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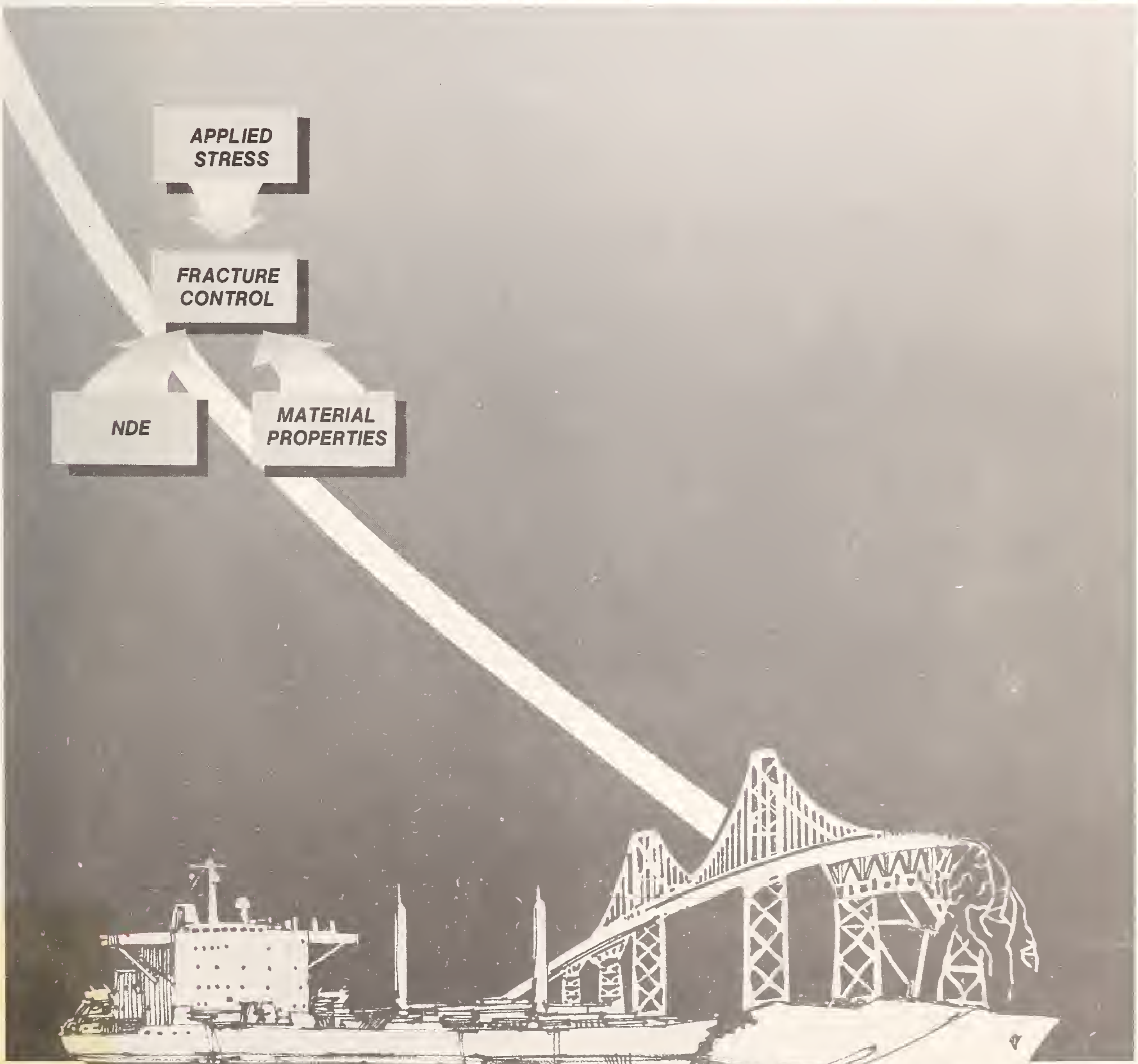
SPECIAL PUBLICATION 647-1

The Economic Effects of Fracture in the United States



FRACTURE PREVENTION

FRACTURE OCCURRENCE

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The Economic Effects of Fracture in the United States

Part 1 — A Synopsis of the September 30, 1982 Report to NBS by Battelle Columbus Laboratories

R.P. Reed, J.H. Smith, B.W. Christ

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The Economic Effects of Fracture in the United States

R. P. Reed, J. H. Smith, and B. W. Christ

Highlights

The National Bureau of Standards and Battelle Columbus Laboratories (BCL) have completed a study to assess the costs of material fracture to the United States for the year 1978. This exhaustive assessment used the econometric input-output model to identify contributions from the entire U.S. economy. The study included all materials and all types of structures and included both fracture occurrence and fracture prevention costs.

The costs were large. In 1982 dollars the total cost was estimated to be $119 billion per year, about 4 percent of the gross national product. An estimated $35 billion per year could be saved through the use of currently available technology. Costs could be further reduced by as much as $28 billion per year through fracture-related research.

The costs are primarily associated with the transportation and construction industries: motor vehicles, aircraft, and the building of homes and non-residential construction. Metal structures contributed substantially larger costs than non-metal structures. A greater percentage of these costs were expended on fracture prevention than on fracture occurrence.

The study concluded that substantial material, transportation, and capital investment costs could be saved if technology transfer, combined with research and development, succeeded in reducing the factors of uncertainty related to structural design. Equally safe or safer structures could be produced with substantial cost savings in material, transportation, and capital investment. This could be done by reducing the uncertainty currently related to structural design through better predictions of structural performance from materials properties, better process and quality control and in-service flaw monitoring, and less materials variability.

Introduction

Materials have a tendency to fracture under stress. Window glass needs only a slight impact, such as from a pebble, to initiate a crack. Highway concrete tends to crack with the freezing and thawing of water in winter. Steels are susceptible to cracking at cold temperatures, to cracking at defects in welds, and to cracking under cyclic loads. Every year it seems that a major airline or train accident, a dam or bridge collapse, a ship disaster or other structural failure, causes our Nation expense and grief.

The design and fabrication of such diverse structures as automobiles, windows, highways, and heavy machinery have as their first priority the prevention of fracture. Here, fracture means the premature failure from material deficiency or from a breakdown in accepted fracture control practice of a structure, component, or container, operating within the intent of design. Most industries allocate substantial economic resources to prevent fracture. These include: materials research; design according to conservative codes and standards; special packaging and handling during shipment; quality control and in-service inspection, maintenance, and repair during service; and specialized training for operators. Spare parts are kept on hand to replace those that fail in service. Some industries require redundant capital equipment to reduce downtime from periodic repair or maintenance. Useful lives are reduced for structures exposed to in-service loads.

Following the National Bureau of Standards (NBS)—Battelle Columbus Laboratories (BCL) study on "The Economic Effects of Metallic Corrosion in the United States" [1][1] reported to

[1] Figures in brackets indicate the literature references at the end of this paper.

Congress in 1978, two subcommittees (Natural Resources and Environment; Science, Research and Technology) of the House Committee on Science and Technology requested that NBS assess the economic effects of fracture in the U.S. economy. The letter request to NBS from these Subcommittees appears as Appendix A. In April of 1980, NBS issued a request for proposals to assist in this study. A contract was subsequently awarded to Battelle Columbus Laboratories. The overall technical scope of the project was jointly developed. Data taking and economic analyses were conducted by BCL [2]. The study was supported by contributions from NBS, the Department of Energy (Division of Materials Sciences), the National Science Foundation, the Department of Interior (Bureau of Mines), and the Department of Defense (Defense Advanced Research Projects Agency).

Following the award of the contract to BCL in September, 1980, the study progressed in two major phases. In phase I (3 months), NBS and BCL jointly agreed to definitions and technical guidelines as discussed in Appendix B. BCL established their econometric basis (including the fundamental input/output model and supplemental models to assess social/personal costs and property damage) and identified 154 sectors of the economy. During this first phase BCL also conducted a pilot study on two sectors—railroads and ophthalmic products—and issued a report to NBS summarizing these activities and discussing prospects for a successful study [3]. With the assistance of a BCL-assembled advisory panel of national experts in fracture and economics and the NBS steering committee, NBS reviewed this phase I report and decided to continue with the major study, phase II.

In phase II, BCL obtained baseline Department of Commerce data on national economic activity in 1978 for their input-output model, collected data relative to fracture costs from a large number of industry and government representatives, and adjusted the coefficients in the input/output matrix and final demands to calculate the total and reducible costs of fracture to the U.S. economy. The study used Department of Commerce input-output data for the latest possible year, 1978. Accident events related to fracture were averaged over several years to obtain more representative data. The BCL advisory panel was convened three times throughout the study to assess the objectives and progress on the project. NBS received the final BCL report in October, 1982.

The final report describes the input/output methodology used to estimate the total, presently reducible and future reducible costs of fracture, and the supplemental models used to establish the direct and indirect (including the costs of death, pain, and suffering from injury and environmental degradation) costs arising from fracture occurrence. Discussion of guidelines used to estimate these costs (e.g., "row rules") is amply provided. A complete set of the input/output tables was generated by BCL for this study [4]. Finally, the report identifies and highlights the total costs of fracture and the costs associated with about 15 fracture-sensitive sectors of the economy.

Objectives

The objectives of the NBS/BCL study were:

I. To assess the total cost of fracture in the U.S. economy. This total includes the costs associated with the occurrence of unintended fracture and the costs associated with the prevention of fracture.

II. To assess presently reducible costs of fracture. The costs of fracture could be reduced if economically best fracture control practices were to be universally applied throughout the economy. This reduction in cost can be approached through transfer of known technology.

III. To assess the future reducible costs of fracture. The costs of fracture could be reduced in the future by conducting research to advance the understanding of material fracture and fracture control technologies.

It was not the intent of this study to assess the costs of going from the present to the economic state of best fracture control practice or of applying the fracture-related information gleaned from research.

Results

The total costs of fracture and potential savings from technology transfer and research are summarized in figure 1 and discussed here.

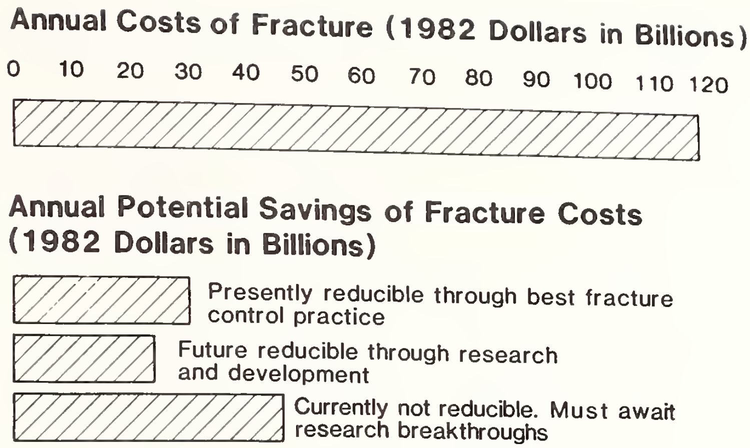

Figure 1

Total Costs of Fracture

The total cost to the United States from material fracture is estimated to be $88 billion (1978 dollars) per year. This cost represents 4 percent of the gross national product. In terms of 1982 dollars it is about $119 billion per year. The estimated uncertainty is ±10 percent.[2]

Several factors contribute most significantly to the costs of fracture:

(1) The imposition of large factors of safety in many structures reflects uncertainty in design and results in increased expenditures for construction, materials production, and transportation.

(2) Many industries devote significant resources to repair and maintenance, replacement, and scrappage associated with equipment failures.

(3) Inspection with respect to material quality control and structural reliability consumes significant resources.

The economic sectors which experience highest costs of fracture are shown in figure 2. Similar to the findings of the corrosion study, the Motor Vehicles and Parts sector has significantly higher costs than other sectors. The aircraft industry is also significantly affected by fracture. In this industry large resources are directed toward quality control and inspection.

A number of sectors absorb fracture costs between $1 and $3 billion per year. This reflects the extraordinarily high price that our basic production technologies pay for capital equipment, resulting from concern for fracture. The economy is seriously affected by the fracture of materials. Sectors such as Fabricated Structural Products, Non-ferrous Products, Petroleum Refining and Structural Metals all are heavily dominated by metals. The Construction, Food and Kindred Products, and Tires and Inner Tube sectors encompass such materials as concrete, polymers and wood and wood products. On the whole, however, metal-based sectors contribute significantly larger costs than do non-metal sectors.

[2] BCL estimated a conservative bias in the total cost of 13 percent because of their consistently conservative assumptions in data taking and analyses. They reflect this conservative bias in summary statements of the "most likely" total cost. However, the economic sector data provided in their report do not reflect this adjustment of 13 percent. NBS has chosen to use the most conservative cost estimates from the BCL study; additional discussion of the statistical uncertainty of the results is contained in Appendix C.

Major Sector Contributions to the Annual Costs of Fracture (1982 Dollars in Billions)

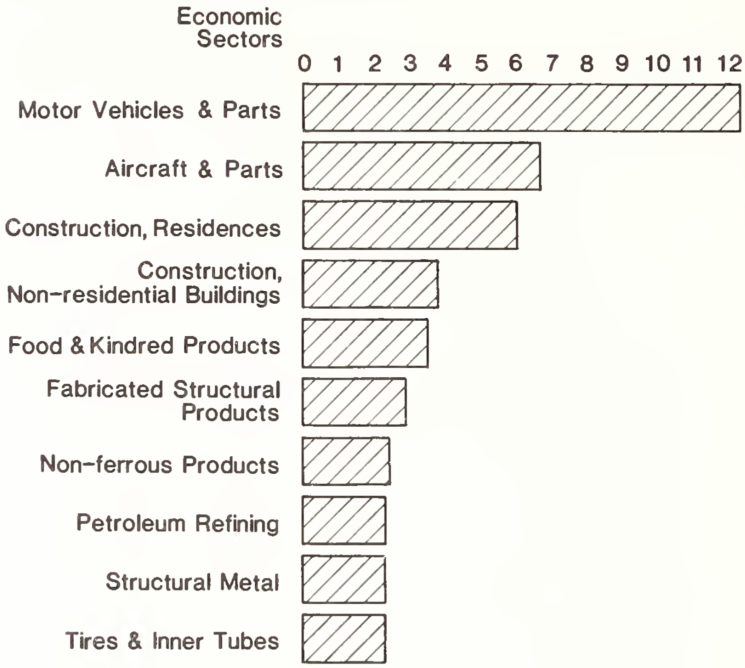

Figure 2

Technology Transfer Savings

The fracture costs of the United States could be reduced by an estimated $26 billion in 1978 dollars ($35 billion in 1982 dollars) per year by the application throughout the economy of best fracture-control including inspection, maintenance and repair, and quantitative prediction of allowable flaw sizes, minimum material toughness, and maximum operating stress. Education, establishment of mechanical property data banks, and accelerated modernization of codes, standards, and regulations are also identified as leading to reduced costs. The study chose aerospace and medical technology as the industries which presently employ best fracture-control practices.

Potential Savings from Fracture-Related Research

Research directed toward fracture-related problems could further reduce the costs of fracture to the United States by an estimated $21 billion in 1978 dollars ($28 billion in 1982 dollars) per year. Two major categories of research were identified: material and structural. Material research includes (1) better understanding of mechanical behavior, (2) reduction of the variability of mechanical properties through improved production processing and defect control, (3) better mechanical and microstructural characterization to provide a broader, more dependable data base, and (4) improvement of the mechanical properties of existing structural alloys through modification of metallurgical variables (e.g., grain size and weldment flaws).

Structural research includes: (1) better fabrication, especially welding and joining to control the occurrence of fracture-sensitive defects in joints, (2) improved performance and lifetime prediction models, techniques and tests to increase structural reliability, (3) increased sensitivity and accuracy of non-destructive inspection to locate fracture-sensitive flaws, and (4) improved design through computer-assisted stress analyses.

Non-Reducible Costs

The remainder of the costs of fracture ($41 billion per year in 1978 dollars, $56 billion per year in 1982 dollars) are not considered reducible at this time. Reduction of these costs must depend on fundamental research breakthroughs. This could be achieved, for instance, by basic research on crack initiation and growth leading to development of significantly stronger materials. Other possible advances include acquiring the ability to produce materials that are mostly defect-free (thus improving their strength above that assumed possible in this study).

Discussion

Durable materials must withstand three processes: fracture, corrosion, and erosion and wear. Fracture costs were evaluated in this study and were found to be large, $119 billion per year in 1982 dollars, of the order of 4 percent of the GNP. This cost is equivalent to the cost of corrosion which in 1975 dollars was estimated to be $70 billion per year and about 4 percent of the GNP [1]. Erosion and wear costs have not yet been evaluated in the United States. Studies for erosion and wear costs have been evaluated in Great Britain [5] and West Germany [6]. These studies suggest that erosion and wear costs are at least 2 percent of the GNP's of those countries. It is apparent that material durability costs are substantial and probably about 10 percent of the GNP.

The total costs of fracture or corrosion can be divided into costs of occurrence and costs of prevention. Occurrence includes those expenses attributed to the aftermath of unintended fracture or corrosion events. Prevention costs include research and development, inspection, design, packaging and handling, and repair and maintenance. There is a relation between occurrence and prevention costs. Greater allocation of resources to prevention tends to reduce the frequency (and, therefore cost) of occurrence. Schematically, this may be illustrated as shown in figure 3. Roughly 70 percent of the total cost of corrosion was found to be associated with occurrence; but in this study only about 20 percent of the total fracture costs were associated with actual failures. Effective technology transfer and research tends to move the curve on figure 3 toward zero.

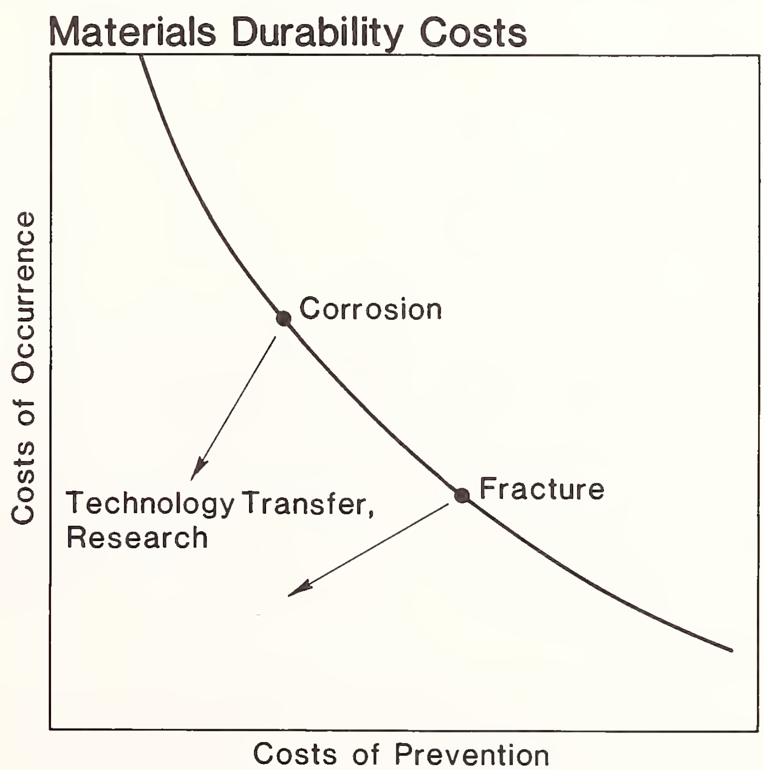

Figure 3

The disparity between the ratio of occurrence/prevention costs for fracture and corrosion is understandable. Typically, fracture results in the immediate loss of use of the structure; corrosion does not immediately reduce the use of the structure. For example, corrosion of automobile fenders is not as restrictive to the owner as is fracture of the crankshaft. Furthermore, fracture costs occur predominantly in the production industries, whereas a relatively large percentage of corrosion costs occur in the consumer area, especially motor vehicle cooling systems and exhaust systems. Hence, fracture has a greater chance of resulting in production losses, as compared to corrosion that tends to result in inconvenience to the consumer.

Other comparisons of the fracture and corrosion studies are highlighted in table I. The costs are quite similar, considering that the fracture estimate is considered more conservative than the corrosion cost. The dominant cost of corrosion in 1975 was absorbed by the automotive sector. The fracture costs are more diffuse. The capital equipment of a large number of production-oriented sectors is made from metals (primarily steels) and is significantly affected by efforts to prevent fracture.

Table I. *Highlights of comparison of fracture and corrosion studies*

Study	Annual amount (1982 dollars in billions)		Uncertainty interval	Materials surveyed	Major cost contributors
Fracture	Total Cost:	119	±10% 13% systematic underestimate	Metals; polymers; glass and ceramics; wood and wood products; asphalt; concrete, composites.	Production and construction industries; transportation (aircraft, automobile); residential and nonresidential construction.
	Technology Transfer Savings	35	±10% 13% systematic underestimate		
	Research Savings	28			
Corrosion	Total Cost:	126	±24%	Metals	Transportation (automobile)
	Technology Transfer Savings	18	+200% -50%		

Whereas the costs of fracture come from many sources which are discussed in the BCL final report [2], a major generic source deserves additional discussion. In structural design, the major ingredients related to safety are material properties, design stresses, inspection, and the appropriate structural codes and standards relating these items. Structural codes include a factor of safety related to the uncertainty of material properties, service stresses, and the ability to predict performance based on known properties and stresses. The range of factors of safety vary from 1.5 to more than 15. Some aerospace designs have managed to lower the factor to as low as 1.2 through careful material processing control and extensive use of fracture mechanics predictions and inspection. In a hypothetical state in which materials did not fracture, this factor of uncertainty would be reduced to 1.0.

Major items that contribute to large design uncertainty include: (1) material variability, (2) time-dependent fracture, and (3) structural reliability predictions based on small-specimen tests. Such common and easy-to-measure properties as the tensile and yield stresses vary at least 10 percent, and sometimes as much as 50 percent. Minimum tensile properties are commonly used in structural design. Time-dependent fractures result from in-service cyclic and constant loads which tend to promote crack growth from existing flaws. In-service inspection or crack growth rate analyses are typically not used sufficiently by most economic sectors. Structural reliability is difficult to predict from small-specimen tests. Therefore, most codes rely on experience and prototype testing and, currently, do not use quantitative analyses.

Cost savings resulting from reduction of design factors of uncertainty can be substantial. Material consumption is reduced in direct proportion to reduction of uncertainty factors. Reduction of structural reliability uncertainties leads to higher operating stresses which are achieved by reduction of cross-sectional area. Transportation costs are reduced, usually in direct proportion to weight reduction. Material production required for such structures is reduced, leading to savings of raw materials plus energy resources.

Fracture costs can be reduced without reducing the level of safety by reducing the factors of uncertainty for structural design. Guidelines are generally provided on allowable stress levels, flaw contents, and material properties through voluntary codes and standards and, in some cases of concern for public safety or environment, Federal regulations. The modernization of these standards is proceeding very slowly, not because the code and standard-making bodies desire that, but because their resources are severely restricted.

There are several major research and development directions to consider. (1) Typically, the variability of the mechanical properties of a given structural alloy from production manufacturing is significant, of the order of 5 to 30 percent in wrought alloys and larger in most cast alloys. Welds frequently contain flaws such as porosity, slag and inclusions, and planar flaws. Design codes must consider this variability. Improved consistency is possible through advanced materials and weld processing techniques. (2) The relation of material properties to structural performance is now predictable in some applications by using fracture mechanics. The development and improvement of fracture mechanics will permit accurate portrayal of performance from knowledge of small-specimen test results, flaw dimensions from inspection, and service loads. This, in turn, will permit reduced factors of design uncertainty while maintaining acceptable levels of safety. (3) Increased use of non-destructive inspection is essential to ensure reduced material variability and increased application of fracture mechanics. This places a premium on development of innovative, sensitive, accurate inspection techniques and procedures.

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[1] L. H. Bennett, J. Kruger, R. L. Parker, E. Passaglia, C. Reimann, A. W. Ruff, and H. Yakowitz, "Economic Effects of Metallic Corrosion in the United States," NBS Special Publication 511-1, May, 1978.

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APPENDIX A

September 11, 1979

Dr. Ernest Ambler
Director
National Bureau of Standards
Washington, D.C. 20234

Dear Dr. Ambler:

We were pleased with your recent participation at our joint June 28 hearing on the "Materials Policy, Research and Development Act of 1979". We would like to follow up our discussion during that hearing concerning the possibility that the National Bureau of Standards might conduct a study of the economic and safety costs of fracture.

The recent NBS study of "The Economic Effect of Metallic Corrosion in the United States", performed at the request of the Senate Appropriations Committee and which found that corrosion cost the nation about $70 billion in 1975, has been very useful. We believe a similar study on fracture would prove equally useful. It is our understanding that the funding of such a study would be made available from current programming funds. Given the importance of such information in making proper policy decisions, we would recommend that the fracture study should include consideration of safety as well as economic aspects.

We are confident that other agencies of the Federal government will cooperate with you as necessary in providing data on the effects of fracture in their operations and areas of responsibility.

Sincerely,

(signed)

JEROME A. AMBRO, Chairman
Subcommittee on Natural
Resources and Environment

(signed)

GEORGE E. BROWN, JR. Chairman
Subcommittee on Science,
Research and Technology

APPENDIX B

CONCEPTS AND DEFINITION

Fracture control depends on a broad range of technical disciplines and decisions in the design, manufacture, and use of all structures and mechanical components. Understanding and controlling fracture requires the integration of knowledge about materials properties and production, structural and mechanical design, fabrication, inspection, maintenance, and repair. Advances in the control and prevention of fracture have been intricately linked with improvements in materials, design methodology, and testing and inspection procedures. Therefore, to make the present assessment of the economic effects of fracture meaningful and manageable, it was necessary to establish at the outset a precise definition of "fracture" and exactly what the basis for the economic assessment is to be. The following outlines fracture as defined and covered in this study:

1. Materials included are:

   Metals and alloys
   Ceramics
   Glasses
   Refractories
   Polymers
   Concrete
   Asphalt
   Composites
   Wood and wood products

2. Fracture processes included are:

   Stress-induced failures—tension, compression, flexure, shear

   Overload
   Deformation
   Delamination
   Time-dependent: fatigue, creep, stress corrosion, embrittlement

3. The fracture events (occurrence)

   Unintentional
   Initiated by material failure or improper fracture control.
   Fracture when operated within design intent; failure is due to deficiency in material or breakdown of accepted fracture control practice (inspection, repair, maintenance, codes, and standards). Fracture is sole relevant cause of failure.

   Excluded failures are:

   Operator abuse (e.g., collision)
   Intended, beneficial fracture—drilling, crushing, grinding, machining
   Overload beyond design intent (natural phenomena—wind, water)

A. Cost of Fracture Prevention
(Factors that result in direct and indirect extra cost of labor, materials, energy)

1. Conservative design (use of large safety factors)

   a. To account for:
      1) Variability in material properties
      2) Unknown stress—residual stresses, notches, uncertainties in occurrences in stress analysis
      3) Unknown (preexisting) defects
      4) Time-dependent stresses and effects (degradation of materials properties)

2. Materials selection

   a. Use of minimum measured (or less than minimum) property values rather than actual values

b. Limit (or avoid) use of fracture prone material
   Increase use of more expensive (resource intense) specialty materials.
c. Limit use of materials subject to time-dependent fracture

3. Inspection/testing/quality control—in-process, in-service

4. Maintenance/replacement/reserve capital equipment—to allow for time-dependent fracture

5. Limit on useful life (scrappage)—to allow for time-dependent fracture

B. Definition and Scope of Costs

1. Costs associated with cost of fracture event
   a. Loss of capital equipment/replacement
   b. Loss of use
   c. Loss of product
   d. Initial damage/cleanup
   e. Clean-up
   f. Injury/death

2. Costs associated with the anticipation and prevention of fracture

   a. Capital costs associated with excess capacity and redundant equipment
   b. Fracture control costs
      Inspection, maintenance, repair, quality control during manufacture/fabrication
   c. Design and construction costs
      1) Materials selection/premium material
      2) Special processing, manufacture, fabrication
      3) Design and engineering

3. Associated costs

   a. Packaging
   b. Materials and fracture research and development
   c. Technical support
      1) Testing and inspection
      2) Development of codes and standards
      3) Limitation on product lifetime

C. Base Level for Cost of Fracture

To assess the total costs of fracture, one must model an economic state in which fracture does not exist. This is similar to the corrosion study, where a "World without Corrosion" was modeled [B-1]. The conditions which NBS and BCL used to define a world without fracture are:

1. Assume that design is carried out with perfect knowledge and that the material usage in design is either load or stiffness limited.

2. Assume that materials are entirely resistant to fracture within the design envelope, then:

   a. There would be no crack initiation, growth, or fracture; and fracture mechanisms such as fatigue, creep, and environmentally assisted crack growth will not contribute to fracture.
   b. A safety factor of unity would be used.
   c. Fracture control including inspection and repair would not be necessary.

3. Mechanical properties of present-day materials are variable, having a Gaussian or Weibull distribution. Assume that each material mechanical property would not have variability and that value of the property be four standard deviations above the mean of the distribution which is now achievable. Furthermore, as the mechanical property values are increased and the variabilities decreased, it is assumed there is no unfavorable effect on other properties.

4. A material may be substituted if the reason for the use in the application was fracture susceptibility.

In summary, to obtain the total costs of fracture, it was necessary to construct an economic state in which materials did not fracture and to construct rational consequences of this hypothetical state. The details of this economic state are also summarized in table B-I.

Table B-I. *Major technical adjustments to assess total cost of fracture*

Present conditions	*Conditions with no fracture*
Materials contain flaws, defects to permit fracture	Materials do not fracture within design intent
Material mechanical properties are variable	No variability in mechanical properties
Design to minimum (or less) property values	Design to maximum, 4 standard deviations above current mean property value
Material can fracture in service under creep, fatigue, impact, or environmental-assisted fracture	No time-dependent fracture
Residual stresses exist	No residual stresses
Design may be limited by stiffness, load, fatigue, creep, or toughness	Design only limited by stiffness or load
Inspection and other preventive means necessary	No costs of prevention
Safety factor on material yield strength to maximum applied stress is much greater than 1.0	Safety factor on stress = 1.0

Economic Methodology

A total national assessment to identify all costs associated with fracture in the U.S. economy and to determine the change in these costs due to changes in technology requires a macroeconomic model of the entire U.S. economy. For this study, a macroeconomic input-output (I/O) model of the U.S. economy was chosen. The I/O model of the economy was developed by W.W. Leontief [B-2] to accurately and completely trace all transactions within an economy and to determine the total level of economic activity (output) in the nation. Accurate and up-to-date data on the output of the entire U.S. national economy is maintained by the U.S. Department of Commerce. For this study of nationwide fracture costs, data from the year 1978 was used because this is the latest year for which complete records are available from the U.S Department of Commerce.

The I/O model of the economy is a series of relationships between the output of a group of productive processes or industries (sales) and the input to a group of users or products (purchases). The I/O model is represented by a matrix describing all business transactions within the U.S. economy. The matrix is formed by dividing the whole economy into individual sectors representing specific productive processes (columns) and users (rows). The I/O model is used to account for the total output of the economy by calculating the resources allocated to interindustry transactions, total capital expenditures, and total final demand for all commodities.

As changes are made in any or all of the economic sectors, through changes in technology, the effect on the economy as a whole can be traced and the total effect on output can be calculated by identifying changes in the individual cells (row-column intersections) in the matrix. In addition to these "interindustry" transactions shown by the I/O matrix, the I/O model of the economy also determines the "final demand" for the output of each sector of the economy.

As used in this study, BCL developed a modified I/O model based on the U.S. Department of Commerce I/O model of the U.S. economy. The BCL I/O model divides the entire economy into 150 sectors based on common technology, productive processes or user characteristics. The effect of any changes in technology of production or use can then be traced through the economy and the changes in the total output of the economy can be determined.

To determine the cost of fracture in this study, the BCL I/O model of the economy was set up to measure the total output of the U.S. economy as it now exists (World I). Then, a second model of the economy was set up for the hypothetical state of no fracture occurrence (World II).

The coefficient in each cell in the World II I/O matrix was adjusted to conform to the condition of no fracture. The total output of the economy under this assumption (World II) was determined, and the difference between World I and World II total outputs was determined as the cost of fracture. In a similar manner, the total output of the economy was determined using the I/O model when best current fracture control practice (World III) was assumed to be used throughout the economy, and the presently reducible cost of fracture was calculated.

The input data to the I/O model were obtained by BCL from several sources and via several data assessment techniques. The primary method of obtaining input data was by the "ex ante" procedure, which depends primarily on specific assessment by technical experts of the value of each coefficient in the I/O matrix. The same expert technical judgement is then used to assess the change in the value of each coefficient when alternate states of the economy are postulated. In the present study, the use of the "ex ante" procedure was further extended with the development of "row rules" to simplify and unify the input data assessment. The "row rules" identify similar technologies or fracture-prone environments that apply throughout an entire row in the I/O matrix, so that a uniform change in the value of entries in the entire row can be used in changing from one state of the economy (World) to an alternate state of the economy (World).

In addition to input data derived from the "ex ante" and "row rules" procedures, this study required the use of "supplemental models" to account for fracture costs that fell outside the full I/O model of the economy. These supplemental models were used (1) to identify the significance and severity of fracture events and (2) to determine the costs associated with death/injury, property damage, and environmental damage due to fracture occurrence. The four specific supplemental models that were developed to assess specific costs of fracture occurrence are described in the BCL report. The costs determined from the supplemental models are added to the total output costs determined by the I/O model to calculate the total cost of fracture.

REFERENCE

[B-1] L. H. Bennett, J. Kruger, R. L. Parker, E. Passaglia, C. Reimann, A. W. Ruff, and H. Yakowitz, "Economic Effects of Metallic Corrosion in the United States," NBS Special Publication 511-1, May, 1978.

[B-2] W. W. Leontief, *Input/Output Economics*, Oxford University Press, New York, 1966.

APPENDIX C

COMMENTS ON THE BCL ESTIMATE OF UNCERTAINTY

by

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National Bureau of Standards

Battelle goes through a systematic analysis to estimate the uncertainty in the final results of the costs of fracture [C-1] (p. 126-137). This analysis is concerned with two aspects of the results: random errors and systematic errors. In a complex calculation, such as that undertaken in this study, tracing through the effect of assumed errors, both random and systematic, in the input data (changes in direct technical coefficients, final demand, and capital/output stock ratios and replacements rates) is a very complicated problem. Given this fact, it is nevertheless felt that the analysis has some faults. These comments will discuss the analysis and suggest that the estimates of uncertainty may be somewhat high. The discussion below will be concerned with random errors and systematic errors.

Random Error

Generally speaking, BCL has made a consistent simplification in the error analysis, namely that the magnitudes of all quantities entering into a computation are the same, and that the errors in them are the same. This will generally underestimate the error in the result. For example, in the discussion on p. 130 of the error in total output from assumed errors in stipulated final demand and in the coefficients of the inverse matrix, it is stated that the error in total output is the error in each of the elements that are summed to make total output (the product of final demand and the inverse matrix coefficients) divided by $\sqrt{150}$. This is only true if all these elements are the same size. That they are not is illustrated by the fact that 21 sectors account for 59 percent of total output, and the remaining 129 for 40 percent. This will increase the calculated error in the calculated total output. Without an in-depth investigation that could be performed by carrying out trial computations, it is difficult to estimate what this increase would be over the BCL result (p. 135), but factors as high as perhaps three could be expected.

Battelle, however, compensates for this by arbitrarily assuming the error in the results for each sector are ± 10 percent for 60 important sectors and ± 20 percent for 90 less important sectors (p. 135). These errors are larger than would be obtained from the discussion of errors in total output, but probably of the right order. However, in calculating the effect of these errors on the results (upper formula of p. 135), two compensating errors appear to have been made. The first appears to be an algebraic one. Even on the assumption that all sectors have the same magnitude of costs (which appears to be an implicit assumption), this formula is incorrect. The error is too large by a factor of $\sqrt{150}$. Hence the errors calculated on this equal-cost assumption should be 1.36 percent rather than 16.7 percent.

However, this equal-cost assumption is not considered a very good one. A direct examination shows that the 10 sectors with the highest costs account for 39.5 percent of the total costs. Indeed, three construction sectors alone (19.01, 19.02, and 19.03) account for fully 12.7 percent of the total costs. Again without a detailed analysis, the actual magnitude of the uncertainty is difficult to decide, but will almost certainly be between 1 percent and 16 percent with the error estimates used by Battelle.

The second formula on p. 135 attempts to estimate the uncertainty arising from errors in stipulated final demand (assumed to be 5%, which is probably low) and those in capital costs, assumed to be 16.7 percent. There are several things wrong with the formula. The weights used (85% and 15%) are based on the distribution of total final demand between stipulated final demand and capital final demand. Clearly, since the attempt is to calculate the error in total final demand *costs,* the distribution should be on this basis. From the figures for final demand costs, this gives a distribution of 40.8 percent for stipulated final demand costs and 59.2 percent for capital costs. Secondly, the formula is in error. The 85 and 15 should be squared, and the 100 should not appear. When the proper figures of 40.8 percent and 59.2 percent are used, and using BCL's estimate of 5 percent and 16.7 percent for the respective errors, the uncertainty in total final demand is calculated to be ± 9.8 percent.

Finally, Battelle estimated the uncertainty in the final result by the procedure in the final paragraph on p. 135. This procedure again is incorrect. The uncertainty should be weighted by the magnitude of each of the components—intermediate output costs and total final demand costs. These are $72.3 and $14.2B respectively. When this is done, and using the BCL figures of 16.7 percent and 7.9 percent, the total uncertainty is ±14.0 percent. The figure of ±26 percent that BCL arrived at appears to assume that uncertainties in intermediate output and total final demand would always be of the same sign. In addition to this, as discussed above, the figures of 16.7 percent and 7.9 percent are respectively too high and too low. Thus, we conclude the uncertainty estimate of ±26 percent made by BCL is too high, and while a more correct estimate cannot be arrived at without detailed calculations, the more correct value may be closer to ±10 percent, using the BCL estimate of errors in the input data.

Systematic Error

To estimate the systematic error, BCL noted that it would always be such as to underestimate the true costs. The reasons for this were two: any coefficients that were not changed would decrease the costs, and a consistent attempt was made to make the estimated changes such as to minimize the costs. We have no quarrel with these observations. However, BCL then argues that the magnitude of this underestimate is just half the random uncertainty, arriving in this manner at a systematic reduction of the estimated costs by 13 percent. No data or supporting material are presented to reinforce this reduction by one-half. The figure of 13 percent underestimate may indeed be correct, but it has to be considered a subjective judgement rather than being based on analysis.

REFERENCE

[C-1] J. J. Duga, W. H. Fisher, R. W. Buxbaum, A. R. Rosenfield, A. R. Buhr, E. J. Honton, and S. C. McMillan, "The Economic Effects of Fracture in the United States," Final Report, September 30, 1982, Battelle Laboratories, Columbus, OH. Available as NBS Special Publication 647-2.

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The National Bureau of Standards and Battelle Laboratories (Columbus) have completed a study to assess the costs of material fracture to the United States for the year 1978. This exhaustive assessment used the econometric input-output model to identify contributions from the entire U.S. economy. The study included all materials and all types of structures and included both fracture occurrence and fracture prevention costs.

The costs were large: in 1982 dollars the total cost was estimated to be $119 billion per year, about 4 percent of the gross national product. The costs could be reduced by an estimated $35 billion per year if technology transfer were employed to assure the use of best practice. Costs could be further reduced by as much as $28 billion per year through fracture-related research.

The study concluded that substantial material, transportation, and capital investment costs could be saved if technology transfer, combined with research and development, succeeded in reducing the factors of uncertainty related to structural reliability. Emphasis on fracture mechanics, inspection and materials processing to achieve better structural reliability and material consistency would result in equally safe or safer structures with less material usage.

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