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The object of this study was to recommend possible improvements in the manner in which structural integrity of Army systems is assured. The elements of a structural integrity program are described, and relevant practices used in various industries and government organizations are reviewed. Some case histories of Army weapon systems are examined. The mandatory imposition of a structural integrity program patterned after the Air Force Aircraft Structural Integrity Program is recommended and the benefits of such an action are identified.

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CONTENTS

SUMMARY

The NMAB Committee on Assurance of Structural Integrity was formed to investigate and document the need for a formal structural integrity assurance program for employment by the U.S. Army. The perceived need for such a program stems from occasional structural failures in Army weapons and transportation systems, which, although few in number, have had a significant cumulative impact economically, in terms of injuries or death to personnel or upon mission success.

As a result of a review of failures as well as of procedures employed in industry and government to preclude failures, a strong committee consensus developed suggesting that a formal structural integrity assurance program would be highly desirable in Army system development and procurement. Important features of a recommended structural integrity program are proposed whereby the basic pattern of existing Air Force regulations (ASIP/ENSIP) is followed, but allowing more flexibility in implementation because of the wide diversity of Army equipment and systems. Details of the organization and operational aspects of such a program were not considered in the belief that the committee recommendations might best be achieved by the full and direct involvement of the Army itself in developing the detailed plan.

Finally, the committee report summarizes anticipated payoffs and benefits of the proposed program in terms of the major reasons for its implementation, which include cost, safety, readiness, visibility, maintenance, and political factors.

INTRODUCTION

The sudden and unexpected failure of engineering structures can have serious human and economic consequences. Numerous examples can be cited where the loss of life is high and the resulting costs are severe. The walkway collapse at the Hyatt-Regency Hotel in Kansas City (National Bureau of Standards 1982), the American Airlines DC-10 engine separation and crash in Chicago (National Transportation Safety Board 1979), and the I-95 bridge failure in Connecticut (Newsweek 1983) are examples of major failures that have compromised public safety.

Many other premature failures occurring in structural components may pass unnoticed by the public but may have important economic consequences for the manufacturer, the user, or the taxpayer. The collapse of welded oil storage tanks (National Research Council 1953a) and the sudden fracture of large generator rotors (Schabtach et al. 1955), events that occurred in the 1950s, are representative of very costly component failures.

Visibility—public awareness—is another concern in reckoning with the possibility of sudden failure. Perhaps no event is more visible to the public than the launching of man into space. The subsequent political and programmatic consequences of a structural failure at the time that national television is giving its full attention to the event can be anticipated to be extreme. Safety, cost, and visibility are only three of many factors on which this class of failures impact.

The causes of such failures are many, and examples of each will be presented here. They include:

1. Improper recognition of loading conditions.

2. Material and design factors contributing to instability.

3. Quality of manufacture of the finished product.

4. Material damage from prior service.

The failure of the Tacoma Narrows Bridge (Paine et al. 1944) is an example of improper recognition of loading. This bridge had one of the longest spans for a suspension bridge when it was completed in 1940. Although it presented a graceful and pleasing profile, its slenderness made it aerodynamically unstable; it developed severe oscillations in the prevailing winds of the Narrows and soon twisted itself apart in a high, sustained wind (Figures 1 and 2). The problem arose because of improper consideration of the wind conditions and the dynamic response of the slender bridge structure to those winds. Wind tunnel tests verified the cause and, subsequently, became a consideration in bridge design.

Although Griffith (1920) developed the basic concept describing the brittle fracture of glass in 1920, stability against sudden fracture did not become a vital issue until World War II when over 200 all-welded ships experienced brittle fracture (National Research Council 1953b) (Figure 3). In this case, the loss in fracture ductility with decreasing temperature in ferritic steels used for ship plate was an important contributing factor to cracking (low fracture toughness) as was a design employing hatches with square corners (high stress intensity factor). Full recognition of the importance of fracture toughness and the stress-intensity factor in the failure of engineering structures did not occur until the late 1940's.

Another example of instability was the catastrophic failure of two de Havilland Comet jet airplanes in the mid-1950s (Bishop 1955). This plane was the first passenger plane of this type to be introduced for commercial use. Cyclic pressurization of the cabin led to the development and growth of small fatigue cracks from rivet holes in window corners causing the structure to become unstable and to burst dramatically in mid-air (Figure 4). These failures were death blows to the Comet and a severe setback to British commercial jet aviation for many years hence.

Many failures in which the quality of manufacture of the finished product was a major factor can be described. One fairly recent case is that of the elevated walkways of the Hyatt Regency Hotel in Kansas City (National Bureau of Standards 1982). In this case, an on-site change in the method of support of the walkway led to tragedy. In July 1981, a crowd was gathered on the walkways as well as in the lobby below when the walkways suddenly collapsed (Figure 5). Although it was later determined from detailed testing that even the original design was inadequate for the imposed load, a change had been introduced during construction that doubled the load on the box beam bearing surface of the fourth floor walkway by the rods suspended from the ceiling, causing the rod to pull through the box beam (Figure 6).

Material damage in service is also a major source of premature failure. The principal cause is fatigue, a process of crack initiation and growth arising from cyclic loading. Since crack initiation is greatly accentuated by local stress raisers (e.g., notches), material defects (e.g., inclusions), and a wide variety of surface conditions and since most structures are subjected to cyclic loading, cracking from this cause is
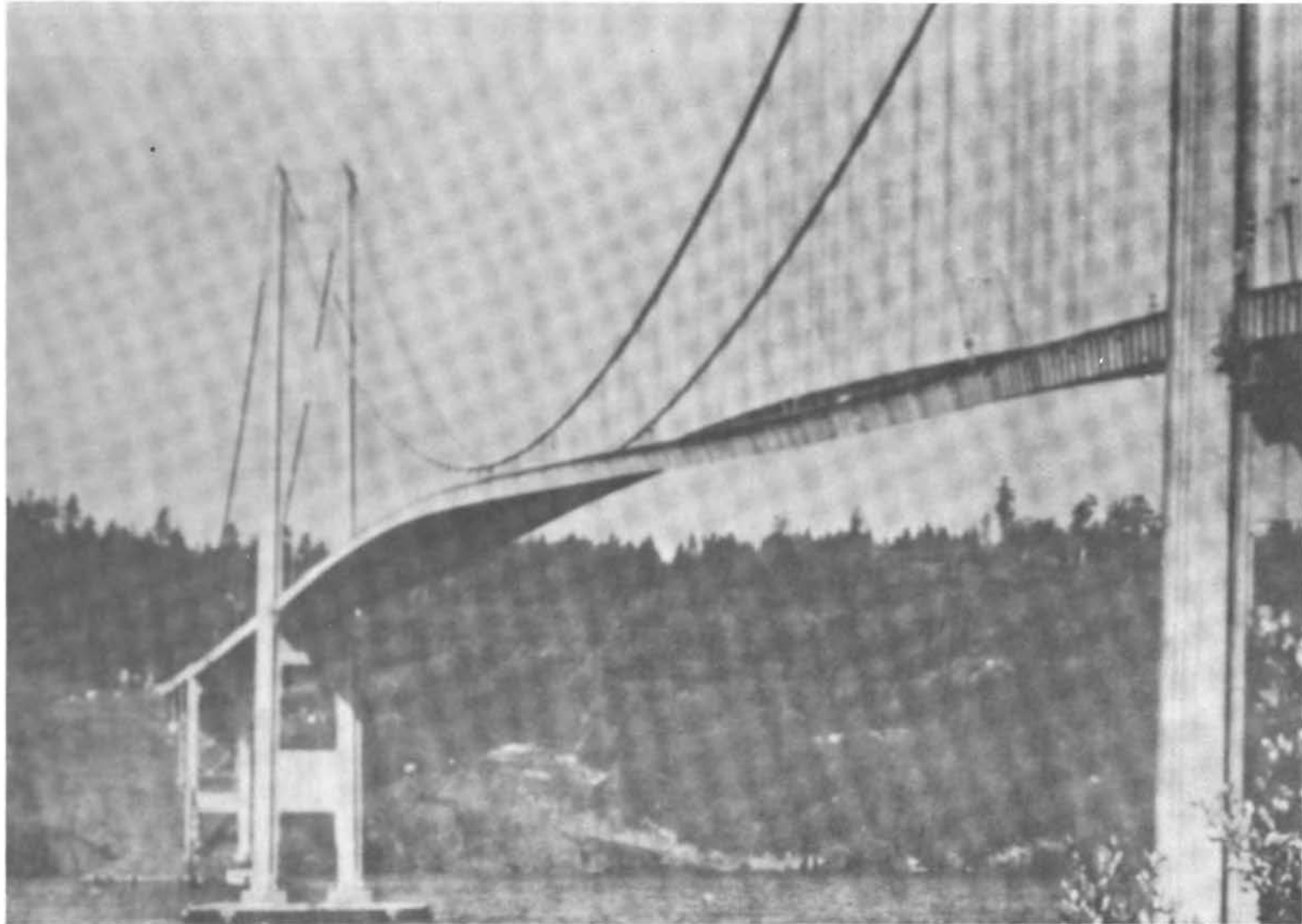
FIGURE 1   Tacoma Narrows Bridge showing torsional oscillation one hour before failure (Paine et al.   1944).
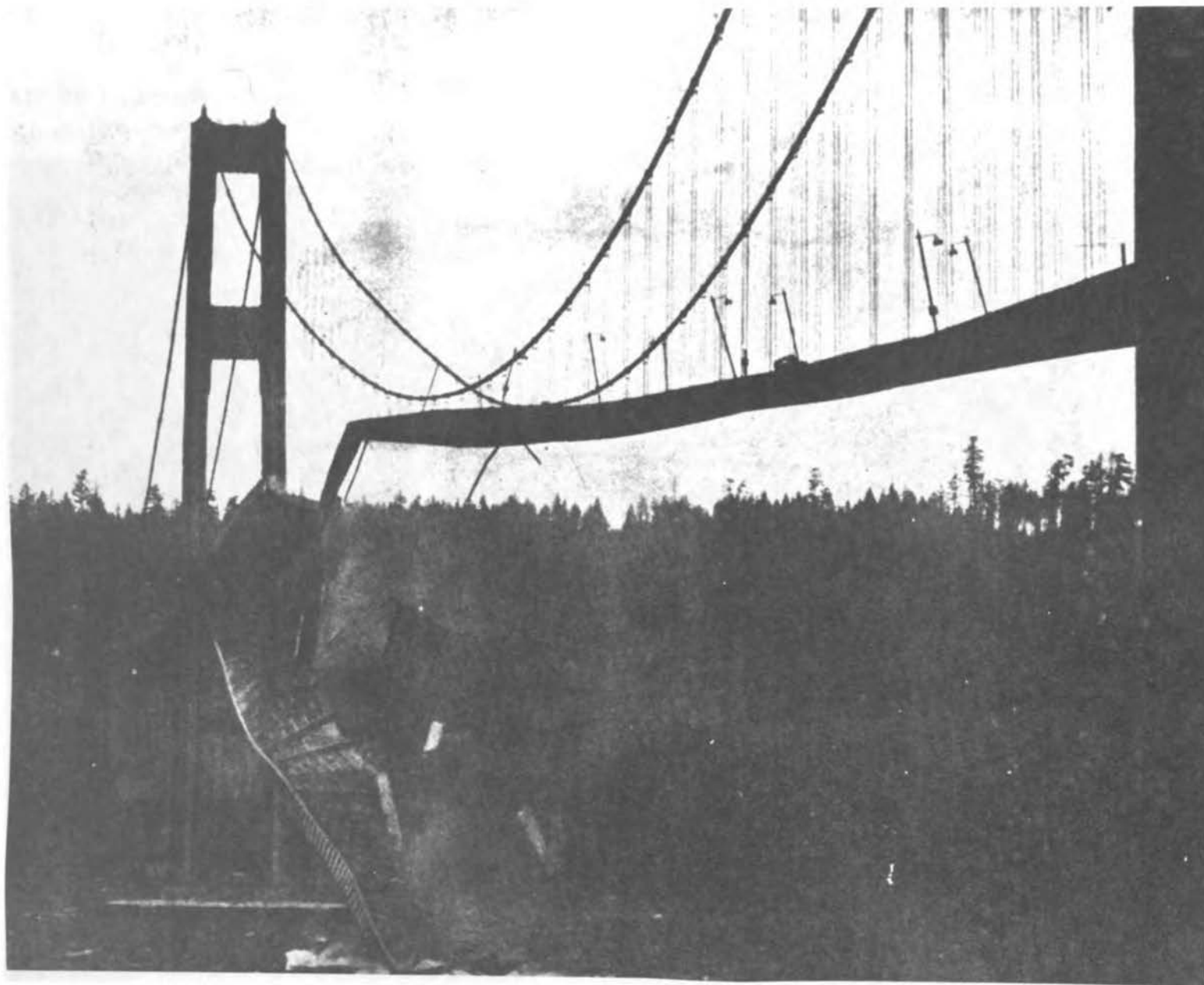
FIGURE 2 Collapse of Tacoma Narrows Bridge (Paine et al. 1944).
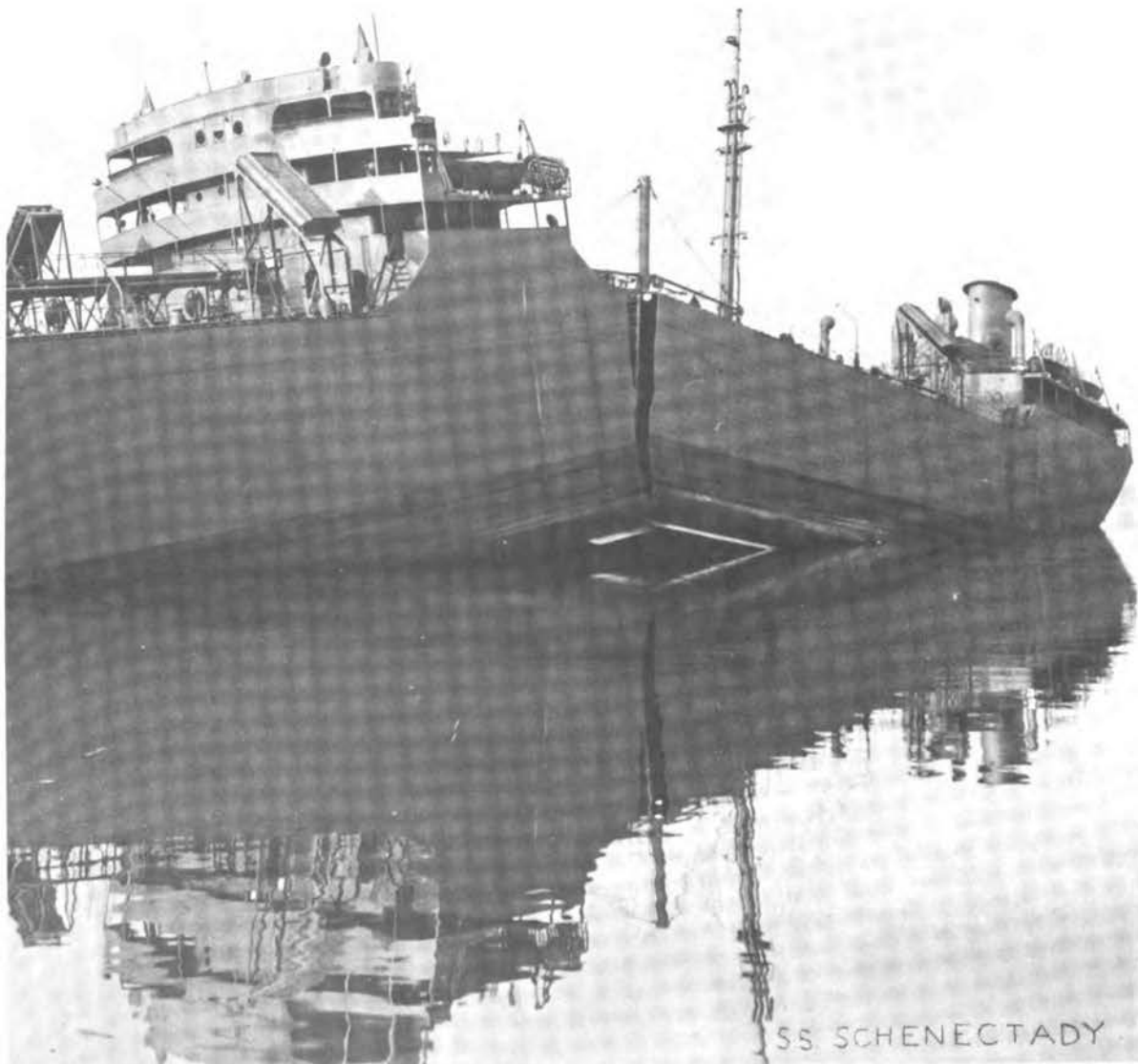
FIGURE 3 Brittle fracture in an all-welded ship (courtesy of the Marine Board, National Academy of Sciences, Washington, D.C.).

FIGURE 4 Failure of de Havilland Comet jet airplane (Oliver 1958).

FIGURE 5 Walkways at the Kansas Hyatt Regency shortly after the collapse (reprinted by permission of the Kansas City Times, © 1981).
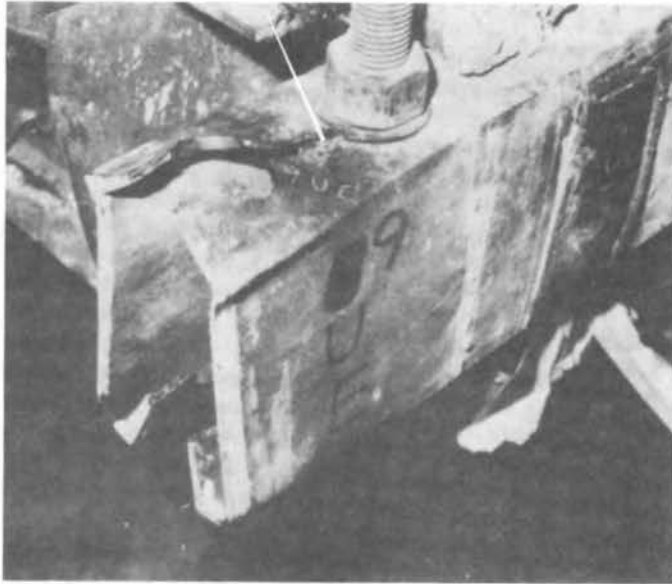
(a)
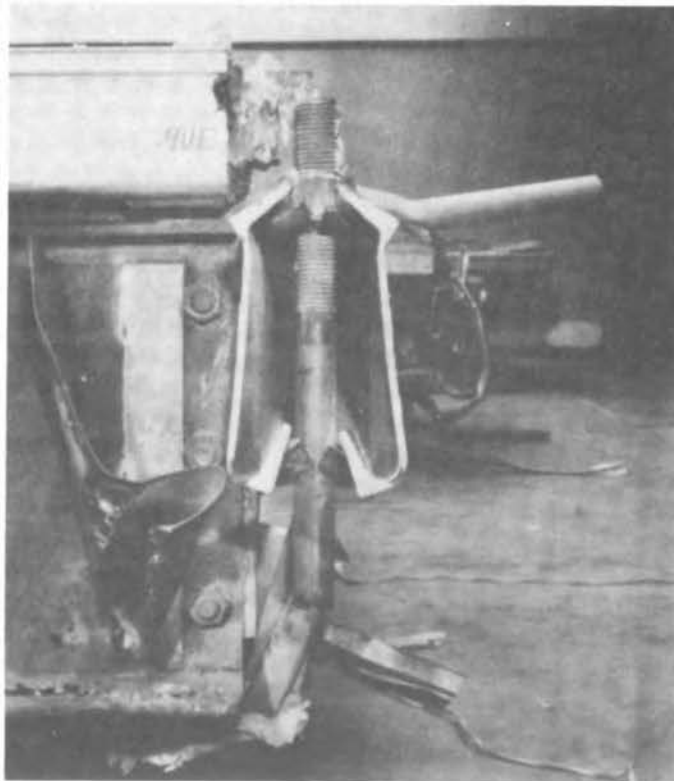
(b)

FIGURE 6   Hyatt Regency walkway support components: (a)   Hanger rod
pull-through and (b)   end view of box beam (National Bureau
of Standards 1982).

common. This form of damage can lead to dramatic consequences when a critical crack size is reached and unstable fracture ensues. This process has already been cited in the case of the Comet crashes. It was also responsible for the fairly recent DC-10 accident in Chicago (National Transportation Safety Board 1979). In this case, a large fatigue crack in an engine mount was initiated by severe (and improper) maintenance procedures associated with the removal and installation of replacement engines. Engine separation during takeoff resulted when the crack had propagated to a critical size.

Another cause of material damage arises from stress and environmental interactions with the structural material employed. A form of such damage is known as stress corrosion cracking and has led to a number of unanticipated structural failures, one of which was the collapse of the Silver Bridge at Point Pleasant, Ohio, in 1967, in which 47 people were killed (Bennett and Mindlin 1973). The bridge (Figure 7) was a suspension type where the cable was, in fact, a series of connecting eyebars. Over the course of time a crack developed in one of the eyes until it reached a critical size (about 0.12 in.) for fracture by the normal working stress. The crack initiated from some combination of fatigue, stress corrosion, and corrosion fatigue. The high hardness of the steel, its low fracture toughness, the creviced nature of the geometry, and the impossibility of protecting the eyebolt from the weather were all contributing factors to the failure.

Thus, serious structural failures result for many reasons including uncertainty in the loading, the presence of unanticipated defects, inadequate design, poor material behavior and the nature of the service. Other possibilities include lack of proper maintenance and professional incompetence. The causes of a structural failure usually are identified after the fact but the goal is to recognize the deficiencies before a problem occurs. This subject is receiving increasing attention in industry and government, and a structural integrity discipline is now emerging. Engineering concepts and processes have been developed to prevent structural failures by systematically providing for consideration of all known causes for failure in a specific structure and by guiding and controlling the functions of design, manufacturing, and in-service operation to ensure a low risk of structural failure. These concepts, however, have not been widely adopted.

The U.S. Army has experienced unexpected and not very well known structural failures. In one case, an anti-tank weapon exploded during a demonstration (Hackley 1983). It was designated the light anti-tank weapon (LAW), a disposable rocket launcher made from a low-ductility aluminum alloy. Although the cause of the accident is unknown, the choice of material was believed to be the principal factor in earlier LAW failures. Another case of structural failure involves the Army's high mobility multipurpose wheeled vehicle (HUMMER). A major complaint has been its low reliability due to engine and drive train, suspension, and weapon mount malfunctions or fractures (New York Times 1983).

Cases such as these raise questions concerning whether adequate engineering could have foreseen and precluded such failures and whether adequate design and material selection procedures could have been
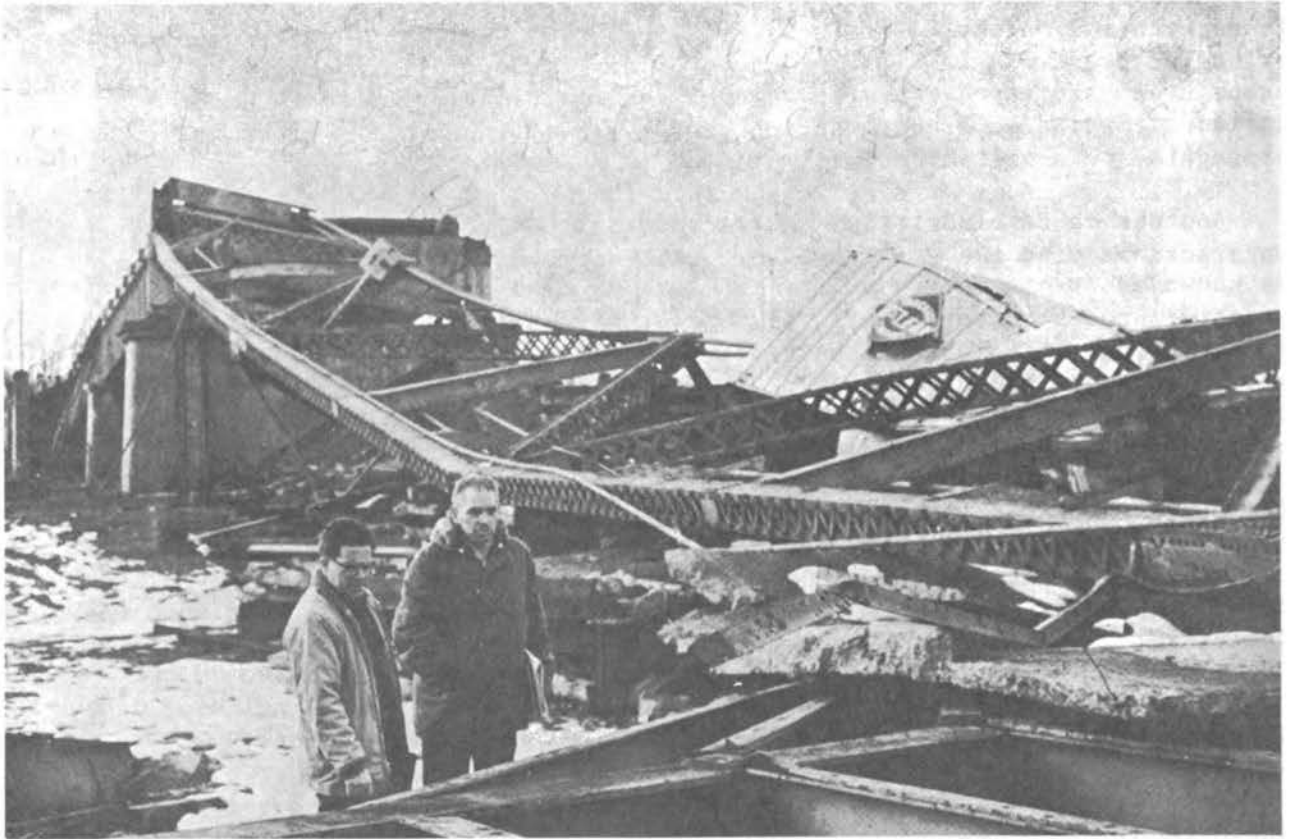
FIGURE 7 Collapse of Silver Bridge at Point Pleasant, Ohio (Lichtenstein 1970).

enforced in some cost-effective way. It is questions such as these that occupied the committee's attention, rather than the more technical issues such as crack detection methodology or specific material performance.

The cost of fracture is high. A study of the cost of failures due to fracture in the United States has recently been performed by the National Bureau of Standards and Battelle Memorial Institute (Reed et al. 1983). The costs were estimated to be very large, $119 billion per year in 1982 dollars. Costs from the occurrence of fracture and from the prevention of fracture were included. Preventive costs include packaging and handling, maintenance and repair, quality control and service inspection, training, research, and codes and standards development. The study estimated that these large costs could be reduced by more than $35 billion per year through extensive use of available technology directed toward more effective and efficient fracture control. Fracture-related research could further reduce these costs by about $28 billion per year.

Fracture costs to the Department of Defense can be roughly estimated to be $6 billion per year. Costs of about $2 billion per year are currently reducible through utilization of the best fracture control practice. The majority of the currently reducible costs are probably associated with the Army since the Air Force and Navy have identifiable structural integrity programs and associated fracture-control plans in practice.

Fracture-related accidents contributed to the Department of Defense costs. The following table, using 1979 data from safety centers of the 3 services (Duga et al. 1983), summarizes the accident contribution.

TABLE 1 Summary of Fracture-Related Accidents in the Army, Navy, and Air Force

Service	Total No. of Accidents	On-Duty Accidents	No. Due to Fracture	% Due to Fracture
Army	20,561	16,040	900	4.4
Navy	16,048	12,892	199	1.2
Air Force	15,015	7,999	97	0.7

The contribution from the Army is 3 times greater than the sum of the Navy and Air Force accidents.

Based on the above background and on the premise that recently developed structural integrity concepts could assure reliable performance if a well-defined method was followed, the committee decided to examine fracture control programs currently used and to recommend any features of such programs that could be utilized by the Army. The committee chose to describe its task as follows:

1. Review structural integrity assurance methodologies currently used by government and industry.

2. Evaluate and document the need for and cost-effectiveness of these methodologies.

3. Assess the merits of requiring use of similar plans by the Army in the acquisition of systems in which structural failures could jeopardize personnel or mission success.

This procedure, as well as alternate methods of accomplishing the result, were considered. This report addresses these tasks.

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2

STRUCTURAL INTEGRITY CONCEPTS

The engineering concepts and processes that have evolved to systematically prevent structural failures are described in this chapter. It should be noted, however, that the historical causes of failure for a given class of structures are fairly unique to that class of structures. Therefore, the details associated with how a specific industry addresses the failures most prevalent in their class of structures may be unique to that industry. In an attempt to facilitate a better understanding of the terms used to describe the concepts and processes of preventing failure, a list of definitions is included. Specific note is drawn to the definitions of a structural integrity program and of a structural integrity plan. The remaining sections of the chapter provide an overview of the engineering concepts and processes associated with failure prevention.

DEFINITIONS

Structure--A mechanical body (e.g., bridge), composed of one or more elements, whose function is to resist forces (loads). The forces may develop from contact, pressure, gravitational, inertial, magnetic and thermal sources and may result in axial, shear, bending, and torsional deformations. The forces could be static (constant), repeated (cyclic/fatigue), transient, or sudden (impact).

Failure--Any change that renders the structure incapable of satisfactorily performing its required function. For example, the presence of a crack may lead to a loss of force (load) carrying capability and/or excessive deformation.

Structural Integrity--A performance characteristic for a structural system. The structural system will perform its function each time that it is used for as long as intended without failure.

Structural Reliability--The probability that a structural system will perform its function without failure. Typically, this probability depends on the time in service, the number of times that the system is used, or both.

Structural Integrity Program—A set of requirements that must be considered to ensure structural integrity for a class of structures. The requirements normally are established to preclude historical causes of failure.

Structural Integrity Plan—A scheme for implementing the structural integrity program for a specific structure.

Durability—The ability of the structure to resist cracking, corrosion, thermal degradation, material changes, wear, delamination, and the effects of other time-dependent damage for a specified period of time (or operation).

Damage Tolerance—The ability of the structure to resist failure due to the presence of flaws, cracks, or other damage for a specified period of operation.

Usage—A description of how the structure is used in terms of the environment and loading to which the structure is subjected.

Quality—A description of defects, dimensional variations, and discrepancies within a structure that could directly cause or lead to failure.

THE REASON FOR STRUCTURAL INTEGRITY PROGRAMS

An engineering system is designed to meet specific performance requirements and a structural design engineer must balance these overall system requirements with the requirement for structural integrity. It normally is not possible to meet overall requirements without some degree of structural integrity. Unfortunately, the direct ties between overall requirements and the structural integrity requirements are not always clear.

As an engineering system develops, the overall requirements are interpreted in terms of trade-offs between budgetary and performance requirements. The trade-off studies tend to emphasize those performance goals most closely tied to an acceptable demonstration of contractual compliance (or lack of subsequent liability). Thus, to ensure structural integrity, it is necessary to have clearly defined structural performance requirements (goals) that can be demonstrated. The structural performance demonstration should be conducted prior to initiating a contractual commitment that releases the manufacturer from liability and burdens the customer with unwanted structural failure problems. From a cost standpoint, it is important that the structural performance requirements be as clearly defined as the overall system requirements.

It is the purpose of structural integrity programs to provide system program managers and design engineers with a set of structural performance requirements that, if met, should ensure a low risk of structural failure. The set of structural performance requirements may dictate preparation of specific failure cause and effect evaluations as well as definition of overall structural system performance.

ELEMENTS OF A STRUCTURAL INTEGRITY PROGRAM

All structural integrity programs must direct adequate attention to the following five elements:

1. Structural design conditions
   a. Design life
   b. Loads
   c. Environment
   d. Damage assumptions

2. Materials and processing controls
   a. Selection
   b. Properties
   c. Specifications

3. Design and analysis controls
   a. Design concepts
   b. Failure modes and effects analysis
   c. Stress analysis
   d. Fatigue analysis
   e. Fracture mechanics analysis
   f. Joining practices

4. Quality assurance controls
   a. Material/fabrication/processing controls
   b. Inspection
   c. Verification or qualification testing (strength, life, and operation)

5. In-service controls
   a. Usage monitoring
   b. Maintenance
   c. Inspection
   d. Repair

These elements include all the factors that are to be considered during design, fabrication, and operation to assure a satisfactory level of structural integrity during the service life of the structure.

The structural design conditions provide the basis for sizing the structure to protect against failure. They define the expected service life, the operating environment (loading, chemical, and thermal history), and the uncertainties associated with structural and material quality and the operating environment. Materials and processing controls are used to select the materials for fabrication, to establish their mechanical properties, and to ensure that the materials conform to the requirements of material and processing specifications applicable to the given structure. The design and analysis controls establish the configuration and sizing of the structure such that it can reliably meet its strength and life objectives.

Quality assurance controls are used to ensure that the as-fabricated structure conforms to the design requirements. These controls are established to ensure quality throughout the design, fabrication, installation, and service life of the structure and include verification (or demonstration) testing.

In-service controls ensure that the structure maintains the required level of structural integrity throughout its service life. When necessary, the structure is periodically inspected and repaired as required, and sometimes the operational history is monitored.

Historically, two different approaches have evolved for applying structural integrity programs (McHenry and Rolfe 1980). The first is based on the use of design and fabrication codes and the second is based on performance specifications. The type of structural integrity program is frequently dictated by the type of structure that is being designed and fabricated.

STRUCTURAL INTEGRITY PLAN

Given the definition of the structural integrity requirements for a selected structural system, the necessary framework can be developed to ensure that these requirements are demonstrated. The structural integrity plan provides the mechanism for meeting the requirements. It defines the analytical framework and the procedures that will be developed and implemented to protect the structure from failure throughout its service life.

To assure that the structural system maintains a defined level of structural integrity (or structural reliability) throughout its service life, it is necessary to relate materials, structural configuration (geometry), usage, and quality type information to potential modes of failure and to life estimates. Mechanics is the science that provides the analytical framework for conducting a series of analyses that balance structural integrity requirements with structural capability (Figure 8). Mechanics is used to calculate relationships between external loadings and the internal conditions that define failure. This science integrates the influences of material behavior and geometry into the relationships so that effects of material changes and geometrical sizing or configurations can be analyzed.

Basic structural analyses deal with bulk calculations; more advanced analyses deal with the influence of cracks. The basic bulk-material type analyses are concerned with precluding the simpler modes of failure due to overloads, excessive deformation, buckling, etc.

Most structural integrity analyses use deterministic values to describe the relationships between structural geometry, materials of construction, quality of workmanship, and operational usage assumptions (Figure 8). The deterministic values are established as worst-case estimates so that the likelihood of fracture is remote (but undefined).
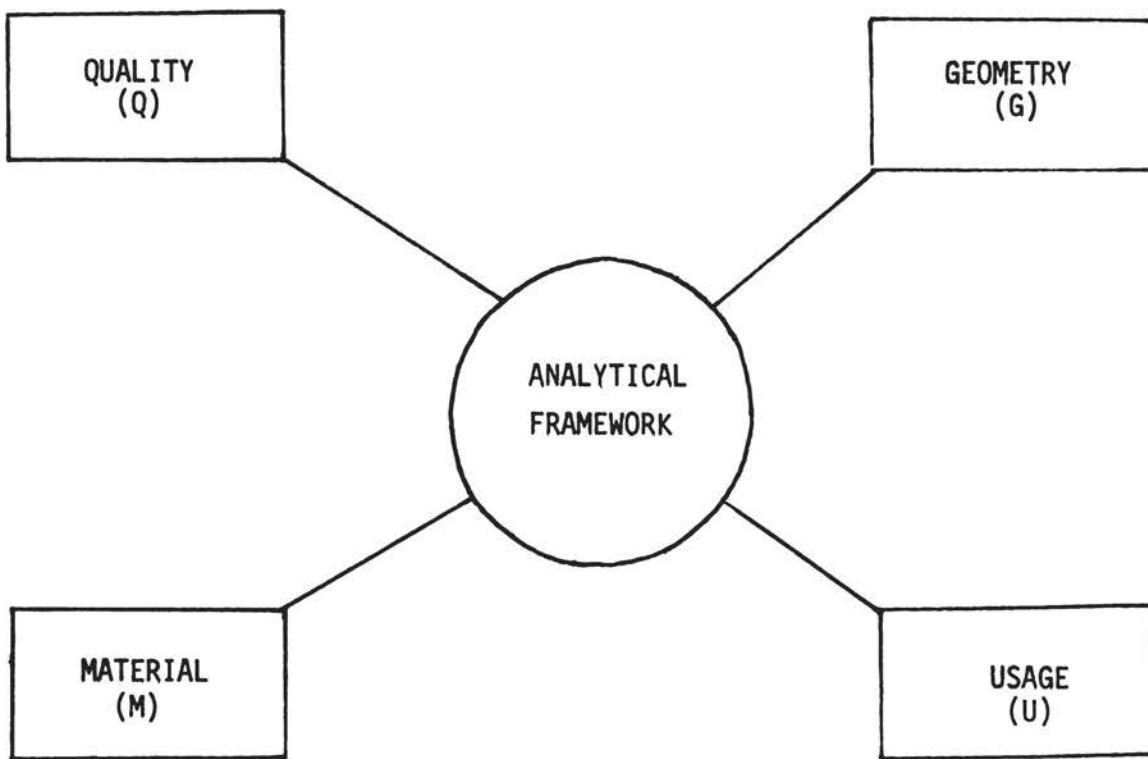
FIGURE 8   Informational elements that must be modeled in a structural
integrity analysis.

Structural reliability calculations normally are conducted utilizing
statistical descriptions of each of the four informational elements shown in
Figure 8 to estimate the probability for different types of failure as a
function of time in service. The structural reliability calculations
utilize the same analytical framework employed for the deterministic
descriptions of the input. Typically, sensitivity studies are conducted to
establish the importance of the deterministic inputs to the final estimate
of structural integrity.

The analytical framework integrating the informational elements shown in Figure 8 is supported by empirical information based on test results and operational experience. Quantification of the informational elements can be both difficult and inexact. The incorporation of new concepts (whether associated with materials, configurations, operations, or quality assurance) always leads to inaccuracies that decrease the confidence in structural reliability. For structural applications, materials behavior is quantified through the use of the mechanical properties (yield strength, elastic modulus, crack growth resistance, etc.). Configurations are evaluated based on structural efficiency factors that measure load carrying capability, load transferred, damage tolerance, stiffness, etc. Operational usage is defined by load and environmental spectra that are characterized with a set of extreme conditions or with a sequence of ordered load and environmental events. Quality assurance is quantified based on surface characterizations, nondestructive evaluations, destructive testing, and other procedures that are difficult to quantify. For additional discussion of the technologies that support structural integrity plans see Pellini (1976) and Gallagher and Crooker (1979).

Prior to applying a structural integrity plan, it is necessary to fully ascertain the potential causes of failure and to define the importance of each of the elements shown in Figure 8 to the different types of failure.

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3

EXAMPLES OF STRUCTURAL INTEGRITY PROGRAMS

This chapter describes a number of structural integrity programs that are
currently employed to ensure the safety and reliability of equipment
designed, sold, procured, regulated, or used by government and commercial
organizations. Each program has evolved to define and emphasize design,
manufacturing, and in-service elements that require controls if one
wishes to preclude failures of a type historically experienced by the
class of structures covered by the program. Some programs described are
unique to a specific organization; this is particularly the case for
commercial organizations that design, manufacture, sell, and service
equipment. Other programs have become industry standards; these
programs are typically imposed on industry by a government organization
that regulates, procures, uses, and/or maintains the equipment. All
programs examined have improved the safety and reliability of the
equipment in the field because of profit stimulation, product reputation,
or government requirements.

STRUCTURAL INTEGRITY ASSURANCE PROGRAM IN THE COMMERCIAL NUCLEAR POWER INDUSTRY*

Purpose

The primary objective of the structural integrity program in the nuclear
power industry is the assurance of plant safety. Structural failures in
equipment and structures important to plant safety could lead to a
malfunction of that equipment and, in severe cases, could pose a threat
to the health and safety of plant workers and/or the general public.
Other important considerations reflect economic factors (repair of
structural failures in nuclear power plants involve higher than normal
costs because of radiation concerns and extremely high plant outage and
replacement power costs) and visibility concerns (there is a high level

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*Based on a May 1983 presentation to the committee by Dr. Sumio Yukawa,
 Turbine Technology Laboratory, General Electric Company, Schenectady,
 New York.

of public and media interest in any problem at a nuclear power plant as evidenced by the attention given the 1979 Three Mile Island accident). Even a minor incident can receive much publicity. These latter considerations, however, are secondary to the primary focus of plant safety.

Description

In order to meet its objective, the nuclear power industry has an intensive and broad-reaching structural integrity assurance program that covers virtually all equipment and structures in a power plant. The program is implemented through industry codes and standards. Their use is mandated by the federal laws and regulations governing the licensing and operation of commercial nuclear power plants. (By and large, overseas operators have adopted the U.S. codes and standards or their equivalent.) The major documents that embody the structural integrity assurance program for nuclear power plants are:

1. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III — Rules for Construction of Nuclear Power Plant Components;

2. ASME Boiler and Pressure Vessel Code, Section XI, Rules for In-Service Inspection of Nuclear Power Plant Components; and

3. Institute of Electrical and Electronics Engineers (IEEE) 344, Recommended Practices for Seismic Qualification of Equipment for Nuclear Power Generating Stations.

The program includes:

1. Classification of equipment with respect to its importance to plant safety.

2. Definition of structural design conditions for the plant lifetime (usually 40 years). Design conditions include normal operational loads, seismic loads, and special loads resulting from certain postulated "design basis accidents" at the plant. Special seismic testing requirements are also specified in IEEE 344 for certain classes of equipment which, by their nature, are not amenable to analysis.

3. Material selection. ASME Section III specifies allowable materials for various classes of equipment as well as the design strength and toughness properties for each. Acceptable welding procedures and process controls also are specified by code.

4. Design analysis rules. ASME Section III imposes various factors of safety for specific combinations of equipment classifications and loading conditions. The design rules also provide for materials fatigue and brittle fracture consideration.

5. Quality assurance rules that are imposed, to ensure that the above requirements will be universally implemented. Extensive pedigrees and paperwork certifying that materials and process requirements have been met accompany each heat of material and each fabricated component. Various levels of nondestructive examination are imposed during construction with associated acceptance standards for flaws or defects.

6. In-service controls. ASME Section XI specifies these controls which include an extensive in-service nondestructive examination program, periodic pressure testing of reactor pressure boundary components, and periodic functional testing of essential pumps and valves. As in design and construction, the level and extent of in-service controls also are geared to the classification of the equipment with respect to its importance to plant safety. Acceptance standards for in-service inspections are based on fracture mechanics flaw tolerance considerations with the criteria being that there be no loss in the structural safety margin for the original design basis for the component.

Benefits

The overriding result of the nuclear power industry's structural integrity assurance program is that the basic safety objective has been met. There has never been a plant structural failure that has had significant public health or safety consequences. Any structural failure or material cracking problems have been detected early, through in-service monitoring, and corrective actions have been implemented long before the problems had any impact on structural safety margins.

FRACTURE CONTROL IN THE POWER GENERATION INDUSTRY
(LARGE ROTATING EQUIPMENT)*

Purpose

Power generation equipment in the United States is manufactured by private industry whose major goal is profit; therefore, the ultimate purpose of a structural integrity program is an economic one. Specific goals are to reduce structural component failures that may cause serious equipment damage and safety hazards, to decrease maintenance requirements, and to increase the efficiency. These considerations can all be influenced by a structural integrity program that attempts to reduce structural failures and all of these issues are related to economics.

Description

The power generation industry has long been aware of the problems associated with the assurance of structural integrity in large rotating

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*Based on a May 1983 presentation to the committee by Dr. John Landes, Westinghouse Research and Development Center, Pittsburgh, Pennsylvania.

equipment. A catastrophic brittle fracture can suddenly release millions of foot-pounds of stored energy and cause damage equivalent to the detonation of high explosives. Work was begun in the late 1940s to try to understand the factors controlling flaw growth and fracture of metals (Robinson 1944). A series of catastrophic failures of large, medium strength, turbine and generator rotor forgings in the mid-1950s greatly accelerated this work (Thum 1956). Much of the work in the 1950s employed spin burst tests (Sankey 1960, Winne and Wundt 1958) of large model rotors with sharp machined notches in the bore to evaluate susceptibility to brittle fracture. With the development of linear elastic fracture mechanics (LEFM) approaches in the late 1950s and early 1960s, fatigue precracked specimens were substituted for notched specimens (Wessel 1960, Yukawa and McMullen 1961). The concept of LEFM K_{IC} fracture toughness was developed and a more convenient laboratory specimen was substituted for the spin burst test. The power generation industry has continued to use fracture mechanics concepts for structural integrity procedures, and these concepts have evolved to consider cyclic loading, adverse environments, and plasticity effects in addition to brittle fracture.

The structural integrity plans implemented by the various manufacturers of large rotating equipment are not uniform within the industry because there is no industry regulatory agency. These plans are often proprietary and the major components of a single power plant can be manufactured by different divisions of a large corporation using different methods for structural integrity assurance.

Usually the main burden of developing and implementing a structural integrity plan lies with the designers of the equipment. They must be aware of all elements in a structural integrity plan and make sure that these elements are included in the design. Very often the designers will rely on support groups to cover the specific elements for ensuring structural integrity. For example, a materials group may recommend an optimum material for an application, a nondestructive inspection group may determine the level of quality of materials and manufactured parts, and an analysis group may provide information on loads and stresses of a component during usage. Nevertheless, it is the equipment designer who must ensure that all needed elements are included. Fortunately, most new designs are based on previous ones and the designers of new systems need not completely develop new structural integrity plans since information relating to the reliability of earlier designs is used to develop procedures that become part of a standard design practice.

Traditionally, the designer has been largely responsible for ensuring that a structural integrity plan was incorporated in the design. With the increasing importance of structural integrity, however, new methods are being developed to assist the designer in ensuring that the structural integrity plan is followed. One of these methods is design review in which experts on all elements of a structural integrity analysis review a design to make sure that nothing is missing in the plan. This is especially important with new designs to ensure that the latest technological advances are included in the design and integrity plan.

Equipment integrity also is reviewed once the equipment is placed in service. Unfortunately, deficiencies in the structural integrity plan are sometimes discovered at this stage and may require immediate design modifications. These modifications can involve costly field repairs and major revamping of manufacturing procedures.

Benefits

The application of a structural integrity plan to ensure the reliability of large rotating equipment produces economic benefits for both the equipment manufacturer and the user of the equipment.

The manufacturer of the equipment is a private corporation and has profit as an ultimate goal. Failure of a piece of equipment can cause direct loss of profit as a result of obligations, lawsuits for property damage, and compensation required for loss of life or serious injury. Structural failure also can result in an indirect loss of profit in that poor performance of equipment, safety problems, inefficient operation and high maintenance costs can create a poor image for a corporation and severely affect sales.

The customer who purchases and uses the equipment also has economic concerns. Poor performance and structural failure can adversely affect the efficiency of the customer's operation. Unplanned equipment outages result not only in unplanned maintenance costs but also in shutdown of a power generating unit and, thus, revenue that would have been generated by that unit is lost for the shutdown period (easily in excess of $1 million a week for a power unit in excess of 100 MW).

FATIGUE ANALYSIS PROGRAM FOR GROUND VEHICLE COMPONENTS*

Purpose

The Ford Motor Company has developed a computerized fatigue analysis supervisory program (FATSUP). It is specifically tailored to the needs of a large industrial engineering organization and provides the Ford engineering staff with the most recent advances in structural fatigue methodologies.

Description

The ground vehicle industry uses fatigue analysis in the following areas:

1. Initial sizing of prototype components,
2. Design of production components, and
3. Revision of production components.

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*Based on a May 1983 presentation to the committee by Dr. R. W. Landgraf, Ford Motor Company, Detroit, Michigan.

In initial sizing, the selection of a design load level by an engineer determines estimated material, size, and durability requirements of the components. This initial design information is based upon past history, handbooks, and supplier material and durability statistics.

Prototypes are built and tested both in the laboratory and on the proving grounds to estimate design loads for production components. Variations in these tests result in the conduct of fatigue life computations.

The design of production components is continuously revised in order to decrease weight (increase mileage rating) or make material changes as a result of differences in proving ground assumptions and actual customer experience. Computations for fatigue damage are made to determine the effects on the modified component.

The Ford design and analysis groups have available, through FATSUP, a versatile computer program that can describe and manipulate the variety of load, stress analysis, and material property data required to perform the various fatigue analyses described above. In reviewing the basic elements of a structural integrity program, FATSUP incorporates into its data files the information from all five major program elements identified in Chapter 2 that are pertinent to designing components for ground vehicles. The program is not really directed at the quality control aspects or the maintenance, inspection, and repair aspects.

Benefits

In this example of a representative ground vehicle structural integrity program, the focus is on a single failure mode, fatigue, known to be of special importance to the automotive industry. The result is a package of interactive computer program modules that enable the designer to formulate and solve a wide variety of ground vehicle problems using state-of-the-art approaches to fatigue analysis. The approach reflects a philosophy on the part of the ground vehicle industry to design out potential fatigue problems before the prototype goes into production so as to achieve recognition as producers of reliable, low maintenance products.

ASSURING STRUCTURAL INTEGRITY OF OIL PIPELINES*

A structural integrity plan has been successfully applied to establish allowable-flaw-size limitations in pipeline girth welds. It was developed in 1976 when the National Bureau of Standards (NBS) assisted the U.S. Department of Transportation (DOT) (Reed et al. 1979) in the

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*Based on a May 1983 presentation to the committee by Dr. Harry McHenry, National Bureau of Standards, Boulder, Colorado.

evaluation of a petition for a waiver of American Petroleum Institute
(API) weld quality standards for certain girth welds in the Trans-Alaska
Pipeline System (TAPS).

Purpose

Federal safety regulations for pipelines stipulate that the acceptability
of girth welds must be determined in accordance with API weld quality
requirements. Allowable flaw sizes for each of the characteristic defect
types are set forth in API 1104 on the basis of workmanship consider-
ations (i.e., flaw size limits are based on quality levels that can
reasonably be expected from a qualified welder using satisfactory
materials, equipment, and procedures). In addition, federal regulations
stipulate that all arc burns must be repaired. The quality requirements
are the same for all pipelines regardless of pipe size, strength and
toughness of pipe and girth welds, or pipeline operating conditions.

The waiver request proposed alternative weld quality standards based
on a fitness-for-service assessment done in accordance with draft British
Standards Institution rules (British Standards Institution 1976). This
investigation was subsequently followed by a DOT decision that permitted
limited use of the alternative standards and set an important legal
precedent: "Fracture mechanics analysis is acceptable as a basis for
granting exemptions from existing standards in appropriate circum-
stances...." A subsequent audit of a statistical sample of TAPS girth
weld radiographs (1500 welds) indicated that 7.9 percent of the girth
welds sampled did not meet DOT weld quality standards. The alternative
standards and the legal precedent provided the basis for deciding that
the weld quality was acceptable, thereby avoiding a potential delay in
pipeline start-up. Additionally, the large costs associated with field
repair of girth welds were avoided.

Alternative allowable flaw sizes for girth welds in a specific
pipeline were calculated on the basis of fracture mechanics analyses in
accordance with requirements set forth by the Office of Pipeline Safety
Operations (OPSO) of DOT.

Description

Critical flaw sizes were calculated using four distinct fracture
mechanics analysis methods and the appropriate maximum credible stress
and material property information. The fracture mechanics models were:
(1) the critical crack opening displacement (COD) method (Knott 1973),
(2) the draft British rules, (3) the plastic instability method, and
(4) a semi-empirical method developed on the basis of pipe rupture
tests. The material property data needed included fracture toughness,
tensile properties, fatigue crack growth rate, and the stress corrosion
threshold. Minimum material properties over the temperature range
represented by pipeline operating conditions were used.

Alternate allowable flaw size curves were calculated using the
applicable fracture mechanics models, material property data, and

pipeline operating stresses for each of four types of flaw: blunt (nonplanar) weld flaws such as porosity and slag, sharp flaws such as incomplete penetration and lack of fusion, arc burns in the weld or heat affected zone, and arc burns in the base metal. The calculated flaw sizes were reduced in magnitude by the safety factors specified in the OPSO requirements. The results were plotted as alternative allowable flaw size curves with flaw depth versus flaw length (Figure 9).

Worst-case operating conditions were used to assign stress values. Girth weld flaws are typically oriented circumferentially and, consequently, axial stresses (including pressure and thermal cycles and earthquake loadings during 30-year pipeline lifetime) were used in the fracture mechanics analysis. Arc burns were typically spots or axially aligned drags and flaw growth would be caused by the hoop stresses (including hydrotests, pressure surges, and on-off pressure cycles).

Since all flaws were considered as surface cracks, the principal differences in the four types were orientation, location, and applicable safety factors. Flaw orientation determined whether the applicable stresses were axial or hoop. Flaw location was used to establish the applicable minimum fracture toughness value. The applicable safety factors include a factor of two on length and depth for all flaws plus an additional factor of two on estimated depth of planar flaws.

Benefits

There are strong economic incentives to apply a structural integrity plan to field welds of large diameter pipelines. The majority of girth weld flaws, whose size exceeds the API 1104 welding workmanship standards, are blunt flaws. Application of a structural integrity plan (using fracture mechanics assessment) permits larger blunt flaws to remain, thus reducing the frequency of very expensive repair welding in the field. Additionally, the API have proposed a generic pipeline structural integrity plan for addition to DOT federal regulations. In support of this, the National Bureau of Standards has been developing fracture mechanics and nondestructive inspection for a generic pipeline structural integrity plan and for possible Alaska gas pipelines.

STRUCTURAL INTEGRITY PROGRAM FOR AIRFRAMES*

Purpose

Another example of a structural integrity program is the U.S. Air Force's Aircraft Structural Integrity Program (ASIP) described in Military Standard 1530A. This document defines the overall requirements necessary to achieve structural integrity of USAF airplanes and specifies acceptance methods of contractor compliance. The standard is used by

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*Based on a July 1983 presentation to the committee by Dr. Frank Adams, Air Force Wright Aeronautical Laboratory, Wright-Patterson Air Force Base, Ohio.
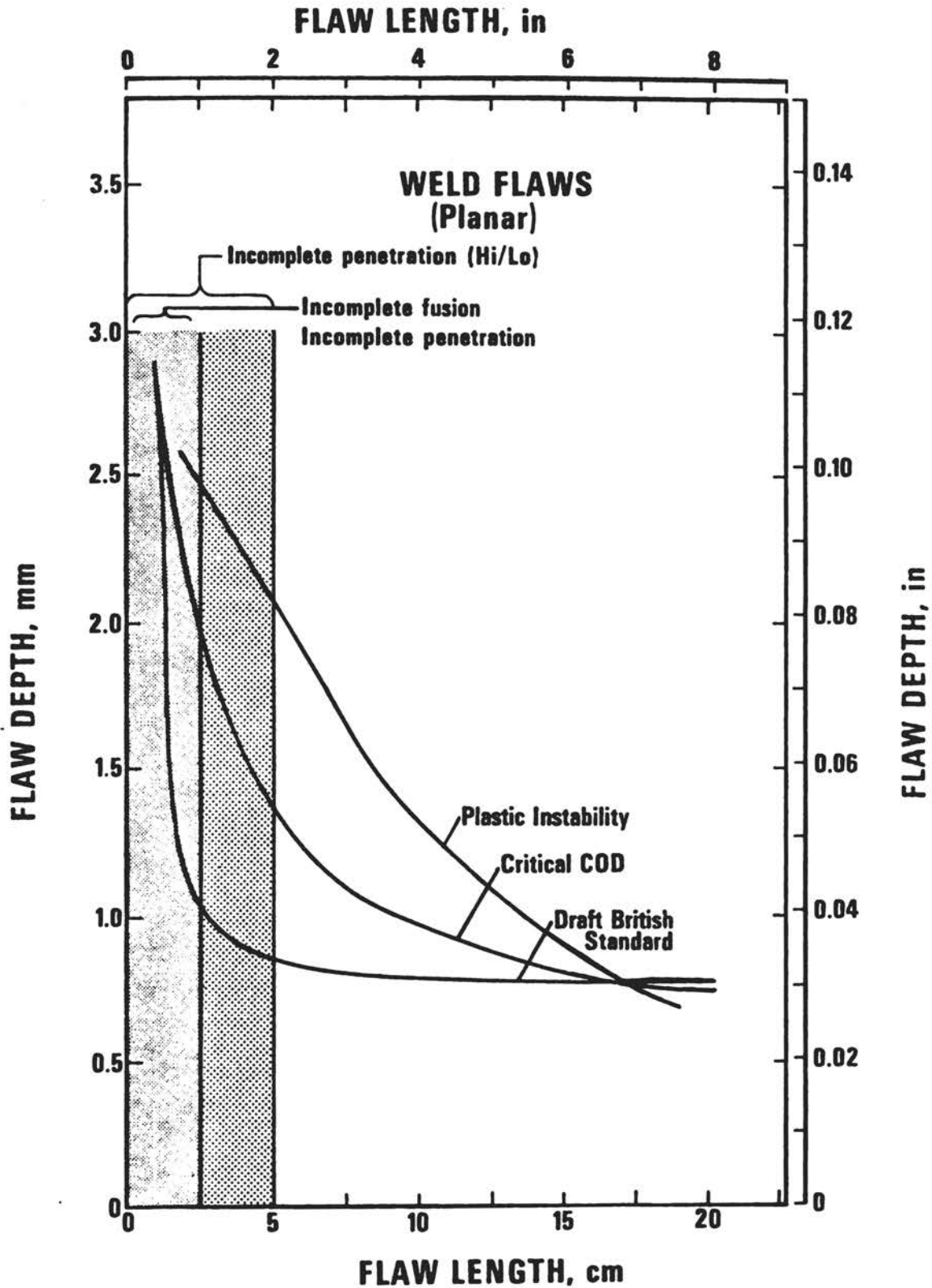
FIGURE 9 Alternative allowable flaw size curve for sharp (planar) flaws in Trans-Alaska Pipeline System girth welds (McHenry 1979).

contractors in developing an airframe for a particular weapon or support system and by government personnel in managing the development, production, and operational support of a particular airplane system throughout its life cycle. It is directly applicable to manned power driven aircraft having fixed or adjustable fixed wings and to those portions of manned helicopters that have similar structural characteristics. Helicopter transmission systems and rotors and other dynamic machinery including engines are not covered by this standard.

Description

Military Standard 1530A was developed in the early 1970s after the catastrophic crash of an F-111 aircraft that had only 100 hours of flight service. The cause of the accident was an undetected flaw in the wing pivot fitting that resulted in the loss of the wing during flight.

Prior to 1970 the Air Force used a "safe-life" approach to structural design to ensure safety and durability. In general, the fatigue life of the structure was determined through testing of materials, components, and full-scale airframes and a safety factor of four applied to reduce the probability of failure to an acceptable value. This approach did not explicitly take into account the possibility of infrequently occurring flaws due to material defects and manufacturing processes. The F-111 crash stimulated the Air Force to adopt a new design philosophy. The basic assumptions underlying this new approach are that flaws are present in new structures and that structures can be designed such that cracks can grow from these flaws for a specified period of unrepaired service without structural failure occurring. This approach is generally referred to as "damage-tolerant" design.

A very important feature of the Air Force's new approach, which can be applied to structural design in an economic way, is that damage tolerance (avoidance of catastrophic failure in flight) and durability are decoupled. This was not the case with the safe-life approach.

The current Air Force structural integrity program is firmly embedded in Air Force regulations. USAF Regulation 80-13 instructs the system program offices (SPOs), which have responsibility for developing new aircraft weapon systems, to comply with Military-Standard 1530A, USAF Aircraft Structural Integrity Program. This program has five tasks that cover an airframe from preliminary design to retirement. Detailed requirements related to damage tolerance, durability structural testing, sonic fatigue, etc., are provided in a set of military specifications. The applicable regulations are outlined in Figure 10 and the five tasks in the ASIP, in Figure 11.

Task I of the USAF ASIP deals with design information. The objective is to develop criteria that must be applied during design so that the specific requirements are met. The first step is the development by the contractor of an ASIP Master Plan for any new aircraft system. This plan includes:

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┌─────────────────────────────┐
│ USAF REG. 80-13             │
├─────────────────────────────┤
│ INSTRUCTS SPO'S             │
│ TO COMPLY WITH              │
│ MIL-STD-1530A               │
└─────────────────────────────┘
            │
┌─────────────────────────────┐
│ MIL-STD-1530A               │
├─────────────────────────────┤
│ DESCRIBES USAF              │
│ STRUCTURAL INTE-            │
│ GRITY PROGRAM (ASIP)        │
└─────────────────────────────┘
            │
┌─────────────────────────────┐
│ MIL SPECS.                  │
├─────────────────────────────┤
│ MIL-A-83444 DAM. TOL        │
│ MIL-A-8866A DURA.           │
│ MIL-A-8867A TEST            │
│ MIL-A-8893 SON. FAT.        │
└─────────────────────────────┘
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TASK I   DESIGN INFORMATION

TASK II   DESIGN ANALYSES AND DEVELOPMENT TESTS

TASK III   FULL SCALE TESTING

TASK IV   FORCE MANAGEMENT DATA PACKAGE

TASK V   FORCE MANAGEMENT
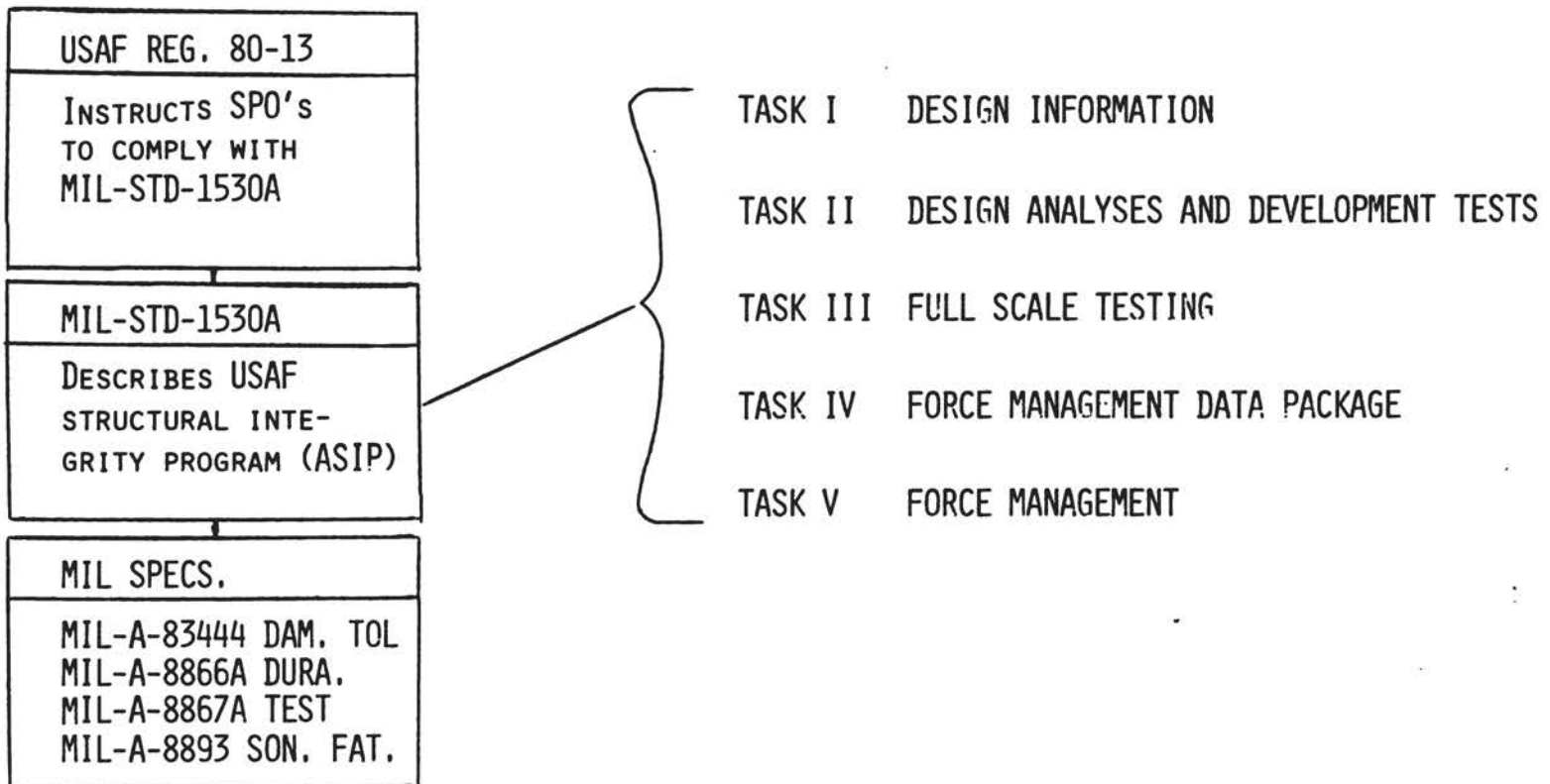
FIGURE 10   USAF Aircraft structural integrity program.

TASK I	TASK II	TASK III	TASK IV	TASK V
DESIGN INFORMATION	DESIGN ANALYSES AND DEVELOPMENT TESTS	FULL SCALE TESTING	FORCE MANAGEMENT DATA PACKAGE	FORCE MANAGEMENT
ASIP Master Plan Structural Design Criteria Damage Tolerance & Durability Control Plans Selection of Mat'ls. Processes, & Joining Methods Design Service Life and Design Usage	Materials and Joint Allowables Load Analysis Design Service Loads Spectra Design Chemical/ Thermal Environment Spectra Stress Analysis Damage Tolerance Analysis Durability Analysis Sonic Analysis Vibration Analysis Flutter Analysis Nuclear Weapons Effects Analysis Non Nuclear Weapons Effects Analysis Design Development Tests	Static Tests Durability Tests Damage Tolerance Tests Flight & Ground Operations Tests Sonic Tests Flight Vibration Tests Flutter Tests Interpretation & Evaluation of Test Results	Final Analyses Strength Summary Force Structural Maintenance Plan Loads Environment Spectra Survey Individual Airplane Tracking Program	Loads/Environment Spectra Survey . Individual Airplane Tracking Data . Individual Airplane Maintenance Times Structural Maintenance Records

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FIGURE 11   USAF aircraft structural integrity program tasks.

1. Time-phased scheduling,
2. Task integration,
3. Unique features,
4. Anticipated problems, and
5. Impact of delays--recovery plans.

It is updated annually or when important changes occur and must be approved by the Air Force. The contractor also must establish structural design criteria. These must be in concert with the applicable military specifications.

Task I also deals with the development of damage-tolerance and durability control plans. In these plans, fracture-critical and durability-critical parts are identified. Drawings showing critical locations are developed. Also documented are the basic fracture data to be used, quality control procedures, inspection techniques, test procedures, material processing specifications, and joining methods. All of the subtasks in Task I are performed taking into account the design service life and design usage specified by the Air Force.

Task II deals with design analysis and developmental tests. Material and joint allowables are developed. Load analyses are performed to obtain the design load spectra (load histories). Thermal and chemical environments are considered. This task also includes the stress analysis work. In addition, fracture mechanics life analyses are required for each structure on the fracture critical parts list. Life analyses are performed on durability critical parts. Other analyses include sonic fatigue, vibration, flutter, nuclear weapon, and non-nuclear weapon effects. Developmental testing to verify all of these analyses is performed under Task II.

Task III involves full-scale testing of the structure. This includes static strength tests of the full airframe and/or selected components. Cyclic durability (fatigue) tests also are performed. Damage tolerance testing is accomplished on structures in which flaws have been introduced at critical locations. Sonic fatigue, vibration and flutter testing are performed when appropriate. The basic objective of all full-scale testing is to verify analyses performed during Task II. This is markedly different from what occurred under the pre-1970 safe-life approach which used full-scale testing to determine the structural life.

Tasks IV and V involve "force management" which is the term the USAF employs to refer to the assurance of structural integrity after the aircraft is operational. Task IV is performed by the contractor while Task V is accomplished by the Air Force.

In Task IV the contractor is required to develop a "force structural maintenance plan." This is the "owners manual" and provides plans for the specific actions needed during the service life. Cost factors also are developed during this task. Another part of Task IV is the development of the plans and data package required to perform a "load/environment spectra survey." This involves instrumenting a portion of the fleet to measure actual load histories. These data are later used

to update life analyses performed using the design load histories. Task IV also includes the development of an individual airplane tracking program. Most of the current operations aircraft in the USAF fleet are tracked to determine individual differences in usage that may affect structural life. Simple instrumentation such as counting accelerometers or pilot/engineer log data are used for this purpose.

Task V covers the force management activities accomplished by the Air Force. This involves implementation of the force structural maintenance plan. Information from the loads/environment spectra survey is used to update this plan. Data from the individual airplane tracking program are employed to modify maintenance and inspection schedules to account for individual usage. This task also involves the development and control of all maintenance records.

Benefits

The basic objectives of the USAF ASIP are being met. Structural failures due to fracture are involved in less than 1 percent of the total accidents reported by the Air Force (see Table 1). The ASIP pays particular attention to obtaining a specified level of damage tolerance in flight-critical structures in order to ensure safety. This is of significant importance in modern high performance aircraft where high strength materials are often required. The cradle-to-grave application of the ASIP provides opportunities to lower life-cycle costs by preventing structural integrity problems rather than by "fixing" through redesign or repair.

STRUCTURAL INTEGRITY PROGRAM FOR AIRCRAFT GAS TURBINE ENGINES*

Purpose

The purpose of the current Air Force structural integrity program for aircraft turbine engine structures is to improve the reliability (for increased readiness) of new designs at lower cost and to minimize the potential for catastrophic failures (Cowie 1975 and 1983, Tiffany and Cowie 1978). This program has evolved over the past 15 years to the point where structural performance specifications were incorporated into the 1973 revision of Military Specification E-5007 (a tri-services specification covering aircraft engines) and a formal Engine Structural Integrity Program (ENSIP) was written and completed in 1978. In early 1983, a mil-prime standard was sent to the specifications office for publishing (Mil-Prime Standard on Turbine Engine Structural Integrity Program) and contains all requirements published in 1978.

Traditional approaches to turbine engine design emphasized system performance criteria (e.g., high thrust to weight ratios) at the expense of structural performance criteria (e.g., high resistance to damage from thermal-mechanical loadings). Early procurement development programs

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*Based in part on a May 1983 presentation to the committee by Mr. Anton Coles, Aircraft Engine Business Group, General Electric Co., Cincinnati, Ohio.

relied heavily on "build 'em and bust 'em" concepts that emphasized the repair of structural problems identified during system performance evaluations. Two major reasons for the lack of any in-depth structural attention were the limited understanding of the usage experienced by the structural members while the engine was operating and the absence of realistic structural qualification testing.

Description

Like the Air Force's ASIP, the ENSIP is time-phased to control structural integrity actions from preliminary design through to system retirement. The five ENSIP tasks are outlined in Figure 12.

Within Task I, the structural design conditions are established and the structural integrity plan is prepared. Cowie (private communication between W. D. Cowie, Wright-Patterson Air Force Base, Ohio and J. P. Gallagher, University of Dayton Research Institute, Ohio, September 27, 1983) considers this task to be the most important since within this task, usage is defined, design criteria are developed, and life requirements are specified. Under Task II, general design conditions for the structure are used to develop the specific duty cycle (usage conditions) for individual structural components. Detailed design and analysis also are conducted on individual components and the materials of construction are chosen, quantified, and controlled.

During Tasks III and IV, quality assurance testing is conducted on the engine structure and its major components. One distinguishing feature of the ENSIP is that it verifies design and analysis assumptions and demonstrates that the structure has met its structural performance objectives. A thorough evaluation of any design deficiencies also is conducted. One important aspect associated with the demonstration tests should be noted: production decisions are directly tied to the schedule and success of the full-scale demonstration tests. For example, one lifetime of testing is required on a designated full-scale engine demonstration prior to production release. The tests conducted under Tasks III and IV provide information for iterating the design and updating the structural integrity plan to include the anticipated impact of real or potential problems on in-service operation.

Task V covers the implementation of the structural integrity plan during the production and operational life of the engine. Task V subtasks include the final output of ENSIP which are production quality assurance controls on material, fabrication, processing and inspections and in-service controls on usage monitoring and on in-service inspections, repairs, and structural maintenance.

Benefits

As the ENSIP has been evolving, benefits to the development and procurement of more reliable engines have been noted. Specifically, mean time between failures has been noted to increase in the operational environment and major failures have been decreasing. It should be noted that the early version of the ENSIP incorporated into the 1973 version of

TASK I	TASK II	TASK III	TASK IV	TASK V
DESIGN INFORMATION	DESIGN ANAL. COMPNT. & MAT. CHARAC.	COMPONENT & CORE ENG. TESTING	GROUND & FLIGHT ENG. TESTS	PROD. QUAL. CONTROL & ENG. LIFE MGT.
• ENSIP Master Plan	• Design Duty Cycle	• Strength Testing	• Envir. Verif. Testing	• Prod. Eng. Analysis
• Design Serv. Life & Usage Requirements	• Mat'ls. and Processes Design Data Characterized	• Damage Tolerance Tests	• (Amt) Test Spec. Deriv.	• Struc. Safety & Durab. Sum.
• Design Criteria	• Structural Thermal Analysis	• Durability Tests	• Durability Tests (Amt)	• Eng. Struc. Maint. Plan
	• Mfg. and Quality Control	• Thermal Survey	• Damage Tol. Tests	• Indiv. Eng. Tracking
		• Vibratory S-rain & Flutter Boundary Survey	• Flight Test Strain Survey	• Lead the Force Prog. (Usage)
			• Updated Dura. & Damage Tol. Control Plan	• Dura. & Dam. Tol. Control Plan Impl.
			• Perfrm. Deterior. Struc. Impact Assessment	• Technical Order Update
			• Critcl. Part Update	

FIGURE 12 Engine structural integrity program (Cowie 1983).

Military Specification E-5007 was applied both by the Army (Helicopter Command, St. Louis) and by the Navy (Naval Air Systems Command) during the development programs for the T700 and F404 engines, respectively. These engines are considered by Cowie (private communication between W. D. Cowie, Wright-Patterson Air Force Base, Ohio and J. P. Gallagher, University of Dayton Research Institute, Ohio, September 27, 1983) to be excellent low maintenance examples of the successful application of the engine structural integrity program.

U.S. NAVY STRUCTURAL INTEGRITY PROGRAM FOR AIRCRAFT*

Purpose

The U.S. Navy structural integrity program is intended to identify for both the Navy and its contractors the requirements to be fulfilled to achieve structural integrity. Some specific goals of this structural integrity program are:

1. To establish, evaluate, and substantiate the structural integrity of the aircraft.

2. To provide assessment of in-service integrity.

3. To provide a basis for logistics and force planning relative to maintenance, rotation, and phase-out.

4. To develop methods for improving design of future airplanes.

Ultimately, the structural integrity program must minimize the incidence of catastrophic failure, improve the reliability and readiness of the fleet aircraft, minimize weight penalties, and hold the line on costs.

Description

The U.S. Navy's aircraft structural integrity program is fundamentally based on fatigue (safe life) philosophy supplemented by durability and damage-tolerance requirements. Navy policy requires design for a long life using a severe load spectrum. The severe load spectrum provides for the "worst-case aircraft" and is tailored to include loads that are critical for all major sections of the aircraft. The combination of fatigue, durability and damage-tolerance (crack growth), severe loads, and long life requirements provides a grueling test for design and structural integrity substantiation.

To ensure that the design and manufacturing processes produce a durable and damage-tolerant structure, basic fatigue and fracture control requirements are included in the aircraft detail design specification. These requirements will include criteria for identification of critical

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*Based on a July 1983 presentation to the committee by Dr. Shih L. Huang and Mr. Allan H. Johnson, Naval Air Development Command, Warminster, Pennsylvania.

components, crack growth requirements for these components, and the development of a fatigue and fracture control plan that, when implemented, will ensure the development of a safe and reliable aircraft structure., For the most recent fighter aircraft (F-18), the detailed analysis, test, manufacturing, and materials processing requirements and controls were delineated in a fatigue and fracture control plan. This plan was prepared by the contractor with review and approval by Navy officials.

For the F-18, long life meant 20 years for the average aircraft. This equated to the following in terms of design spectrum lifetime: flight hours, 6000; ground-air-ground cycles, 3000; field taxi runs, 3500; catapult launchings, 2000; landings, including field, 3000; field carrier landing passes, 3000; arrested, 2000; and carrier touch and go, 300.

The severe design spectrum has two important facets. The first is the frequency of maneuvering load factor experiences. The design spectrum is tailored to reflect the expected usage for the worst-case aircraft. Second, all load factor exceedances are assumed to take place at "points in the sky" critical for major structural components.

The F-18 fatigue and fracture control program resulted in 50 structural parts being classified as fracture critical and 210 parts, as maintenance critical. Fracture critical parts involved safety of flight whereas maintenance-critical parts related to significant operational or cost impact. All critical components were subjected to crack growth as well as total life requirements.

The critical component crack growth analysis was required to show one design spectrum lifetime from a 0.010 in. initial flaw to critical crack size in addition to two lifetimes prior to crack initiation. Design spectrum hours from detectable flaw to component failure and maximum initial flaw size that would still result in one design spectrum lifetime, also were determined.

The Navy aircraft structural integrity substantiation requirements place heavy emphasis on full-scale article and component test results. A full-scale airframe is subjected to repeated loads until it has demonstrated an endurance of at least two design spectrum lifetimes. Cracks found in structural components during these tests are treated as failures requiring redesign and retest. To ensure that necessary structural changes are identified and incorporated with minimum cost and risk, these tests are accomplished as early in the program as possible.

Finally, to provide a means of scheduling timely actions to detect structural problems, and to facilitate force management decisions, a fatigue life tracking program has been established for individual fleet aircraft. This program provides the status of the individual aircraft fatigue life expended for fleet aircraft determined by comparing actual usage to the full scale test results. This requires on-board monitoring equipment. The older fleet aircraft generally were equipped with counting accelerometers for this purpose whereas the newer aircraft probably will be equipped with microprocessors.

Benefits

The benefits of a structural integrity program can be ranked in various categories. Certainly safety is an important consideration, perhaps ranking higher than all others. The reliability and need for maintenance affect the readiness of the fleet aircraft economics; visibility and political factors are also important in developing hardware for government procurement. The structural integrity program implemented by the U.S. Navy for aircraft has resulted in remarkably improved reliability and performance.

CONCLUDING COMMENTS

Several additional structural integrity programs were reviewed by the committee; these programs were associated with the NASA space shuttle program (McHenry and Rolfe 1980), the NASA Titan III program (May 1983 presentation to the committee by Mr. Robert Heymans, Martin Marietta Corporation, Denver, Colorado), and the Army helicopter program (Gustafson 1977 and Hoffrichter and McCracken 1978). The committee also reviewed both the Air Force airframe requirements (July 1983 presentation to the committee by Dr. Frank Adams, Air Force Wright Aeronautical Laboratory, Wright-Patterson Air Force Base, Ohio) and the industrial implementation of these requirements (May 1983 presentation to the committee by Mr. Richard Circle, Lockheed Georgia Company, Marietta, Georgia). These reviews further illustrated various approaches to developing failure prevention programs for given types of structures.

The process of developing and implementing a successful structural integrity program that incorporates the use of new or advanced technology requires a substantial commitment by company and project management, and project engineering organizations. This commitment normally comes as a result of contractual obligations or economic pressures. Organizational structure becomes important and involves project management that provides programmatics, cost, schedules, basic requirements, and customer liaison. Engineering provides staffing, quality of engineering, engineering tools, and state-of-the-art methodology to the project management relative to design choices.

To ensure that adequate consideration is given during design to structural integrity, both internal and external design reviews are conducted. The internal reviews involve teams of company structural and materials engineering specialists who deal with problem solving, analysis procedures, and design approaches for preventing failures. Typically, the internal reviews extend beyond the project engineering team with the primary design responsibility.

When the industrial organization is contractually liable for implementing a customer-required structural integrity program, the customer typically conducts independent reviews of the design. These reviews can involve an approval cycle for the structural integrity plan and its supporting technology as well as in-depth evaluations (or audits) of the design capability, qualification test failures, quality control procedures,

and any other facet that the customer believes essential to the success of the design and his product.

As a final note to this chapter some comments by Robert Heymans of Martin Marietta Corporation (presentation to the committee, May 18, 1983) are instructive. Although personal, they reflect one individual's characterization of an on-going and successful structural integrity program as:

> We don't do a good job of rewarding good design; over-engineering is seldom recognized.
>
> Fracture control plans are probably imposed on an organization by the customer. It's overseeing, demeaning, and is a great inconvenience but imposes beneficial discipline.
>
> The structural integrity system is expensive, frustrating, time consuming, stifling, demotivating, dehumanizing, but it works.

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4

STRUCTURAL INTEGRITY ISSUES IN THE ARMY

INTRODUCTION

This chapter presents several case studies of Army systems that illustrate
how structural integrity was or was not implemented in the development
process. The use of a structural integrity plan reflects an overt decision
by the program manager that was essential to the development of the system.
When a structural integrity plan was not used, it was simply taken for
granted, not intentionally ignored. The cases considered are examples. No
attempt was made to develop or assess the full scope of recent Army
structural failures.

CASE STUDY: THE M72 LIGHT ANTITANK WEAPON (LAW)

History

The M72 light antitank weapon (LAW) system was developed in the early 1960s
for Army and Marine Corps use. The system consists of a self-contained
lightweight shoulder-fired launcher and a high explosive antitank rocket.
Major components of the launcher and rocket are identified in Figures 13 and
14.

From very early in its history, the LAW has experienced a series of
failure problems in the rocket closure and motor body that resulted in
failure to perform its mission and, in some cases, injury to personnel. In
the early 1970s, failures occurred in the rocket closure. Figure 15
illustrates the basic nature of the failures. This early problem was
corrected by strengthening the closure with a fiberglass overwrap. A second
series of failures occurred in the mid-1970s. In this case, the failures
were in the rocket motor body. A second "fix" of fiberglass wrapping of the
highly stressed and flaw-initiation regions of the motor body was then
implemented. However, failures have continued to occur even in the
fiberglass wrapped bodies at failure rates significantly greater than those
considered acceptable by the Army.

LIGHT ANTITANK WEAPON

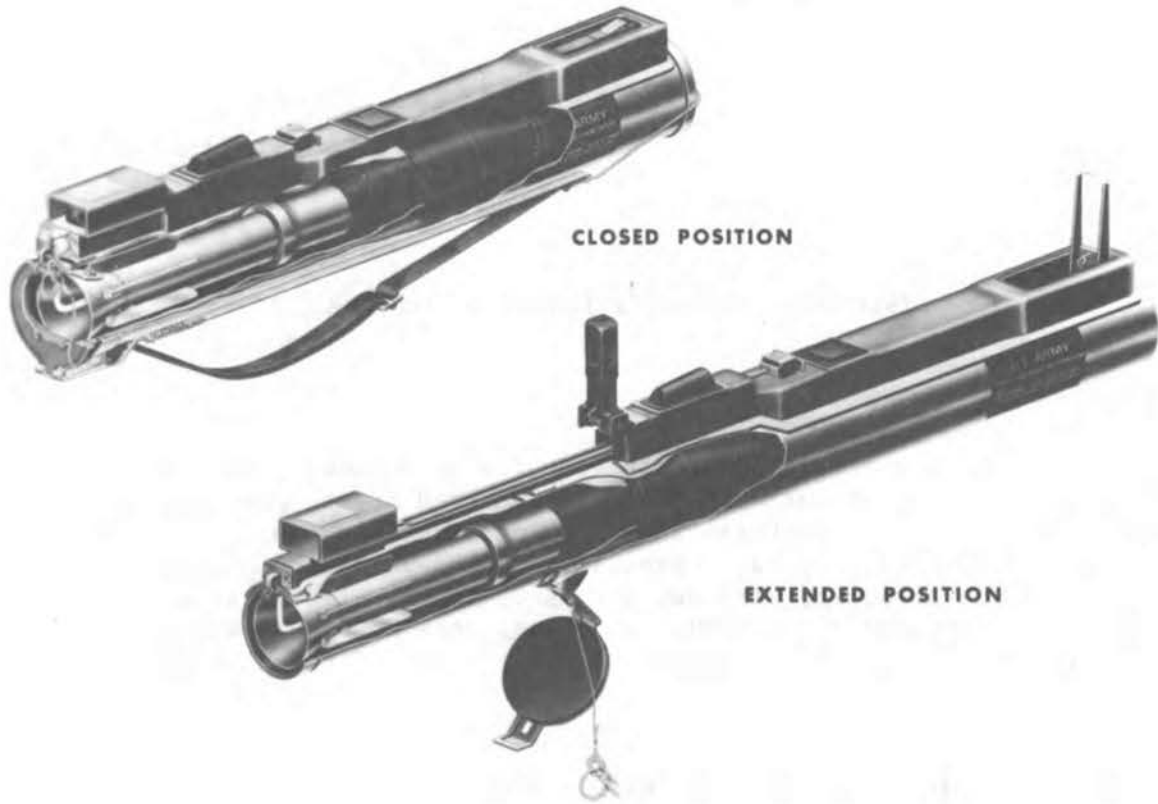CLOSED POSITION

EXTENDED POSITION

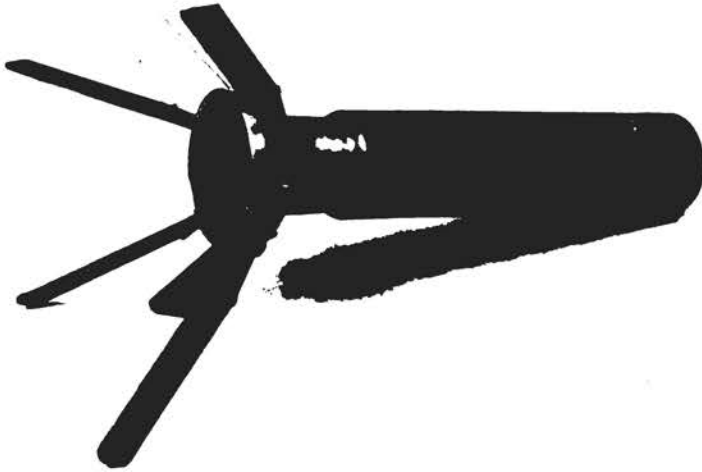FIGURE 13   The M72A2 LAW system (Bruggeman 1981).

FIGURE 14 Fiberglass-wrapped LAW rocket motor (Bruggeman 1981).
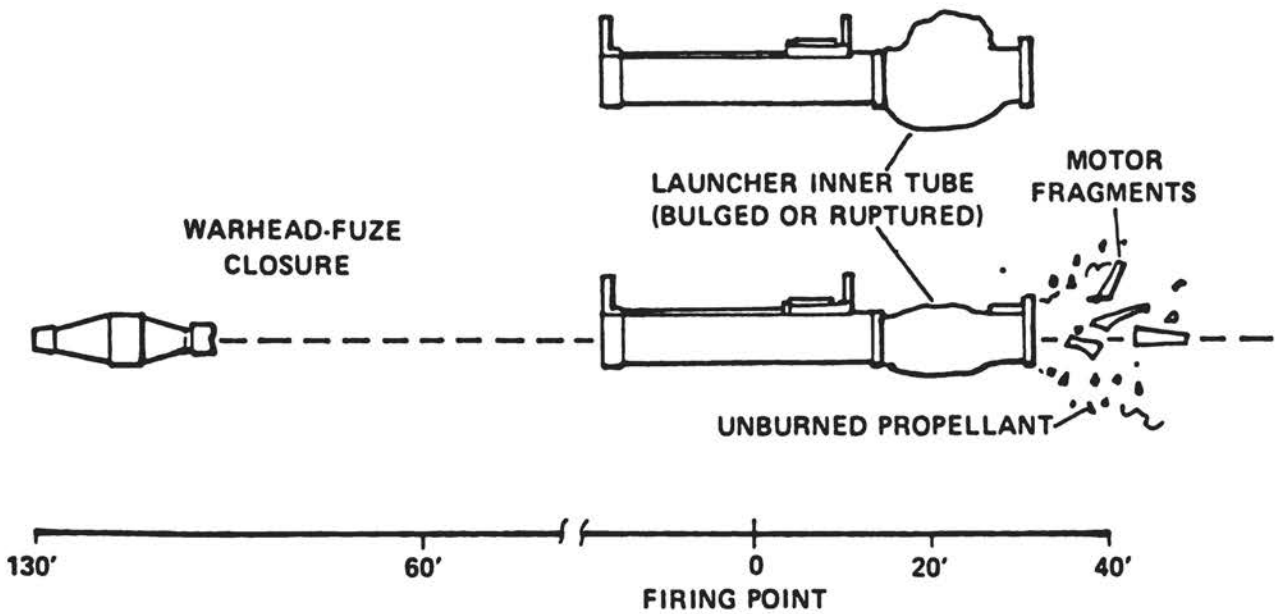

FIGURE 15 Schematic representation of typical LAW rocket motor malfunction (Bruggeman 1981).

Detailed failure investigations have indicated that the primary cause of the failures was the unusually low fracture toughness of the high strength aluminum alloy 7001-T6 of which the rocket motor and closures were fabricated (average toughness on the order of 10 ksi $\sqrt{\text{in.}}$ with measured values as low as 7 ksi $\sqrt{\text{in.}}$). The problem was aggravated by the susceptability of the material to stress corrosion cracking, which produced enlarged flaw sites. The occurrence of different failures rates among LAW systems from different manufacturers was investigated, but only subtle differences in manufacturing processes were observed. It was concluded that the problem was basically one of poor material selection rather than one of poor manufacturing or quality control.

Possible Effects of a Structural Integrity Plan

Had a structural integrity program like that outlined in Chapter 2 been in place during the development of the LAW system, the first step would have been to identify components critical to life and mission, which would have clearly included the rocket motor and closure components. Identification of design loads and environment would have been similar to the procedure actually used, but an additional step of assuming some damage to be present would have been included as input to the design analysis. This may have identified the stress corrosion mechanism, with some controls on levels of residual stress or crack propagation rate. As a minimum, a design basis flaw would have been assumed, and fracture mechanics calculations performed to determine minimum acceptable material fracture toughness. Fracture toughness measurements would then have been part of the material selection process, and it is likely that aluminum alloy 7001-T6 would have been shown to be unacceptable for the intended usage. If an acceptable alternative material could not be identified, compromises would have been made, in terms of either increased weight or reduced performance requirements to reduce stress. Finally, even if the above changes were not implemented during intial design, improved in-service structural integrity controls might have provided better feedback from the initial series of structural failures such that more effective "fixes" could have been implemented in later production runs.

CASE STUDY: M60 TANK

History

Until sufficient quantities of the M1 (Abrams) tank are produced the Army will continue to rely on the M60, developed in the 1960s, as its principal heavy tank. To increase the effectiveness of the M60 during this interim period, the Army has undertaken a major "rebuild" program. In December 1981, the M60 program manager expressed concern about the reliability of various components of overhauled tanks as a result of failures experienced during proving ground tests. In response to that concern, one of the Army laboratories formed an interdisciplinary task group consisting of specialists in materials science, engineering, structural mechanics, nondestructive testing, and statistical analysis.

This group was chartered to evolve life prediction methodology for application to a structural component of the M60 tank. The torsion bar was chosen for the application because failure of bars was of concern and because a fairly comprehensive history was available.

Failure of a torsion bar in an M60 tank does not generally result in an accident that threatens life; however, if a failure occurs during a dangerous maneuver, the ensuing accident could! Most often, torsion bar failure results in reduction of mobility that, in turn, affects the mission success. Furthermore, even if mobility is only reduced and not lost, the failure of a bar results in other bars being loaded beyond design limits, thereby accelerating total loss of mobility. Exacerbating the situation is the Army M60 maintenance policy; bars are simply replaced at fixed intervals and no records of individual torsion bar service history are kept.

Given the unsatisfactory failure history of the M60, the program manager wished to "develop a position with regard to durability of reconditioned vehicles, and feasibility of predictive testing as part of the overhaul process." In effect, the goal was to implement a structural integrity program.

With this background the Army laboratory's task group undertook the assignment of developing a life prediction methodology for assuring the structural integrity of the M60 torsion bar. Information and data were collected from the U.S. Army Tank-Automotive Command, Anniston Army Depot, Army Systems Analysis activity, Aberdeen Proving Ground, and relevant contractors. These included failure data, failed torsion bar tests, fatigue data, quality assurance procedures and load spectra.

The approach taken by the task group involved materials characterization, stress analyses, probabilistic design studies, sensitivity analyses, and analysis of failed components. It was found that failures inevitably were initiated within the splines at the ends of the bar, even though the final fracture surfaces extended into the body.

The characterization of the torsion bar material was quite extensive and included chemical analysis, light microscopy, analysis of retained austenite, hardness traverse, tensile properties, Charpy properties, and fracture toughness properties. The initial intent was to use fracture mechanics analysis and knowledge of the fracture toughness of the material to determine an allowable flaw size that could be used during depot or unit level maintenance to decide whether or not to replace a torsion bar.

It was quickly determined by the task group that inspection for an allowable flaw was not a feasible approach for the torsion bar. The bulk of the life of a bar involves the coalescence of microcracks into a macrocrack. The analysis indicated that cracks as small as 0.005 inches would propagate to final fracture in about 15 miles of travel. Since reliable detection of flaws that small is not possible even under

controlled laboratory conditions and since scheduled maintenance is not carried out every 15 miles, an alternative approach had to be pursued.

The alternative approach consisted of statistically analyzing the extremely comprehensive fatigue data generated by torsion bar manufacturers in conjunction with load spectra information and making probabilistic life predictions. Using this approach, the life of a torsion bar was predicted to be 292 miles with 99 percent probability (i.e., on the average, only 1 bar out of 100 would fail before 292 miles). The prediction was consistent with actual failure information from Aberdeen Proving Ground, which showed a 99 percent survivability of 262 miles.

A number of sensitivity analyses were carried out. These addressed such questions as the effects on life of various material properties, stresses in the torsion bar, etc. For example, by redesigning the bar to reduce the stress level by 20 percent, a fourfold increase in life can be obtained (Figure 16). On the other hand, increasing material properties, such as fracture toughness, resulted in only marginal improvements (Figure 17).

Probability of Survival vs Miles
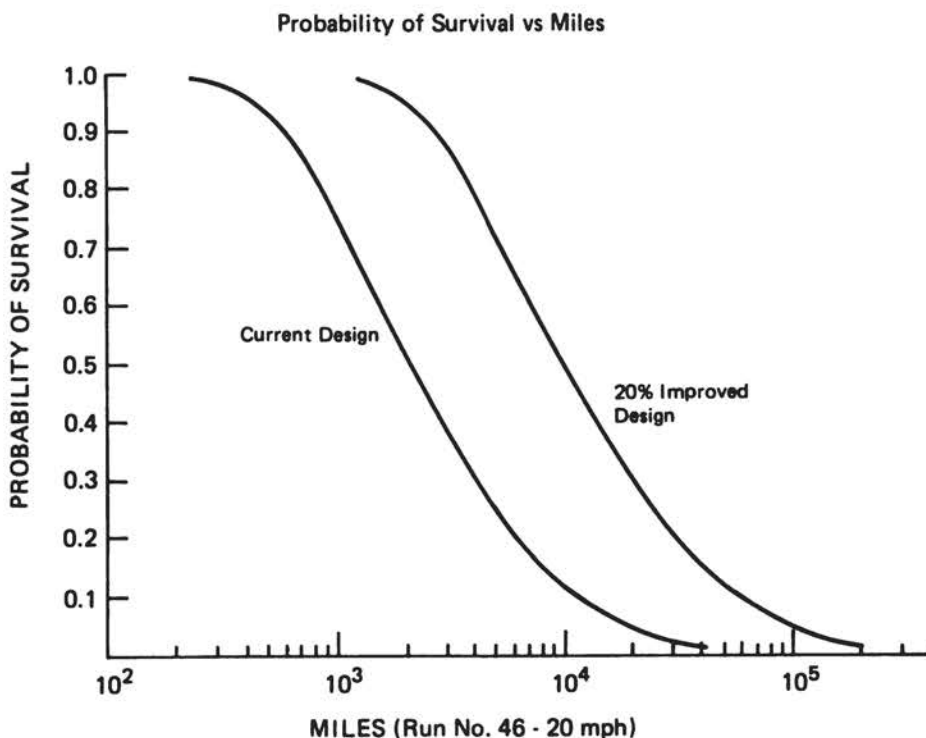
FIGURE 16   Life of tank torsion bars as a function of stress (Neal, Matthews, and DeAngelis 1983).
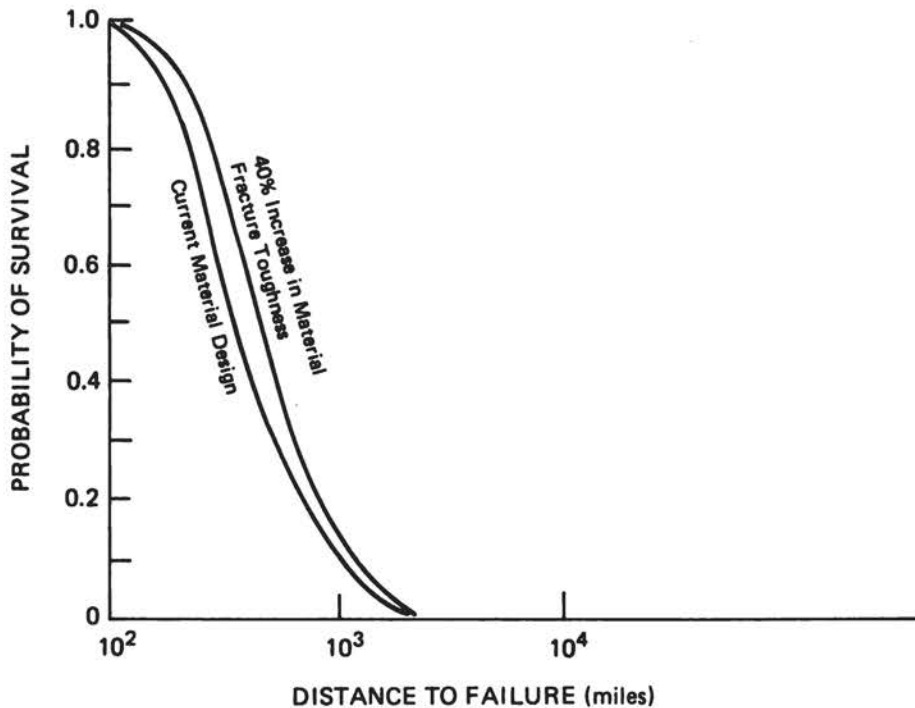
FIGURE 17 Influence of material improvement on service life (Neal, Matthews, and DeAngelis 1983).

One interesting problem faced by the task group involved obtaining load spectrum information. No load spectra for the M60 could be found and it was necessary to adapt load spectra that were available for the new Abrams tank. The gross weight of the tanks is not identical and the wheel-suspension characteristics are different. However, an engineering analysis to approximate the M60 spectra was considered satisfactory since the spectral data were skewed toward higher loads--that is the bulk of the load was not highly variable. The conclusion was borne out by the good agreement between the predicted survival estimate and proving ground results.

Possible Effects of a Structural Integrity Plan

It is clear that if a structural integrity plan had been implemented during the development of the M60, the problems that occurred would have been identified. It is possible, but not likely, that the torsion bar

could have been designed so that an allowable flaw approach for torsion bar replacement would have been feasible. It is more likely that trade-off studies would have been made of operating stress and materials selection with the associated costs and weight implications related to the probabilistic estimate of life (with the associated logistics and maintenance implications).

After the fact, the implementation of structural integrity offers far less flexibility. The options are:

1. To replace bars only after they fail. Although this may be an acceptable option in peacetime (i.e., training) operations, it would be risky in wartime conditions. Since there are 12 torsion bars on the M60, after 500 miles there is about a 30 percent probability that on a given tank all bars will have survived. However, with another 100 miles of service the likelihood of a bar failing is now one out of two; after 200 miles, three out of four!

2. To replace all bars on a scheduled basis. The schedule would be based on a trade-off between desired (probabilistic) availability of the M60 with the logistics costs of replacement at various scheduled mileage accumulation. The problem here is one of scheduling replacement to be compatible with existing scheduled maintenance requirements for the myriad of other components.

3. Replace bars selectively on a scheduled basis. This implies that maintenance records be kept on all bars. Specifically, if a bar is replaced because of failure, the replacement bar's probabilistic life estimate would be factored into the next scheduled maintenance. This would require maintaining records of nonscheduled replacement of bars. Manual records would be expensive and of questionnable reliability. Application of sensors on individual bars and/or on-board microprocessors for data accumulation could be quite cost-intensive.

4. To redesign to adjust (probabilistic) life with overall maintenance schedules. Redesigning after the fact inevitably creates many problems, most of which result directly in increased costs. Trade-off studies have not been performed to quantify these costs.

The substance of what has been discussed has been directed to only one component of the M60 tank. There are many other structural elements of the system that contribute to the overall structural integrity of the M60 tank. Even restricting attention to the track and suspension subsystem, there are numerous other issues, such as track-pads and track-pins. The problems with these other components are analogous to those with the torsion bar. In the case of the (rubber) track-pad, specifications for the material are not sufficiently spelled out. In the case of track-pins (which connect individual track segments) the situation is analogous to the torsion bar; it is impossible to detect allowable flaws in the pins.

A system-wide structural integrity program for the M60 would have provided the Army with the means for making cost-effective decisions during the development of this vehicle.

CASE STUDY: COPPERHEAD

History

Copperhead is a cannon launched guided projectile (CLGP) fired from a
155-mm cannon. It is manufactured for the Army by Martin Marietta
Corporation. During test firings the control section (Figure 18) failed
on some of the projectiles. The control section was produced from a 4340
steel with a specified hardness of R_c 52-55; the corresponding yield
strength is approximately 250 ksi. Martin Marietta believed that the
high material strength requirement was necessary to meet the high
operational stress requirements. However, higher strength also means
lower toughness and the failures appeared as a result of inadequate
toughness in the presence of defects.
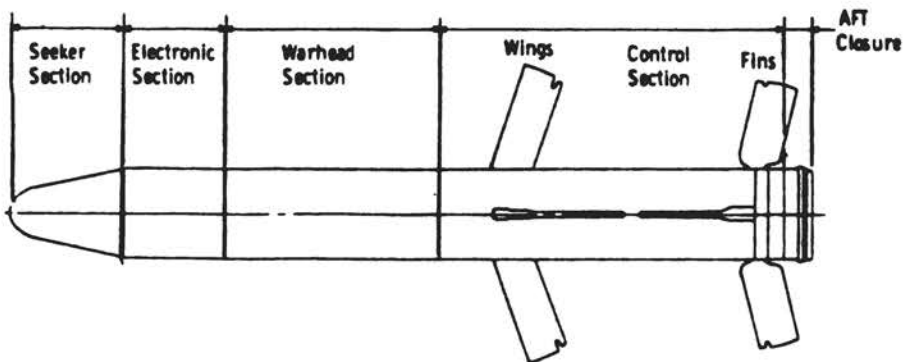
FIGURE 18 CLGP structural configuration (Bluhm and Freese 1978).

Personnel from the Army Materials and Mechanics Research Center
(AMMRC) used fracture mechanics principles to estimate a critical defect
size. Based on an estimated minimum K_{Ic} of 30 ksi $\sqrt{in}$. and 200 ksi
operating stress, a defect size of 0.01 in. by 0.03 in. would be
critical. A program to develop nondestructive testing (NDT) procedures
for detecting these defects was suggested, but many felt that it would be
impossible to detect such small defects with any regularity. Other
complicating factors were that neither the exact toughness of 4340 steel
nor the correct stress requirements were known very well.

Possible Effects of a Structural Integrity Plan

A structural integrity plan based on fracture mechanics principles could
have greatly helped to avoid the firing test failures and to minimize the
possibility of field failures. A schematic of the fracture mechanics
approach is shown in Figure 19. Three elements are required; stress

Material Properties

Related
in Terms of
K_I Parameter

Stresses   Defect Sizes

FIGURE 19   Areas of information required in the utilization of fracture
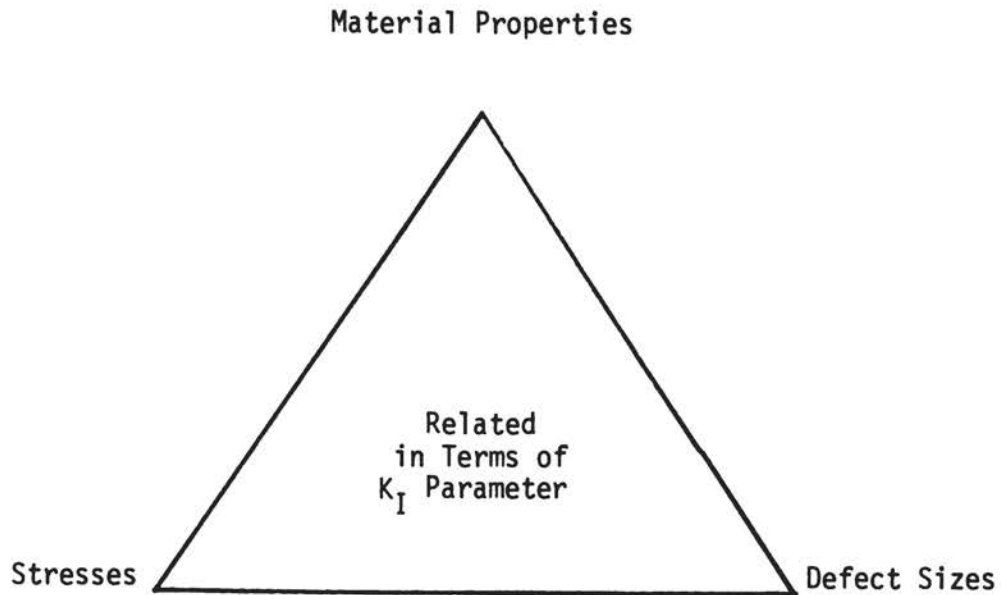mechanics technology.

analysis, defect sizes, and material properties. A structural integrity
plan would consider these three elements and make compromises to arrive
at a design for the control section that would have a margin against
failure.

The material strength level was specified to insure a margin against
plastic overload of the control section. This was based on an estimated
stress analysis rather than an exact one. The maximum stress
requirements should be known before the material strength level is
specified. The failures experienced in test were from inadequate
toughness rather than plastic overload. Strength and toughness are
inversely related in a 4340 steel. If toughness is inadequate, strength
requirements must be reduced. With an accurate stress analysis, these
compromises can be made rationally.

To make a full analysis of the design, NDT inspection capabilities
must be considered. Critical defect sizes of 0.01 in. cannot be found
repeatedly. A more reasonable inspection limit must be proposed. This
could be a starting point for the fracture mechanics evaluation. The
approach taken could then be as follows: Given a maximum defect size
that might be missed by inspection and the required design stress, a
required toughness level can be determined. A small materials test
program could be initiated to determine toughness versus strength for
this material. These results would identify the maximum strength level
of the material that can still meet the toughness requirements (obviously

the 250 ksi strength is too high to give the needed toughness). If it turns out that this strength level is inadequate to meet the stress requirements (danger of plastic overload), some further compromise is needed (e.g., the design must be modified to lower the stresses or a new material must be substituted to meet both the required strength and toughness levels).

The procedure needed to implement this structural integrity approach is well established and known to guarantee structural reliability. It must be implemented based on a knowledge of all three factors in the fracture mechanics approach (Figure 19). Stress analysis must be conducted to get accurate stress requirements. Material properties must be determined through a test program rather than estimated from the literature. A realistic inspection limit must be established; this depends on the facilities and the accessibility of critical areas on the structure. Finally, if the structural integrity analysis shows that failures are possible, compromises must be made in the design or material selection for the component. Putting this effort into the initial design and evaluation could be very cost-effective by reducing or eliminating failures. Repeated failures could require a redesign and possible scrapping of manufactured components. The end result could be orders of magnitude more expensive than a simple structural integrity plan implemented in a timely manner.

CASE STUDY: NUCLEAR SHELL

History

Failure of the JFF-1 engineering development test (EDT) projectile during test firings in December 1976 appeared to result because the threaded joint between the rocket motor and the bulkhead of the XM-753 projectile did not hold together. Therefore, the joint between the rocket motor and the bulkhead of the projectile had to be redesigned. The successful solution of the joint problem was developed through the combined efforts of the Army Armament Research and Development Command (ARRADCOM), Sandia Livermore Laboratories, and the Army Materials and Mechanics Research Center (AMMRC). The new joint design used a total of 16 pins held in place by snap rings (Figure 20).

Effects of a Structural Integrity Program

The AMMRC was assigned the task of verifying the structural integrity of the new joint design based on the requirements of the ARRADCOM configuration manager. These design requirements for structural integrity included:

1. Peak set-back and torque at 10,400 g, under impulsive torque resulting from free run and under negative set-back (elastic release) at barrel exit.

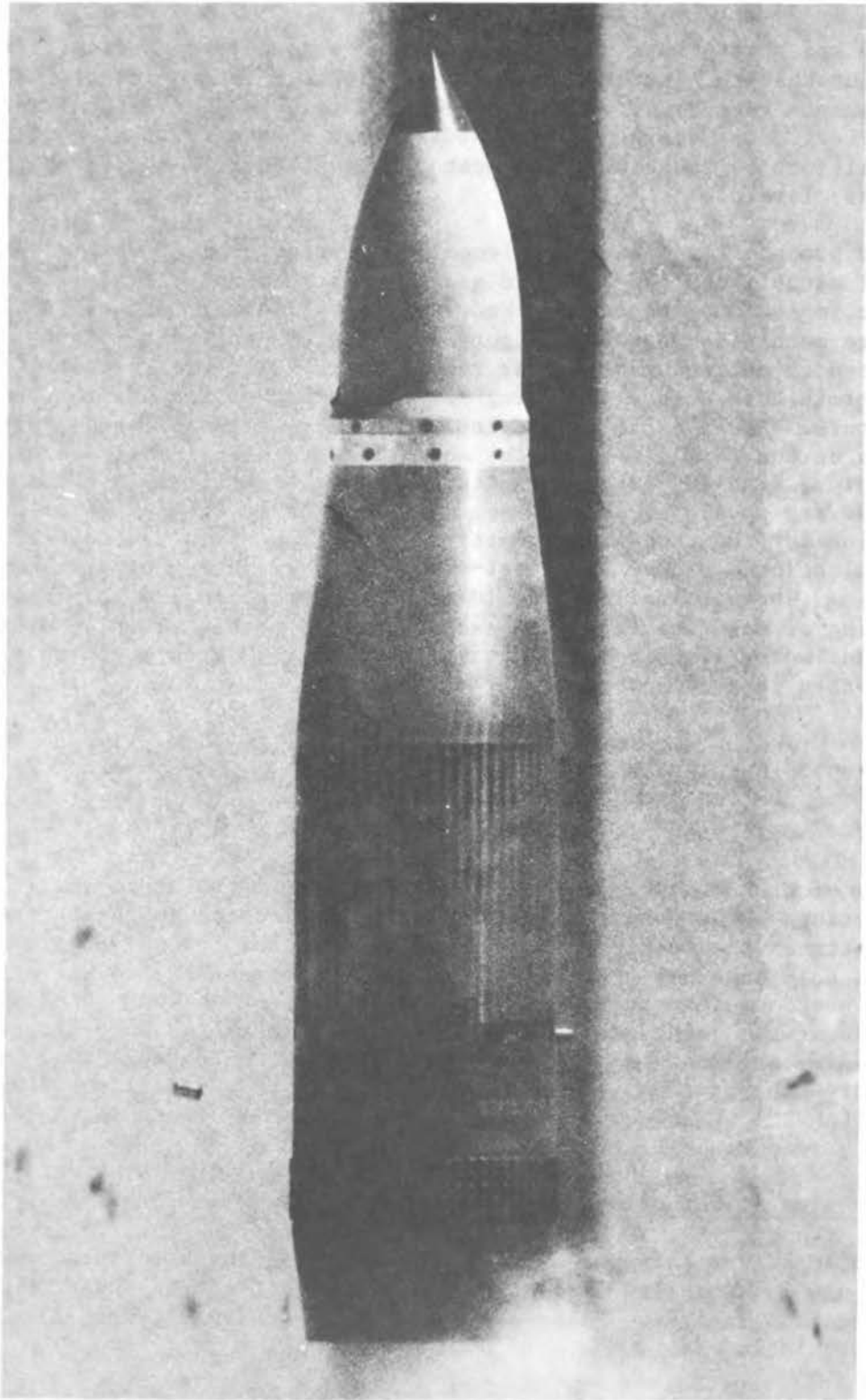2. Pin retention under centrifugal force at barrel exit.

FIGURE 20   Test firing of XM-753 projectile with pin joint using snap
ring retainers (courtesy of J. Adachi, M. Benicek and T. Tsui,
Mechanics and Structural Integrity Laboratory, Army Materials
and Mechanics Research Center).

3. Gas pressure of 3000 psi at rocket-motor-on condition.

4. Equal bending stiffness of the threaded joint.

5. Pin extraction and joint disassembly and reassembly without damage to components.

6. Control of pin interferences and bulging effect on seal surfaces.

7. A reliable propellant gas seal at the joint.

The design effort utilized finite element analysis, photoelastic analysis, and firing tests of the bulkhead-to-structural case joint and analyses and tests specifically developed for evaluation of possible pin joints. The results of the analytical analyses were verified by experimental tests to ensure that the results were reasonable. The study went beyond the normal structural analysis and evaluated the overall reliability of the pin joint between the rocket and the bulkhead of the projectile.

In reviewing a new projectile design, there are a number of groups which must interact in order to develop a functional yet reliable projectile. The design drawing for the proposed projectile comes from ARRADCOM along with the design specifications that the configuration manager deems needed. These may include maintenance requirements, interchangeability of parts, range and projectory, payload, classified requirements, and launch conditions. The Department of Energy prepares the physics calculations to ensure that the design can carry the required payload.

AMMRC is tasked with defending the structural reliability of the design before the ARRADCOM Nuclear Weapons Safety Committee. In order to properly defend the design, the AMMRC does a complete stress analysis of the design.

Three dimensional analyses are conducted on the design and critical parts identified. The analysis will not only include mathematical calculations but also experimental testing of hardware to verify initial analytical results. Efforts are made to identify other materials that would be more appropriate to the design specifications. Criteria used during this evaluation might include: yield strength, brittle fracture, buckling modes. All of this activity is directed at maintaining the structural reliability of the projectile. Other failure modes also might be identified during these activities and will be communicated to the configuration manager for his consideration. AMMRC will provide critical quality assurance criteria based upon the preliminary design of the projectile in order to maintain the reliability of the structure. These criteria would assist in establishing the limits on the contractor's manufacturing processes and specifications for the materials used.

Throughout this process of developing a new projectile, it is apparent that the configuration manager must believe that the activities of AMMRC on the project serve his interests. This type of cooperation is created when all parties involved are willing to listen to the others' concerns and to compromise on design specifications in order to develop a functional and yet structurally reliable projectile.

COMMENTS ON ARMY ACQUISITION PRACTICES

Within the U.S. Army material development and acquisition process, project managers are assigned responsibility for managing that activity under specific charters approved by the Secretary of the Army. Unless specifically addressed by charter, there is no formal procedure for mandating the implementation of structural integrity plans. Consequently, structural integrity assurance is a matter most often left to the judgment of the individual project manager. As the case studies presented in the preceding pages indicate; a well planned, comprehensive structural integrity program has been implemented in some instances and not in others.

As in industry and the other services, the Army project manager is faced with the conflicting demands of cost, schedule, performance, and reliability. Up to any three of these attributes can be established explicitly but the fourth will seek its own level (Coutinho 1977). Within the Army system the typical project manager is assigned for about three years and then is reassigned. Hence, cost and schedule become the drivers in the acquisition process since these are attributes that can be measured readily and are used in evaluating the project managers' performance. It is little wonder that structural integrity is not always explicitly factored into the development process and is not the most important issue to the project manager since the odds are high that it will not become a problem during his tenure.

Furthermore, in the development of modern systems, high technology often becomes the focus for management of the development. Materials and structures technologies are often taken for granted and languish in the background until a problem arises. When a structural integrity (or structural reliability) problem does arise, the options for solving it are constrained because the design is so far down the road. The result is that the solutions are not optimal and generally have an adverse impact on the other attributes.

For example, life-cycle cost will suffer when an after-the-fact structural integrity solution is implemented. The schedule is certainly delayed by an unanticipated structural failure. Because an optimal solution is not possible, performance often suffers.

Although the Army has the technical capability to deal with most of these problems through competent laboratory staff, there is no mandated requirement for the project manager or his staff to avail themselves of such resources. Further, although industrial suppliers may apply structural integrity concepts in producing products for sale under their

own name, there is no requirement that such practices be used in supplying equipment for the Army.

The problem, then, would appear to be the lack of a structural integrity program that is institutionalized in the Army acquisition system. For example, the Air Force structural integrity program is firmly embodied in Air Force regulations to cover "cradle to grave" airframes procurement, but no such program is in place in the Army. Although some project managers may introduce some structural integrity controls, the system has not been formalized. Until such procedures are introduced, there is no guarantee that the problems of failures, excessive costs, and fatalities arising from present practices cause will disappear.

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5

PROPOSED STRUCTURAL INTEGRITY PROGRAM FOR THE ARMY

REGULATION

The case studies presented in the preceding chapter illustrate a need for the Army to institutionalize structural integrity. It is recommended that the Army develop a formal procedure that requires the consideration and implementation of a structural integrity program. This procedure should be mandated by the Department of the Army and incorporated into the Army regulations. The intent is to ensure that program managers recognize their responsibility for structural integrity and that explicit consideration be given to this aspect early in the concept definition phase. The intent of the regulation should be to lower the probability of discovering costly structural integrity problems late in the development cycle or after the system has been deployed.

SCOPE OF COVERAGE

The Army produces and procures a large variety of equipment and systems with widely differing structural reliability consequences. Therefore, a unique structural integrity plan should be prepared for each system acquisition considering its specific application and the consequences of structural failures within that system in terms of human life, mission success, and economics. The results could range from a highly detailed and comprehensive plan for fracture critical systems or components to minimal plans for components deemed by the project team to be of small consequence or not fracture critical. In extreme cases, a structural integrity plan may be waived entirely, but this should involve a conscious decision to do so.

Given the flexibility permitted by this recommendation, the committee is strongly of the opinion that a knowledgeable organization outside project management should be assigned review and approval responsibility, including review and approval of decisions to waive development of a structural integrity plan.

Thus, structural integrity plans would become a key element of the procurement or production process for the system and would be included in relevant contracts and specifications. Major considerations in the preparation of such plans should be developed and documented in a generic military standard (Army Structural Integrity Program) as described in the following pages.

MILITARY STANDARD

The recommended Army regulation should refer to a new military standard that defines a structural integrity program considered generic for all Army equipment. This generic structural integrity program should be developed to include structural design conditions, materials and processing controls, design and analysis controls, quality assurance controls, and in-service controls. In developing this new military standard, the Army should define how its structural integrity program is time-phased relative to the design, verification, production, and operational phases of the equipment lifetime. The Army structural integrity program should be sufficiently general that it defines structural integrity requirements and outlines the essential features of a satisfactory (adequate) structural integrity plan for a given procurement. It is essential that the new military standard give serious consideration to how structural integrity requirements will be verified prior to acceptance of design for production release. Chapter 3 provides a number of examples of structural integrity programs that might be reviewed for their relevance to this new military standard.

IMPLEMENTATION

It is the committees' belief that the Army must develop its own structural integrity plan reflecting the specific character, organization, and operational procedures unique to that branch of the service. Implementation should be by directive from the highest level of the Army. The committee has not involved itself with the details of the organization and operational aspects of such a plan for the Army, considering this to be outside its area of knowledge and experience, but recommends that such be done by the Army itself, following closely the guidelines given in this chapter.

PAYOFFS

The importance to the Army of operating with a structural integrity plan involves far more than the mere practice of sound engineering principles. The committee has identified six factors that could be used to measure possible payoffs from the introduction of such procedures into the procurement process:

1. Cost--Although the "costs" of a malfunctioning or otherwise defective part are difficult to measure, they can be very high. For

example, as indicated in Chapter 1, the cost of fractures each year in the United States has been estimated to be in excess of $100 billion with some $6 billion of that directed to the DOD.

2. Safety--Protection of the public as well as military personnel against a serious accident involving Army weapons is of prime importance. Of special concern are those systems involving nuclear weapons. However, the more conventional weapons (e.g., the LAW and artillery) are also of concern since premature ignition of projectiles or inadequate toughness and sudden fracture of gun barrels can lead to injury and loss of life. Problems associated with loss of confidence and morale of operating personnel can also result if the accident rate is high.

3. Readiness (reliability and performance)--An inoperative weapon or vehicle at a time of national emergency is an extremely serious problem. Although difficult to quantify in dollars, there can be no justification for the existence of a weapons system that is not available for use in time of need due to a "structural failure."

4. Visibility--The unsuccessful performance of a new weapons system during its various trials prior to commission can generate unfavorable publicity that has serious consequences in terms of both public and congressional opinion concerning the capability of the Army to undertake and satisfactorily complete such projects. Although a structural integrity plan will not prevent all possible operational problems, it can help avoid many of these embarrassments.

5. Maintenance--Undue maintenance because of repeated malfunction can have serious economic and operational consequences. Skyrocketing repair costs have serious budgetary consequences. Excess downtime means more equipment must be procured to perform a given function. Breakdowns in remote locations are extremely costly.

6. Politics--A positive attitude in the mind of the public and particularly the Congress is highly desirable if a given weapons system is to be adequately funded. The several factors given above all contribute to the development of this attitude.

The four weapons systems described in Chapter 4 have been examined in terms of these factors and it was concluded that a more comprehensive structural integrity plan in place in advance would have prevented or could have prevented the difficulties experienced. An attempt has been made by the committee to evaluate the several payoff factors described above for each of these systems. This evaluation was aimed at measuring the relative importance of each payoff factor on a scale of one to six, where one is most important and six the least important of the several factors identified. While only representing the views of the committee, it was clear that safety was the most important of the various payoff factors and maintenance the least. While other groups might come up with a different ranking, ours was, in order of importance, safety, readiness, political factors, cost, visibility, and maintenance.

APPENDIX

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

LOUIS F. COFFIN, the committee chairman, was educated at Swarthmore College
(B.S.) and Massachusetts Institute of Technology (Sc.D. in mechanical
engineering). While he taught at M.I.T., Rensselaer, and Union College, his
career has been at General Electric, both at the Knolls Atomic Power
Laboratory and at the Research Laboratory. His various research efforts
have typically integrated metallurgy with mechanical behavior. His list of
honors and awards is long and includes membership in the National Academy of
Engineering.

JOSEPH P. GALLAGHER received his B.S. degree in civil engineering from
Drexel University, and his M.S. and Ph.D. degrees in theoretical and applied
mechanics from the University of Illinois. After teaching at Illinois he
was associated for 16 years with the Air Force Flight Dynamics Laboratory.
This was a time of rapid development of understanding of fatigue crack
growth, and of modeling procedures, and led to the development of service
life prediction techniques that now support structural integrity planning.
Since 1978 he has been a group leader in the University of Dayton Research
Institute, directing research aimed at controlling damage introduced in
structures, such as by fatigue or corrosion. He was co-author of a paper
that received the 1975 ASTM Sam Tour Award as the best corrosion research
paper of the year.

JOHN D. LANDES has more than 20 years of research experience in mechanical
behavior of materials, principally in the application of fracture mechanics
techniques to material behavior. His B.S., M.S., and Ph.D. degrees, all in
applied mechanics, were received from Lehigh University. In particular, he
has studied brittle fracture of metals, subcritical flaw growth including
environmental effects, and stress analysis of cracked bodies. Most
recently, he has been concerned with developing a fracture criterion for
elastic-plastic behavior, with studies of the effects of aggressive
environments on crack growth behavior for materials under both fatigue and
static loading, and with high temperature creep crack growth behavior. More
than 50 of his papers have been published in the open literature.

PETER C. RICCARDELLA received his B.S., M.S., and Ph.D. degrees in mechanical engineering from Carnegie Mellon University. He has worked for Westinghouse, General Atomics, General Electric (San Jose), Nutech, and is now president of Structural Integrity Associates. He deals largely with utilities, assessing structural problems in nuclear reactors.

ORPHA B. THOMAS obtained his B.S. degree in mechanical engineering and his M.E. degree in industrial engineering, both from Texas A&M University. His employer, National Loss Control Service Corporation, serves the insurance industry in examining accident reports and in drafting criteria for safety standards.