughness test procedures (ASTM E-399 for K_{Ic} ¹⁴ or ASTM E-813 for J_{Ic} ¹⁵) or dynamic

tear test methods.¹⁶ Relations between dynamic tear test energies or NDT temperature (nil ductility transition) and fracture toughness are readily available in the literature.¹³ The single exception to this test requirement is that for steels, a maximum toughness of 20 ksi-in^{1/2} (22 MPa-m^{1/2}) can be assumed if material testing is not possible. This value is decreased from that required in Category II and III because of the relative seriousness of an accident should failure occur. A fracture control plan is required of all Category IV components.

CATEGORY V

Because of the potential for injury and/or the release of hazardous or radioactive materials, no failure can be tolerated. Components falling into Category V must be carefully analyzed and must meet the fully plastic yield criterion through its life—regardless of crack size, environment, temperature, loading or material degradation. Section thicknesses less than B_p are required where B_p is calculated using dynamic material behavior. If the fully plastic criterion cannot be met, adequate secondary systems must be provided to ensure safety and to adequately contain hazardous and/or radioactive materials. Fracture toughness testing— K_{Ic} and/or dynamic tear test—is required. A detailed fracture control plan must be developed for Category V components. Questions relating to the safety of these components should be referred to the ME Safety Committee.

CATEGORY VI

This category is established for components that do not fall into any of the previous five categories. In particular this category pertains to test or temporary equipment generally for "one time usage." Examples of such components are remotely loaded test pressure vessels or structural members to support an explosive device. While failure of such components may be expensive, often design or fabrication requirements limit these components from meeting the appropriate category of safety. In such cases, safety must be ensured (i.e., remote operation) and hazardous and/or radioactive materials must be contained. Thus, while the component itself may not meet the necessary safety requirements, remote operation

or secondary systems must provide equivalent fracture control.

Low stress application. A special case useful for Category T components, where the material properties are not known or the material is not certified, is to ensure that a fracture-critical component is loaded to stresses below a maximum allowable level. Based on the concepts discussed earlier, an allowable nominal working stress is defined under the following restriction¹⁷:

1. Use the minimum value of fracture toughness available for the class of materials. Low temperature and high loading rate must be assumed unless otherwise justified.

2. Consider that a large, undetected flaw exists in the structure. Flaw depths greater than or equal to half the section thickness must be assumed.

3. Calculation of the nominal working stress must include the effects of all stress concentrations as designed into the structure.

Then, using a single-edge-notch configuration (Fig. 2), the maximum allowable nominal stress can be calculated (Table 1).

For virtually all structural steels the lower bound toughness is $25 \text{ ksi-in}^{1/2}$ ($27.5 \text{ MPa-in}^{1/2}$). This value, highlighted in Table 1, includes studies

TABLE 1. Maximum nominal stress (ksi) level for unqualified materials.

Lower bound fracture toughness (ksi-in. ^{1/2})	Section thickness (in.)					
	1	2	3	4	5	10
5	1.4	1	0.8	0.7	0.6	0.5
10	2.8	2	1.6	1.4	1.3	0.9
15	4.2	3	2.5	2.1	1.9	1.3
20	5.7	4	3.3	2.8	2.5	1.6
25	7.1	5	4.1	3.5	3.2	2.2
30	8.5	6	4.9	4.2	3.8	2.7
35	9.9	7	5.7	5	4.4	3.1
40	11.3	8	6.5	5.7	5.1	3.6

of welds and heat-affected zones,¹⁸ alloy and common structural steels^{2,19,20} at low temperatures and high loading rates. Thus, for unqualified steel structures, the maximum stress that must not be exceeded is simply a function of the section thickness. For instance, for a 2.0-in.-thick component, the maximum nominal stress level is 5.0 ksi (35 MPa). For all other materials the lower bound value of fracture toughness should be obtained from a thorough search of the literature.

FACTORS IMPORTANT FOR FRACTURE CONTROL

In the previous sections the basic elements of fracture mechanics and fracture control have been presented. Fracture control guidance were established for five categories of risk as defined in the Introduction. In addition to the general rules discussed, the designer and engineer must be aware of various other factors important for fracture control. These factors are grouped into three sets: (1) environment, (2) loading, and (3) materials. Each of the sets is not independent, however. For instance, changes in loading can effect how an environment influences fracture. Thus, each of the factors and their interactions must be evaluated in fracture-safe design.

Environment. The service environment and service temperature can strongly influence both the safe life (e.g., stress corrosion cracking and/or corrosion fatigue) and fracture resistance (e.g., low temperature brittle behavior or hydrogen embrittlement) of a fracture-critical component.

Even seemingly benign environments such as air contain moisture and can have detrimental effects on the fatigue and fracture behavior. Liquid metal environments also have a large effect on material properties. Service environment must be carefully evaluated and appropriate materials chosen. If material-environment interaction is anticipated, it must be accounted for in the design and safety analysis.

Minimum operating temperature may be the greatest design uncertainty since fracture resistance may change markedly in some temperature ranges. Designing for an unduly low (or overly safe) minimum temperature may require an excessively costly material. Where appropriate, operating procedures and component labels should specify a minimum operating temperature.

Loading. Loading, while an important aspect of the design analysis, is often not well-defined due to complex design geometries, variable service

requirements, and accident conditions. Small cracks may propagate under fatigue loading until the component is weakened and fails by gross overload or until the critical crack size is reached and brittle fracture occurs. Environment, frequency of loading, and the ratio of maximum to minimum load are factors that must be considered in a fatigue analysis.

High rate and impact loading reduces the fracture resistance of most materials. If impact loads are anticipated in either normal or faulted operation, dynamic fracture toughness $K_{I\dot{D}}$ should be used in the safety evaluation. Intermediate rate loading can also have an effect on fracture resistance, and the corresponding toughness should be used where the loading rate is above static but below dynamic conditions.

Stress concentrations, such as the root of threads, increase the stress level and thus reduce the critical flaw size. It is important to include all geometric stress risers (stress concentration, weld bead corners, contact points, etc.) in the stress analysis.

A concise set of operating limitations and requirements for inspection must be specified to ensure that the actual loading and fatigue life do not exceed the design assessment. If design loading is exceeded, the fracture critical component should be inspected and repaired, and/or replaced if necessary.

Materials. Material properties can change dramatically due to temperature, environment,

processing and heat treatment, welding, and radiation exposure. Material testing and analysis must be conducted for the material in the anticipated service condition. Welding, for instance, can create locally embrittled zones, areas of material segregation, and microcracking. As such, it must be assumed that cracks exist in all welded structures. When material degradation is expected due to radiation, excessive heat, or other environmental conditions, a material surveillance program is necessary. Such a program requires that specimens made from the same material as the fracture-critical component are stored in the same service environment as the fracture-critical component (generally adjacent to the fracture-critical component). At predetermined times throughout the anticipated life of the part, specimens are removed and tested to ensure that fracture properties have not degraded below acceptable levels.

Fracture toughness is often strongly influenced by orientation of the material relative to the rolling or forging direction. Test specimen orientation and location must always be specified and, if there is a significant directional effect, proper orientation must be specified in the design.

In all cases in which environment, loading, and/or materials effects are a factor in the fracture safety, they must be analyzed and included in the fracture control plan. The Engineering Sciences Division will help in obtaining information on the influence of the important factors, and will aid in the analysis necessary for a fracture-safe design.

FRACTURE CONTROL SUMMARY

Table 2, a summary of the fracture control guidance for the six categories of components, provides a comparison of the different levels of

risk. Refer to the section on Fracture Control Guidance for a more complete analysis.

TABLE 2. Fracture control guidance summary.

Category	Risk	Fracture guidance	Fracture control plan required?
I	Very low: no injury, low cost (cost < \$5000)	Good design	No
II	Low: no injury, moderate cost (\$5000 < cost < \$50000)	$a_{critical} < a_{inspection}$; no testing required.	No
III	Moderate: minor injury, (first aid), moderate cost (\$5000 < cost < \$50000)	$a_{allowable} < a_{inspection}$ and $a_{allowable} \leq 1/4 a_{critical} + \Delta a^*$. Material test suggested or lower bound data used.	Yes
IV	High: moderate injury, (no hospitalization), high cost (cost > \$50000)	$a_{critical} > 2B$, or $B \leq B_c$. Material test recommended.	Yes
V	Very High: severe injury and/or release of hazardous material	Design for fully plastic behavior required. $B > B_c$. Material test required.	Yes
I	Varies: test or temporary equipment	Design option: No injury or release of hazardous material accepted.	Optional

* Δa is the crack growth anticipated between inspections.

ACKNOWLEDGMENTS

I would like to thank Professor E. Finni of the University of California, Berkeley for his advice, examples, and for his review of the manuscript. The work was completed under the guidance of the Mechanical Engineering Fracture Control Committee and the Mechanical Engineering Department Safety Committee.

REFERENCES

1. H. McHenry and S. T. Rolfe, *Fracture Control Practices for Metal Structures*, NBSIR 79-1623, National Bureau of Standards, Jan. 1980.
2. S. T. Rolfe and J. M. Barsom, *Fracture and Fatigue Control in Structures* (Prentice-Hall, Inc., New Jersey, 1977).
3. *Fracture Mechanics in Engineering Practice*, P. Stanley, Ed (Applied Science Publishers, London, 1977).
4. *Health and Safety Manual*, Lawrence Livermore National Laboratory, Livermore, CA, Manual M-010 (current issue).
5. *Design Safety Standards/Mechanical Engineering Department*, Lawrence Livermore National Laboratory, Livermore, CA, in preparation (1982).
6. W. S. Pellini, *Manual of Engineering Procedures for Fracture-Safe Design*, Association of American Railroads, Chicago, IL, AAR Report R451, Nov. 1980.
7. American Society of Mechanical Engineers (ASME), *Boiler and Pressure Vessel Code*, Section III-NB-2300, NC-2300, Appendix G (1981).
8. E. M. Ehret, "Material Control and Fracture Control Planning for the Space Shuttle Orbiter Program," in *Structural Integrity Technology*, ASME (1979).
9. J. M. Barsom, "Development of the AASHTO Fracture-Toughness Requirements for Bridge Steels," *Engn. Fract. Mech.*, **V7** (1975), pp. 605-618.
10. C. M. Hudson and S. K. Seward, "A Compendium of Sources of Fracture Toughness and Fatigue Crack Growth Data for Metallic Alloys," *Int. J. of Fracture*, **14** (4) (1978), pp. R151-R184.
11. H. Tada, P. Paris, and G. Irwin, *The Stress Analysis of Cracks Handbook*, Del Research Corp., Hellertown, PA (1973).
12. D. P. Rooke and D. J. Cartwright, *Compendium of Stress Intensity Factors* (H. M. Stationary Office, London, 1976).
13. *Rapid Inexpensive Test for Determining Fracture Toughness*, Nat'l. Mat'l. Advisory Board, Nat'l. Academy of Sciences, NMAA-328 (1976).
14. American Society for Testing and Materials (ASTM), Annual Standards, E399-81, Part 10 (1981).
15. American Society for Testing and Materials (ASTM), Annual Standards, E813-81, Part 10 (1981).
16. American Society for Testing and Materials (ASTM), Annual Standards, E604-80, Part 10 (1981).
17. R. Streit, Memorandum MTE80-1 to A. Blake, Lawrence Livermore National Laboratory, Livermore, CA, Jan. 8, 1980.
18. E. Banks, "Toughness Properties of HAZ Structures in Structural Steel," *Welding Res. Supp. Welding J.*, **53** (1974), pp. 299-306.
19. R. O. Ritchie, J. F. Knott, and J. R. Rice, "On the Relationships between Critical Tensile Stress and Fracture Toughness in Mild Steel," *J. Mech. Phys. Solids*, **21** (1973), pp. 395-410.
20. A. K. Shoemaker and S. T. Rolfe, "The Static and Dynamic Low-Temperature Crack-Toughness Performance of Seven Structural Steels," *Engineering Fracture Mechanics*, **2** (June 1971).