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Fracture-Mechanics-Based Failure Analysis

Prepared by
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Oak Ridge National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Abstract

Twenty case studies involving the application of fracture mechanics to structural integrity have been reviewed and compared with a similar report published in 1978. Sixteen of the new cases discuss failures, while four are fitness-for-purpose analyses (i.e., evaluation of safe operating conditions of defect-containing structures). In reviewing the case studies, the calculated value of stress intensity at failure was usually found to be only approximately equal to the reported value of fracture toughness. Furthermore, in a number of cases, the calculated stress intensity was significantly less than the reported fracture toughness, thereby indicating a nonconservative fracture mechanics analysis. The probable cause for this relatively poor correlation was that the inputs into the analyses, particularly fracture toughness, were often approximations. Both studies suggest that the likelihood of failure is particularly large when there is a defect >25 mm in size and when the fracture-toughness:yield-strength ratio is <0.16 $\sqrt{m} = 1.0 \sqrt{in.}$

Compared with the earlier study, no significant improvement in accuracy of failure analysis was detected. However, expert opinion suggests that there has been significant improvement in fitness-for-purpose analysis.

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1 Introduction

1.1 Objectives and Background

The objective of this program was to evaluate the adequacy of fracture mechanics as a predictor of failure loads of engineering structures containing defects. At the outset, it was decided to use the case study method and to concentrate on reports of service failures. Case studies have the advantage that they are from real-life experience and are the best method for revealing the strengths and weaknesses of applied fracture mechanics. However, this approach has a drawback, because pressure-vessel failures, which are of major interest to the Nuclear Regulatory Commission, are relatively rare and have not included any known nuclear reactor pressure vessels.

This report is, in part, an update of a 1978 survey by Rich and Rosenfield[1] and is summarized in Table 1. About half of the 21 failure analyses in that study were associated with fatigue. Overall, weld defects were the second leading problem, including the two pressure vessels included in the survey. One of those vessels failed when the calculated stress intensity was close to the measured value of K_{Ic}, while the other failed at only 0.75 K_{Ic}. Although no reason for the latter discrepancy was found at the time, it was possibly a result of using a mean value for fracture toughness and not taking data scatter into account properly.

In addition to the evaluation of load predictions, the 1978 survey revealed two other characteristics of structural failures: 80% of the failures occurred in materials for which K_{Ic}/Y was $<0.16 \sqrt{m}$ ($=1.0 \sqrt{in.}$), where Y is yield strength, and 60% occurred in structures where the maximum crack dimension was >25 mm (1 in.); all structures had at least one of these characteristics. Of course, it is not possible to estimate the number of structures operating safely under either of these conditions.

1.2 Uncertainties in Fracture Mechanics Analyses

1.2.1 Overview

As an initial task in this study, the 1978 Rich and Rosenfield paper[1] was reviewed to evaluate possible difficulties in using fracture mechanics to predict failure loads. Reference 1 states that the analysis was hampered by a combination of a limited data base and uncertainties in experimental inputs. For these reasons, it should not be inferred that discrepancies between theory and experience reveal an inherent deficiency of fracture mechanics. While any theory should be regarded with skepticism, there is ample evidence that fracture mechanics provides a valid method of calculating failure loads of cracked bodies. However, as with any idealization, certain approximations need to be made in practical cases. In the particular case of failure analysis, there are several possible sources of error, including the following.

Uncertainty in fracture toughness is probably the major contribution to overall uncertainty.[2] This situation arises because scatter in toughness measurements is often large, particularly in the ductile/brittle transition region of steels. The problem can be compounded by localized material variability and, in nuclear applications, by uncertainties in the amount of radiation damage. Unfortunately, the best practice, which involves fracture-property measurements in the vicinity of the failure, is not always followed. In fact, handbook values of toughness are often used in failure analyses. The magnitudes of the associated errors are discussed in the next section.

Uncertainty in flaw size and shape can occur because the failed part was lost or severely damaged. Even if the fracture surface is intact, there may be problems in correctly evaluating the fracture-surface markings. These uncertainties also arise in safety analysis of operating components, involving potential errors arising from estimates of flaw size, shape, and location based on nondestructive evaluation.

Uncertainty in stress will arise in situations where there are unknown loads, unanticipated loads, or unknown loading rates. In addition, there is often insufficient information to assess residual stresses.

Uncertainty in stress-intensity evaluation can be minimized by finite-element analyses. In cases of fatigue failure, it is also sometimes possible to obtain stress-intensity estimates independently by analyzing striation-spacing measurements.

Because of all of the uncertainties described above, it is reasonable to assume that a fracture-mechanics analysis

TABLE 1. SUMMARY OF PRE 1978 FAILURE ANALYSES[a]

Ref.	Component	Alloy	Yield Strength (MN/m^2)	Principal Op. Stress (MN/m^2)	σ/σ_y	Critical Crack Size (mm)	K_{IC} ($MNm^{-3/2}$)	K_I/K_{IC}	Major Crack Growth Stage
2a	Aircraft Wing	7075-T6 Al	482*	193†	0.40‡	80 (from Hole)	77*	1.0†	Fatigue
THROUGH CRACK: subcritical crack detected during routine inspection 15 months before failure; monitored periodically thereafter.									
2b	Aircraft Stabilizer Support Fitting	HP 9Ni-4Co-0.2C Steel	1240	469 max.	0.38	125‡	253	1.05 max.	Fatigue
THROUGH CRACK: crack detected during proof test; grew from semi-elliptical surface flaw.									
2c	Missile Motor Case	4340 Steel	1460	935	0.64	2.3 x 12.8	57-61	1.3-1.4	Weld Defects
SURFACE CRACK: (semi-elliptical), failed during proof test.									
2d	Helicopter Rotor Hub Lug	6Al-4V Ti	923-1137	288-463	0.25-0.50	22 x 33‡	108-125	1.0**	Fretting Fatigue
SURFACE CRACK: (1/4-elliptical/corner), failed during proof test.									
2e	Military Bridge Girder	18% Ni Maraging Steel	1390	737 max.	0.53	46	274-312	1.0-1.1	Fatigue
THROUGH CRACK: crack grew from weld detail; failed during prototype testing.									
2f	Helicopter Float Support	7075-T6 Al	482*	415	0.86	2 x 4.5	30-39	0.8-1.1	Fatigue
SURFACE CRACK: (semi-elliptical), support tube failed during routine landing in Alaska.									
2g	Diesel Engine Crankshaft	Steel	>430	90 max.	<0.21	2	6.2+	1.2	Fatigue
SURFACE CRACK: crack originated in forging lap; failed in prototype test.									
2h	Ammonia Pressure Vessel	Low Alloy Steel	761	606□	0.80	8	58	0.75	Weld Defects
INTERNAL CRACK: (penny-shaped), failed in proof test.									
2i	Cannon Tube	~4340 Steel	1175	345#	0.29	9.4 x 28	88	1.1	Fatigue
SURFACE CRACK: (semi-elliptical), crack initiating from thermal shock; failed in service.									
2j	Railroad Rail	Pearlitic Steel	450	250-400□	0.56-0.89	14	35	0.7-1.1	Fatigue
INTERNAL CRACK: (penny-shaped), uncertainty in stress arises from unknown loading and residual stresses; failed in service.									
3	Mining Elevator Brake Rod	Medium C Steel	348	96	0.28	27	41	2.3	Fatigue
SURFACE CRACK: crack grew from screw thread; fatal accident in service.									
4	Solid Propellant Rocket Motor	Welded Maraging Steel	1390	689#	0.50	2.5 x 36	~82	0.5-0.8	Weld Defects
INTERNAL CRACK: (distorted-elliptical), failed under proof test at 56% of desired proof pressure.									
5a	Plate	D6AC Steel	1500	830	0.55	86 x 173	102	0.95	Fatigue
SURFACE CRACK: (1/4-elliptical/corner), failed in laboratory test.									
5b	Aircraft Hydraulic Cylinder	2014-T6 Al	385‡	103 max.#	0.27	6.4 x 14.2	19.8*	0.7	Fatigue
SURFACE CRACK: (semi-elliptical), crack growth possibly assisted by stress corrosion, high overloads possible; failed in service.									
5c	Electrical Rotor	Alloy Steel	570	350	0.61	25-38	34-59	0.7-1.6	Hydrogen Flaking
INTERNAL CRACK: (penny-shaped), failure during balancing test prior to being placed into service.									
5d	Electrical Rotor	Alloy Steel	510	165	0.32	50 x 125	37-45	0.9-1.1	Inclusion Cluster
INTERNAL CRACK: (elliptical), subcritical growth associated with inclusion cluster; failed during routine overspeed test after 2 years service.									
5e	Bridge	SAE 1060 Steel	550	345○	0.63	≤ 3 x 16	51	0.7	Stress Corrosion Cracks
SURFACE CRACK: (1/4-elliptical/corner), complex flaw geometry causes uncertainty in critical crack length; fatal accident in service.									
5f	Bridge	Low Alloy Steel	365	345□	0.95	125	>125	<0.7	Fatigue/Weld Defects
THROUGH CRACK: major residual stress contribution; failed in service.									
6,7	Steam Turbine	Cr-Ni-Mo Steel	664	1010□	1.52	1.6 x 6.4	66	1.0	Stress Corrosion Cracks
SURFACE CRACK: (semi-elliptical), assumed flaw shape in temper embrittled steel; failed in service.									
8	Pressure Vessel	Carbon Steel	295	138	0.47	114 x 14	67	1.05	Weld Defects
SURFACE CRACK: (semi-elliptical), possible stress corrosion entered into this failure in service.									
9	Bridge	A517H Steel	758	179	0.24	38	61	~1.0	Weld Defects
SURFACE CRACK: (1/4-circular/corner), bad design detail; failed in service.									

* Handbook value.

† Failure assumed to occur at $K_I = K_{IC}$, unknown operating stress calculated accordingly.

‡ Structural integrity maintained.

** Failure assumed to occur at $K_I = K_{IC}$, unknown fracture toughness calculated accordingly.

\+ Critical situation deemed to be fatigue crack initiation. Tabulated K_c is ΔK (threshold).

□ Nominal stress and estimated residual stress.

\# Calculated from internal peak pressure.

○ Design stress; actual stress may exceed yield.

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[a] See next page for references used in generating Table 1.

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    b) "Fracture Mechanics Correlation Study on Cracked Aircraft Structures" by J. B. Chang
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    d) "Analysis of Heavy Lift Helicopter (HLH) Rotor Hub Lower Lug" by J. C. Zola
    e) "The Characterization of Crack Growth and Fracture in a Military Bridge" by N. J. Adams and D. Webber
    f) "Case Study in Utilization of Fracture Mechanics in the Failure Analysis of a Helicopter Float Cross Tube" by D. W. Hoeppner
    g) "Diesel Engine Crankshaft Failure" by L. P. Pook
    h) "Explosion of an Ammonia Pressure Vessel" by A. R. Rosenfield and C. N. Reid
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    b) "Analysis of Aileron Power Control Cylinder Service Failure" by R. J. Gran et al, as in (a)
    c) "Failure of Arizona Generator Rotor Forging" by S. Yukawa, D. P. Timio, A. Rubio, and C. Schabtach, E. L. Fogelman, A. W. Rankin, and D. H. Winnie
    d) "Failure of Pittsburgh Station Generator Rotor Forging" by S. Yukawa et al, as in (c)
    e) "Stress Corrosion Cracking Failure of the Point Pleasant Bridge" by J. A. Bennett and H. Midlin
    f) "Weld Cold Crack-Induced Failure of Kings Bridge, Melbourne, Australia" by R. Madison.

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will provide an accurate assessment of failure conditions only if all of the inputs are known accurately and the fracture toughness does not exhibit large scatter. In most cases there are deficiencies in one or more of the inputs; therefore, the correctness of the failure condition $K = K_{Ic}$ (K is the stress intensity at failure and K_{Ic} is the fracture toughness) cannot be tested closely. Either accurate inputs or canceling of errors should lead to a close correspondence between theory and experiment. However, it is not likely that errors will cancel in all cases and that there will be situations of apparent inequality, either $K > K_{Ic}$ (conservative result) or $K < K_{Ic}$ (nonconservative result). For example, in the 1978 compilation, ~60% of the analyses were accurate (to within ~10%), 25% were nonconservative, and 15% were conservative. One question to be addressed in this report is whether advances in the technology have changed significantly this accuracy estimate.

1.2.2 Fracture Toughness Variability

As noted previously, uncertainty in fracture toughness is probably the greatest impediment to improving the practical application of fracture mechanics. Ideally, it would be desirable to have a complete statistical evaluation of the properties of the material being investigated; however, this information is not generally available. The nearest approach to general agreement is for structural steels and weld metals in the ductile/brittle transition region, where a three-parameter Weibull distribution[3] is used,

$$F = 1 - \exp\{-[(K_{Ic} - K_1)/K_o]^4\} \quad . \qquad (1)$$

where F is the cumulative failure probability and K_1 and K_o are the fitting parameters.

Coefficients of variation (standard deviation/mean) for a variety of plates and weldments are given in Table 2. Although a complete survey of scatter is beyond the scope of this report, Table 2 is believed to be representative. Individual data sets for the MIL-HDBK-5E entries in this table are unique combinations of alloy designation, heat treatment, product form, and orientation, while the other high-strength-alloy entries are less restrictive. It appears that the typical coefficient of variation for handbook values of these materials is on the order of 10 to 20%, depending on how well they are characterized.

An analogous situation holds for upper-shelf toughness values for structural steels. Note that this section of the table includes J_{Ic} variability, which appears to be about twice that for K_{Ic}. For multiple base-plate data sets, the coefficient of variation of K_{Ic} is somewhat larger than 13%, compared with ~8% for single plates. Based on all of the upper-shelf data, a working hypothesis is that the coefficient for handbook values is also 10 to 20% for both plates and weld metals.

The first entry for the lower-shelf and transition regions of steel was calculated using Eq. (1), which represents a very large data base.[4] If the coefficient of variation of crack-tip-opening displacement (CTOD), in terms of which much of the weld data are reported, is also twice that of K_{Ic}, a typical value for K_{Ic} below the upper shelf would be on the order of 20% for both base plate and weld metal. The heat-affected-zone data exhibit an even larger coefficient of variation, but this class of material represents a very small fraction of the volume of any structure.

1.3 Safe Operation of Structures Containing Defects

In view of the scatter in toughness, it is necessary to determine the appropriate value for use in design and analysis. MIL-HDBK-5E (Ref. 5), which uses the term "allowables" to characterize desired combinations of probabilities and confidence levels of mechanical properties, unfortunately does not apply its complete analysis to fracture toughness. Conversely, the lower-bound approach of the *American Society of Mechanical Engineers ASME Boiler and Pressure Vessel Code*, which is used in the nuclear industry, treats fracture toughness but lacks statistical rigor.

Choosing the appropriate fracture-toughness value is important for engineering analysis of operating structures where cracks have been discovered. These analyses, which provide another approach to evaluating the accuracy of fracture-mechanics predictions, include residual-lifetime and fitness-for-purpose methods. The common thread in these techniques is a determination of whether the existing cracks will propagate catastrophically before the next scheduled inspection. Fitness-for-purpose is used in this report as a generic term to describe these approaches, which appear, from expert comments, to have developed more rapidly than has the application of fracture mechanics to failure analysis. Specifically, more attention is now given to the incorporation of fracture mechanics in design and inspection than was the case a decade ago.

Table 2 Variability in fracture toughness

Material	Coefficient of variation (%)			
	K_{Ic}	J_{Ic}	CTOD	Reference
	High-strength alloys[a]			
Aluminum-base alloys	3–33			5
Aluminum-base alloys[b]	8.9–10.4			5
Aluminum (7075-T6)	32			6
Steels	7–23			5
Steel (4340)	22			6
	Structural steels			
Upper-shelf region				
Base plate	7	13		7
Base plate		16		8
Base plate	8.8	15		9
Base plates[a]	>13[c]			10
Weldments[a]		>17[c]		11
Weldment	20.5	36		9
Lower-shelf and transition regions				
Base plates[a]			40[e]	2
Base plates and welds[a]	18–28[d]			3
Welds[a]	25	47		11
Weld HAZ[a]			50–75[f]	12

[a] Multiple lots of material; otherwise, single plates or weldments are reported.
[b] Data sets with >100 entries.
[c] Values at 100 to 150°C. Each entry is the coefficient of variation of means of multiple heats. The coefficients of the data sets are unknown but might not be very much larger.
[d] Based on the three-parameter Weibull distribution, with exponent = 4, variability arises from variation in the K_1:K_o ratio.
[e] Estimated.
[f] Estimate based on the tenth percentile of 485 tests.

As an example of fitness-for-purpose, Tait and Spencer[13] analyzed a pipeline containing 1- to 2-mm weld defects. They concluded that these defects would cause failure only if the pipe was not stress relieved; full stress relief would increase the critical crack size to several meters. Based on these calculations, the pipeline operator avoided an extremely expensive repair. Because of examples such as this, savings claims in excess of $2.5 billion have been reported for the fitness-for-purpose approach.[14] Interest in such analyses and the opportunity to provide a separate estimate of the limiting value of stress intensity for safe operation led to the inclusion of four fitness-for-purpose cases in this study.

2 Methodology

Case studies were limited to those reported in the past 10 years (1980–1990) to provide a survey of recent technology. While three-quarters of the studies in this report were published between 1986 and 1989, the date of occurrence is unknown for almost all of the failures. It is also not possible to state how representative these studies are, because many cases are never reported publicly due to litigation and other considerations. Indeed, it was not possible to obtain any unpublished case studies for this report due to an apparently increased reluctance to reveal details of service failures.

Laboratory tests were excluded from this report because they contain a degree of control over variables that is not possible in the field. Thus, all of the cases involved actual structures or components, with emphasis on locating reports of brittle fracture of pressure vessels.

A form was prepared to organize the data consistently. In addition to describing the component, operating conditions, cause of failure, and bibliographic information, space was provided for the following key numerical inputs:

- operating stress,
- residual stress,
- flaw size and shape, and
- fracture toughness.

The reported case studies were taken at face value because the data were used as published and without change. Values of K/K_{Ic} and K_{Ic}/Y were calculated when not reported explicitly.

Some case studies, based on United Kingdom practice, provided neither K nor K_{Ic}. Instead, both the actual defect size and the critical defect size were reported. In these cases the K/K_{Ic} ratio was calculated as the ratio of the square roots of the two defect sizes if failure occurred by brittle fracture.

3 Results

The Appendix contains the individual forms used to report each of the case studies. About half of the cases involved pressurized components, including one nuclear incident (Case 3 is the rupture of a Zircaloy tube). In half of the cases the material was low- to medium-strength steel. The causes of failure varied over a wide range, including manufacturing defects, fatigue, and environmental degradation. One-quarter of the failures occurred in weldments. It is believed that these case studies, in aggregate, provide a reasonable picture of the state-of-the-art of fracture-mechanics-based failure analysis. However, this statement rests on the tacit assumption that published case studies are representative of fracture-mechanics-based failure analyses as a whole, an assumption that cannot be proven.

Quantitatively, the most striking feature of the analyses is the uncertainty in the inputs. In virtually every case there are assumptions, approximations, and data scatter. Some authors used handbook values, and some had so little information that the analyses are not of much value for generating conclusions. In some of these cases there is a spread in stress arising from uncertainty in residual stress.

The deficiencies in the case studies can be illustrated with some of the following randomly chosen examples:

Case No. 1 was a propane-tank explosion where the stress and strength of the weld were unknown and the range of fracture-toughness values for the weld varied by a factor of 2.

Case No. 3 involved the previously mentioned rupture of a Zircaloy reactor tube, with scatter reported in strength and toughness. Even though this was one of the most completely documented cases, the uncertainty in the $K = K_{Ic}$ criterion was ±20%, which is not surprising based on Table 2.

Case No. 8 was a powder-pressing die where the operating stress had to be estimated.

Case No. 10 was failure of a centrifugal fan in which the strength of the material was unknown and there was typical scatter in the fracture-toughness value.

Because of these data deficiencies, it is difficult to evaluate the applicability of fracture mechanics with a high degree of certainty, as can be seen in Table 3, which summarizes the estimated values for the key properties. Because slightly different pictures emerge from the failures and from the fitness-for-purpose cases, the two groups are discussed separately.

The failures tended to have common characteristics, with a predominance of large cracks (>25-mm maximum dimension), low operating stresses (less than half of the yield

Table 3 Summary of post-1980 failure analyses

Case No.	a[a] (mm)	σ/Y	K_{Ic} (MPa•√m)	K_{Ic}/Y (√m)	K/K_{Ic}
			Failure analyses		
1	127	>0.11[b]	39–74	0.07–0.14	>0.2–0.4
2	108[c]	[d]	15	0.12	[d]
3	100	≈0.13	40–50	0.06–0.08	0.8–1.2
4	31[c]	0.63	88	0.10	>1.4
5	100	0.08	24	0.06	>1.1
6	31	0.22	30–35	0.06–0.07	0.8–1.1
7	[e]	0.46	11–33	0.01–0.02	[e]
8	1.2	0.26	22	0.01	1.0
9	400–450	0.23	50	0.15	0.2[f]
10	≫15	[g]	65	[g]	1.0–1.1
11	9.4	≈0.5	44–50	0.09–0.12	≈1.0
12	4.4	0.37	[h]	[h]	[h]
13	130	0.17–0.38	55–99	0.22 [illegible]	0.1–0.8
14	100	0.17–0.28	75–90	0.06–0.[illegible]	0.6–1.0
15	4(?)	[g]	40–50	[g]	1.4–1.8
16	18	1.0	53	0.23	0.7–0.8
			Fitness-for-purpose analyses[i]		
F1	997	0.14	40	0.14	0.4
F2	6–10	0.68–0.96	65	0.23	<0.5–1.3
F3	<30	[g]	70	[g]	<0.2
F4	8	0.53–0.69	45	0.09–0.10	0.5

[a] Maximum dimension of crack.
[b] Subsequent examination revealed that applied stress was unknown.
[c] Estimated.
[d] Stress and flaw size unknown.
[e] Flaw size unknown.
[f] Authors believe that unreasonable result is due to unknown residual stress and material inhomogeneity.
[g] Yield strength unknown.
[h] Fracture toughness unknown.
[i] Cracked structures operating safely.

strength), and low-to-moderate toughness values (<100 MPa•√m). The failures also tended to exhibit low K_{Ic}/Y ratios (<0.16 √m). In short, the situation is not appreciably different from that existing in 1978.

The K/K_{Ic} ratios at failure also appear to be consistent with the earlier study because there is no discernible bias toward conservatism or nonconservatism. Beyond this statement, no definite quantitative observations are possible. In fact, fewer of the failures occurred within 10% of K_{Ic} than was the case in 1978. The reason for this implied regression in technology is unknown but may be due to the limited data base and/or lack of progress in reducing scatter in K_{Ic}.

The fitness-for-purpose cases appear to have somewhat higher quality data than the failures. Three of these fitness-for-purpose cases suggest that safe operation is possible at and below 0.5 K_{Ic}, if conservatism is used in the choice of toughness level. These cases also suggest that safe operation can be achieved even when there are large cracks and low K_{Ic}/Y ratios, provided adequate care is taken. For example, two of the analyses (F2 and F3) recommend low pressures for cold startup of pressure vessels.

However, fitness-for-purpose analyses are also sensitive to the quality of their inputs. For example, a recent compilation of four independent fitness-for-purpose studies of irradiated reactor supports[15] showed that the individual authors employed K_{Ic} values that varied by a factor of 2.4, stress values that varied by a factor of 1.6, and calculated critical flaw sizes that varied by a factor of 5.2.

4 Discussion

Because failures by their very nature are unpredicted and uncontrolled, it is not surprising that their analyses contain ambiguities. As a result, it is also not surprising that no precise numerical conclusions can be made regarding the accuracy of fracture-mechanics predictions of failure loads. The uncertainty is compounded by the impossibility of knowing how representative are the reported case studies. While resolution of the representation issue is beyond the scope of this report, it should be considered seriously if these results are to be incorporated into the regulatory process.

Despite the issues raised in the preceding paragraph, the following data gathered for this report do allow for setting some ground rules in defining limits on operating stresses of structures containing flaws:

1. Detection of cracks is not an automatic reason to withdraw a structure from service. If the crack dimensions and geometry are known, it may be possible to adjust the stress and/or operating conditions and operate safely.
2. No safety analyses should be completely deterministic. Either upper and lower bounds must be set on the inputs (i.e., upper-bound stresses and crack sizes combined with lower-bound toughnesses) or data scatter must be specified statistically.
3. No-failure case studies, such as the fitness-for-purpose approach, can be as useful in setting limits on operating stress as can those that involve actual failures.

It is believed that these ground rules are not particularly controversial. Each of them either represents current engineering practice or has been widely discussed in the technical literature. The more difficult question is quantitative implementation. For example, Ref. 1 suggests that a safety factor be applied to fracture toughness as well as to yield stress. The specific suggestion for toughness was that $K_{Ic} \geq 2K$, and the more recent data contained in this report tend to support that suggestion. As discussed earlier, the reason for incorporating a safety factor is not an inherent inadequacy in fracture mechanics but a difficulty in evaluating the individual components of stress intensity and the actual value of toughness.

5 Conclusions

1. Although fracture mechanics analysis may be accurate in theory, in practice nonconservative predictions of failure load can occur because of the uncertainties in the inputs, particularly fracture toughness.
2. Two conditions that appear to require particular care, relative to the possible occurrence of fracture, are flaw sizes >25 mm and fracture-toughness:yield-strength ratios $<0.16 \sqrt{m}$.
3. It is not clear why no significant improvements in the accuracy of fracture-mechanics analyses of structural failures over the past 12 years have been made. However, some improvements in fracture-safe design and inspection have occurred.

6 References

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3. D. E. McCabe et al., "Investigation of the Bases for Use of the K_{Ic} Curve," presented at the ASME Pressure Vessel and Piping Conference, San Diego, Calif., June 1991.

4. K. Wallin, "Statistical Aspects of Constraint with Emphasis to Testing and Analysis of Laboratory Specimens in the Transition Region," presented at the ASTM Symposium on Constraint Effects in Fracture, Indianapolis, Ind., May 1991.

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7. D. J. Naus et al., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., "Crack Arrest Behavior in SEN Wide Plates of Quenched and Tempered A 533 Grade B Steel Tested Under Nonisothermal Conditions," USNRC Report NUREG/CR-4930 (ORNL-6388), August 1987.[†]

8. R. S. Gates et al., Central Electricity Generating Board Operating Engineering Division, "Statistical Analysis of Fracture Toughness Data," Report OED/STM/87/10125/N, December 1987.

9. J. L. Hawthorne and A. L. Hiser, Materials Engineering Associates, "Influence of Fluence Rate on Radiation-Induced Mechanical Property Changes in Reactor Pressure Vessel Steels," USNRC Report NUREG/CR-5493, March 1990.[†]

10. Y. Tanaka, T. Iwadate, and K. Suzuki, "Small Specimen Measurements of Dynamic Fracture Toughness of Heavy Section Steels for Nuclear Reactor Pressure Vessels," *Inter. J. Press. Vessels and Piping* 31, 221–236 (1988).[*]

11. H. A. Domian, "Vessel V-8 Repair and Preparation of Low Upper Shelf Weldment," USNRC Report NUREG/CR-2676, June 1982.[†]

12. D. P. Fairchild, "Fracture Toughness Testing of Weld Heat Affected Zones in Structural Steel," pp. 117–141 in *ASTM STP 1058* (1990).[*]

13. R. B. Tait and D. P. Spencer, "A Fitness for Purpose Evaluation of Pipe Weld Defects Using BS PD 6493," in *Fracture and Fracture Mechanic Case Studies*, R. B. Tait and G. G. Garrett, Eds. (Pergamon, Oxford, 1985), pp. 209–215.

14. J. D. Harrison, "The Economics of a Fitness-for-Purpose Approach to Weld Defects," paper 45 in *Fitness for Purpose Validation of Welded Construction*, Anon., Welding Institute, Cambridge (1982).

15. R. E. Lipinski and R. W. Garner, Idaho Natl. Engineering Lab., "Review of Current Literature Related to Generic Safety Issue 15," USNRC Report NUREG/CR-5556 (EGG-2598), June 1990.[†]

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[*] Available in public technical libraries.

[†] Available for purchase from National Technical Information Service, Springfield, VA 22161.

7 Additional Bibliography

In addition to the volumes cited in the case studies, the sources given below were searched. While they all contain much useful information on failure analysis, none report case studies involving fracture-mechanics evaluations.

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D. N. French, *Metallurgical Failures in Fossil-Fired Boilers*, Wiley, New York, 1983.

G. W. Powell et al., Eds., *Failure Analysis and Prevention, Metals Handbook*, Ninth ed., Vol. 11, ASM, Metals Park, Ohio (1986).

Praktische Metallographie, monthly journal in German and English (searched from 1978 to 1987).

C. R. Walker and K. K. Starr, *Failure Analysis Handbook*, Report WRDC-TR-89- 4060, AFSC, Wright-Paterson Air Force Base, Ohio, 1989.

D. J. Wulpi, Understanding How Components Fail, ASM, Metals Park, Ohio (1985).

Appendix

Summaries of Failure Analyses

This appendix contains the data summary sheets used in preparing this report. Case Studies 1–16 are actual failures, while F1–F4 are fitness-for-purpose analyses.

Log No. 1 Date: February 9, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Pressure vessel (propane tank)
Section size/shape	1680-mm OD, 12.1-mm wall thickness
Material	AISI 1030 steel, welded construction
Operating conditions	Ambient temperature, 1.48-MPa pressure
Cause of failure	Improper maintenance and operation
Consequences of failure	One death and considerable damage

Material properties

Yield strength, Y (MPa)	550 (est.)
Ultimate strength, U (MPa)	Unknown
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	39–74
Ductile-brittle transition	
Temperature (°C)	Unknown
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.071–0.135

Operating conditions

Operating stress, σ_o (MPa)	62
Residual stress, σ_R (MPa)	Unknown
Total stress, $\sigma_o + \sigma_R$ (MPa)	62 (min, see notes)
Temperature at failure (°C)	Unknown ambient

Flaw

Size (mm)	12.7 mm deep, 127 mm long (est. max.)
Shape	Elliptical surface

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	>13.1
K/K_{Ic}	>0.18–0.36
σ/σ_Y	>0.11

Notes: Properties are of weld representative of failure location; critical flaw was caused by stress-corrosion cracking; initial fracture-mechanics assessment indicated that the tank should have been safe; closer examination strongly indicated unintentional overloading.

Source of data: H. S. Pearson and R. G. Dooman, "Fracture Analysis of Propane Tank Explosion," ASTM STP 918, pp. 65–77, 1986.

Log No. 2 Date: March 2, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Cement tank hatch cover
Section size/shape	500 mm diam, 6.4 mm thickness/lenticular
Material	A 356-T6 aluminum
Operating conditions	Tank being depressurized
Cause of failure	Design and material inadequacies
Consequences of failure	Apparently minor

Material properties

Yield strength, Y (MPa)	131
Ultimate strength, U (MPa)	150
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	15.2
Ductile-brittle transition	
Temperature (°C)	N.A.
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.12

Operating conditions

Operating stress, σ_o (MPa)	Unknown
Residual stress, σ_R (MPa)	Unknown
Total stress, $\sigma_o + \sigma_R$ (MPa)	N.A.
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	Unknown (see notes)
Shape	Unknown (see notes)

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	Unknown (see notes)
K/K_{Ic}	N.A.
σ/σ_Y	N.A.

Notes: Stress corrosion cracking is likely cause of critical flaw; hatch cover that failed was lost but similar cover contained edge crack 108 mm deep, fracture mechanics analysis, using estimates of stress and flaw size, suggested that failure was plausible.

Source of data: M. T. Kaplan, T. Willis, and R. L. Barnett, "A Pressure Vessel Hatch Cover Failure: A Design Analysis," ASTM STP 918, pp. 46–64, 1986.

Log No. 3 Date: March 2, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Reactor pressure-vessel tube
Section size/shape	108-mm OD; 5-mm wall thickness
Material	Zircaloy-2
Operating conditions	240–290°C, heavy water
Cause of failure	Improper construction or operation leading to hydrogen pickup
Consequences of failure	Reactor shutdown

Material properties

Yield strength, Y (MPa)	662–719
Ultimate strength, U (MPa)	Unknown
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	40–50
Ductile-brittle transition	
Temperature (°C)	260
Criterion	Critical crack length vs temperature
K_{Ic}/Y ($\sqrt{m}$)	0.06–0.08

Operating conditions

Operating stress, σ_o (MPa)	90
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	90
Temperature at failure (°C)	240–290

Flaw

Size (mm)	100 mm long × c. 4.5 mm deep
Shape	Surface elliptical

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	40–50
K/K_{Ic}	c. 0.8–1.2
σ/σ_Y	c. 0.13

Notes: As a result of the failure, Zircaloy-2 was replaced by Zr–2.5 Nb to reduce hydrogen pickup.

Source of data: C. A. Chow and C. A. Simpson, "Analysis of the Unstable Fracture of a Reactor Pressure Tube Using Fracture Toughness Mapping," ASTM STP 918, pp. 78–101, 1986.

Log No. 4 Date: March 2, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Compressor wheel
Section size/shape	965 mm diam by 82.6–101.6 thickness/cylinder
Material	AISI 4140 steel
Operating conditions	15 min after startup; operating temperature = 288°C
Cause of failure	Quench cracks plus fatigue
Consequences of failure	Turbine shutdown and wheel replacement

Material properties

Yield strength, Y (MPa)	844
Ultimate strength, U (MPa)	1020
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	88
Ductile-brittle transition	
Temperature (°C)	Unknown
Criterion	Unknown
K_{Ic}/Y ($\sqrt{m}$)	0.10

Operating conditions

Operating stress, σ_o (MPa)	533
Residual stress, σ_R (MPa)	None reported
Total stress, $\sigma_o + \sigma_R$ (MPa)	533
Temperature at failure (°C)	288 (?)

Flaw

Size (mm)	31 (?, see notes)
Shape	Quarter-elliptical corner crack

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	>120
K/K_{Ic}	>1.36
σ/σ_Y	0.63

Notes: Flaw size reported above was obtained via fractography and based upon the location of transition from mixed ductile/intergranular fracture to cleavage fracture. The authors do not clearly state how their fractography observations relate to the point of criticality.

Mechanical, thermal, and interference stresses are all present.

Source of data: R. Cippola, J. L. Glover, and R. H. Richman, "Analysis of a Compressor Wheel Failure," ASTM STP 918, pp. 181–210, 1986.

Log No. 5 Date: February 24, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Compressor blade
Section size/shape	1.7 m long; failure in shank, 152-mm diam × 229-mm length
Material	Aluminum 2014-T6
Operating conditions	High-speed rotation
Cause of failure	Fatigue
Consequences of failure	Not stated

Material properties

Yield strength, Y (MPa)	415 (Handbook)
Ultimate strength, U (MPa)	485 (Handbook)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	24
Ductile-brittle transition	
Temperature (°C)	N.A.
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.06

Operating conditions

Operating stress, σ_o (MPa)	34 (see notes)
Residual stress, σ_R (MPa)	Not stated
Total stress, $\sigma_o + \sigma_R$ (MPa)	34
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	100 (see notes)
Shape	Through crack growing in axial direction

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	>26 (see notes)
K/K_{Ic}	>1.1
σ/σ_Y	0.08

Notes: Initial defect was surface flaw 0.13 mm deep by 25 mm long. Similar scratches were detected on surfaces of other blades.

Tabulated critical flaw size corresponds to Stage II/III fatigue transition; operating stresses are cyclic values at Stage II/III transition.

Source of data: R. G. Hampton and H. G. Nelson, "Failure Analysis of a Large Wind Tunnel Compressor Blade," ASTM STP 918, pp. 153–180, 1986.

Log No. 6 Date: March 2, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Aircraft horizontal stabilizer
Section size/shape	46 mm × c.70 mm/rectangular section with extension arms
Material	Aluminum 7079-T6
Operating conditions	Intermittent cyclic loading
Cause of failure	Fatigue
Consequences of failure	Plane crash, six deaths

Material properties

Yield strength, Y (MPa)	470 (Handbook)
Ultimate strength, U (MPa)	535 (Handbook)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	30–35 (author estimate)
Ductile-brittle transition	
Temperature (°C)	N.A.
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.06–0.07

Operating conditions

Operating stress, σ_o (MPa)	104
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	104
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	31 (see notes)
Shape	Irregular quarter-circle corner crack

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	32
K/K_{Ic}	0.8–1.1
σ/σ_Y	0.22

Notes: Crack propagated by fatigue with occasional long jumps interspersed; analysis is of first long jump, which arrested due to load transfer.

The very irregular crack front makes the stress-intensity calculation extremely approximate.

Source of data: I. C. Howard, "Failure of an Aircraft Horizontal Stabilizer," ASTM STP 918, pp. 259–276, 1986.

Log No. 7 Date: March 1, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Swaging die
Section size/shape	Split block with 44-mm-diam cylindrical hole
Material	Tool steel, S2
Operating conditions	First load application
Cause of failure	Material toughness too low
Consequences of failure	Not stated
Material properties	
Yield strength, Y (MPa)	2000
Ultimate strength, U (MPa)	N.A.
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	11–33 (author estimate)
Ductile-brittle transition	
Temperature (°C)	N.A.
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.01–0.02
Operating conditions	
Operating stress, σ_o (MPa)	912
Residual stress, σ_R (MPa)	Not stated
Total suess, $\sigma_o + \sigma_R$ (MPa)	912
Temperature at failure (°C)	Ambient
Flaw	
Size (mm)	(See notes)
Shape	(See notes)
Fracture-mechanics analysis	
Stress intensity, K (MPa•$\sqrt{m}$)	Unknown
K/K_{Ic}	Unknown
σ/σ_Y	0.46

Notes: Inner surface of die was harder and more brittle than interior of block due to low hardenability. The critical flaw was too small to be detected by the techniques used.

Source of data T. P. Rich and J. P. Orbison, "Analysis of Two Metal-Forming Die Failures," ASTM STP 918, pp. 311–335, 1986.

Log No. 8 Date: March 4, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Powder-pressing die
Section size/shape	12.8-mm-ID × 76-mm-OD/cylinder
Material	Cr steel, medium C
Operating conditions	630-MPa internal pressurization
Cause of failure	Low toughness, possible hydrogen embrittlement
Consequences of failure	Not stated

Material properties

Yield strength, Y (MPa)	2000
Ultimate strength, U (MPa)	Unknown
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	22
Ductile-brittle transition	
Temperature (°C)	Unknown
Criterion	Unknown
K_{Ic}/Y ($\sqrt{m}$)	0.01

Operating conditions

Operating stress, σ_o (MPa)	505 (see notes)
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	505
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	1.2
Shape	Semicircular surface

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	23
K/K_{Ic}	1.0
σ/σ_Y	0.26

Notes: Failure stress is rough estimate.

Source of data: R. W. Hertzberg, "Deformation and Fracture of Engineering Materials," 3rd ed., Wylie, New York, pp. 640–642, 1989.

Log No. 9 Date: March 8, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Liquid propane gas cylinder
Section size/shape	1.28-m-long × 336-mm-OD × 3.3-mm-thick/cylinder
Material	Plain carbon steel
Operating conditions	1.38-MPa pressure
Cause of failure	Manufacturing defect
Consequences of failure	Multiple failures; consequences not stated

Material properties

Yield strength, Y (MPa)	335
Ultimate strength, U (MPa)	492 (see notes)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	50 (see notes)
Ductile-brittle transition	
Temperature (°C)	Not stated
Criterion	Not stated
K_{Ic}/Y ($\sqrt{m}$)	0.15

Operating conditions

Operating stress, σ_o (MPa)	78
Residual stress, σ_R (MPa)	Unknown
Total stress, $\sigma_o + \sigma_R$ (MPa)	See notes
Temperature at failure (°C)	Not stated

Flaw

Size (mm)	400-450 long × 1.3 deep
Shape	Elliptical surface

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	11
K/K_{Ic}	0.22
σ/σ_Y	0.23

Notes: Steel near failure was harder than away from failure.

Toughness data is from one specimen only; two other specimens failed by ductile fracture.

Authors suggest that discrepancy between K and K_{Ic} is due to unknown residual stress and local embrittlement associated with insufficient postweld annealing.

Source of data: K. Mogami et al., "Failure Analysis of a Liquid Propane Gas Cylinder," V. S. Goel, ed., *Analyzing Failures*, ASM, Metals Park, Ohio, pp. 75–80, 1988.

Log No. 10 Date: March 9, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Large centrifugal fan
Section size/shape	Rectangular cross section/size not given
Material	Low C, medium-strength steel
Operating conditions	Power plant, temperature varies from 0 to 40°C
Cause of failure	Fatigue
Consequences of failure	Not stated

Material properties

Yield strength, Y (MPa)	Unknown
Ultimate strength, U (MPa)	Unknown
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	65 ± 9
Ductile-brittle transition	
Temperature (°C)	53
Criterion	Not stated
K_{Ic}/Y ($\sqrt{m}$)	Unknown

Operating conditions

Operating stress, σ_o (MPa)	160–170 (see notes)
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	160–170 (see notes)
Temperature at failure (°C)	Within operating range of 9–40°C

Flaw

Size (mm)	15 mm long × 1.8 mm deep (see notes)
Shape	Semielliptical surface

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	Not stated
K/K_{Ic}	1.0–1.1 (see notes)
σ/σ_Y	Unknown

Notes: Final flaw size not stated; photograph in text suggests that unstable growth initiated when crack length was six to seven times as large as that of original flaw.

Reported operating stress is sum of finite-element calculation of steady-state stress plus one-half of cyclic stress deduced from fatigue striation measurements. K/K_{Ic} ratio can be calculated because authors state that peak failure stress would be 156 MPa if $K = K_{Ic}$

Source of data: R. B. Tait, G. G. Garrett, and D. P. Spencer, "Failure Analysis of a Large Centrifugal Blower," V. S. Goel, Ed., *Analyzing Failures*, ASM, Metals Park, Ohio, pp. 37–41, 1988.

Log No. 11 Date: March 10, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Bridge flange
Section size/shape	70 mm thick × 80 mm wide/plate
Material	ASTM A588 steel
Operating conditions	Relevant State and Federal Regulations
Cause of failure	Probable pre-existing defect
Consequences of failure	Bridge out of service for 1 year

Material properties

Yield strength, Y (MPa)	403–469
Ultimate strength, U (MPa)	622–710
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	44–50
Ductile-brittle transition	
Temperature (°C)	>4 (see notes)
Criterion	Charpy test
K_{Ic}/Y ($\sqrt{m}$)	0.09–0.12

Operating conditions

Operating stress, σ_o (MPa)	227 (see notes)
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	227 (see notes)
Temperature at failure (°C)	Unknown, crack discovered in May

Flaw

Size (mm)	9.4 mm deep
Shape	Not stated

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	c. 45
K/K_{Ic}	c. 1.0
σ/σ_Y	c. 0.5

Notes: Load transfer prevented bridge collapse.

Charpy data exhibit extreme scatter at some locations within plate and extreme point-to-point variability. Numerous specimens did not meet specification (41 J at 4°C).

Basis for operating stress estimate is not clearly stated.

Source of data: J. M. Hanson, M. J. Koob, and G. T. Blake, "Tie Girder Fracture in Siouxlands Veterans Memorial Bridge," *Transportation Research Record* [1180], pp. 33–39, 1988.

Log No. 12

Date: March 13, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Natural gas pipeline
Section size/shape	760 mm O.D. × 9.5 mm thick/cylinder
Material	Plain carbon steel
Operating conditions	152-MPa pressure
Cause of failure	Stress-corrosion cracking or hydrogen embrittlement at a local hard spot
Consequences of failure	Explosion and fire

Material properties

Yield strength, Y (MPa)	414 (see notes)
Ultimate strength, U (MPa)	597 (see notes)
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	Unknown (see notes)
Ductile-brittle transition	
Temperature (°C)	Unknown
Criterion	Unknown
K_{Ic}/Y ($\sqrt{m}$)	Unknown

Operating conditions

Operating stress, σ_o (MPa)	152
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	152
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	4.2 mm wide × 4.4 mm deep
Shape	Semielliptical surface

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	29
K/K_{Ic}	Unknown
σ/σ_Y	0.37 (see notes)

Notes: Fire caused local heat treatment of steel, making properties difficult to estimate. Tabulated strengths are for undamaged pipeline. Author suggests that the failure origin was at a hard spot whose ultimate strength was 1860 MPa before the fire.

Source of data: W. L. Bradley, "Application of Fracture Mechanics to Pipeline Failure Analysis," V. S. Goel, Ed., *Analyzing Failures*, ASM, Metals Park, Ohio, pp. 173–184, 1988.

Log No. 13

Date: March 23, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Pressure vessel
Section size/shape	2.5 m diam × 12 mm thick/domed vessel
Material	Low carbon steel
Operating conditions	Temperature = –130°C
Cause of failure	Stress corrosion
Consequences of failure	Loss of vessel

Material properties

Yield strength, Y (MPa)	250–320 (see notes)
Ultimate strength, U (MPa)	Unknown
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	55–99 (see notes)
Ductile-brittle transition	
Temperature (°C)	>–130
Criterion	Brittle fracture of vessel
K_{Ic}/Y ($\sqrt{m}$)	0.22–0.31

Operating conditions

Operating stress, σ_0 (MPa)	80
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_0 + \sigma_R$ (MPa)	80
Temperature at failure (°C)	–130

Flaw

Size (mm)	40 to 130 mm long (est.)
Shape	Through wall

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	14–45
K/K_{Ic}	0.14–0.82 (see notes)
σ/σ_Y	0.17–0.38

Notes: Strength estimated from Ref. 3 of paper; fracture toughness estimated from crack-opening displacement; authors state that British Standard PD6943 provides correct prediction of critical flaw size. Insufficient information is given to validate this statement.

Source of data: R. B. Tait et al., "A Fracture Mechanics Based Failure Analysis of Cold Service Pressure Vessel," V. S. Goel, Ed., *Analyzing Failures*, ASM, Metals Park, Ohio, pp. 43–46, 1988.

Log No. 14 Date: March 31, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Hydraulic clamp
Section size/shape	43- × 100-mm rectangular cross section
Material	Quenched and tempered steel
Operating conditions	Periodic clamping and release
Cause of failure	Fatigue plus localized heating due to wear
Consequences of failure	Prototype failure and redesign
Material properties	
Yield strength, Y (MPa)	1300 (see notes)
Ultimate strength, U (MPa)	1550 (see notes)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	75–90 (see notes)
Ductile-brittle transition	
Temperature (°C)	Unknown
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.06–0.07
Operating conditions	
Operating stress, σ_o (MPa)	220–370 (see notes)
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	220 –370
Temperature at failure (°C)	Ambient
Flaw	
Size (mm)	20 mm deep × 100 mm wide
Shape	Semielliptical surface
Fracture-mechanics analysis	
Stress intensity, K (MPa•$\sqrt{m}$)	53–89
K/K_{Ic}	0.6–1.0
σ/σ_Y	0.17–0.28

Notes: Overheated material near bearing surface had softened somewhat by localized tempering. The higher value of toughness results from a high stress intensity during fatigue crack propagation. The lower estimate of stress is estimated from fatigue-striation spacing; the higher value is from an approximate stress analysis.

Source of data: G. G. Garrett, "Wear-Induced Fatigue Failure and the Prediction of Critical Flaw Sizes in Service Components," pp. 125–153 in *Fracture and Fracture Mechanics Case Studies*, R. B. Tait and G. G. Garrett, Eds., Pergamon, Oxford, 1985.

Log No. 15 Date: March 31, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Ammonia pressure vessel
Section size/shape	7 m long × 1 m ID × 62 mm t/cylinder
Material	Mn-Ni-Mo steel
Operating conditions	30-MPa pressure
Cause of failure	Hydrogen embrittlement
Consequences of failure	Vessel completely destroyed

Material properties

Yield strength, Y (MPa)	<1160 (see notes)
Ultimate strength, U (MPa)	c. 1160 (see notes)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	40–50 (see notes)
Ductile-brittle transition	
Temperature (°C)	90
Criterion	40-J Charpy impact energy
K_{Ic}/Y ($\sqrt{m}$)	>0.04

Operating conditions

Operating stress, σ_o (MPa)	256
Residual stress, σ_R (MPa)	Unknown
Total stress, $\sigma_o + \sigma_R$ (MPa)	256 (est.)
Temperature at failure (°C)	25

Flaw

Size (mm)	4 mm deep
Shape	Thumbnail

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	70 (see notes)
K/K_{Ic}	1.4–1.75
σ/σ_Y	Unknown

Notes: Reported toughness is that of base metal; fracture initiated in weld HAZ of unknown toughness. HAZ had Vickers hardness of 353, which was used to estimate an upper bound on strength.

Source of data: J. D. Harrison, S. G. Garwood, and M. J. Dawes, "Case Studies and Failure Prevention in the Petrochemical and Offshore Industries," pp. 281–295 in *Fracture and Fracture Mechanics Case Studies*, R. B. Tait and G. G. Garrett, Eds., Pergamon, Oxford, 1985.

Log No. 16 Date: May 14, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Oil storage tank
Section size/shape	36.6 m diam; wall thickness 21.4 mm at bottom where failure occurred
Material	Plain carbon steel
Operating conditions	14.6-m head of diesel oil
Cause of failure	Pre-existing flaw; high NDT; embrittled flaw-tip region
Consequences of failure	Extensive oil spill into major rivers

Material properties

Yield strength, Y (MPa)	235
Ultimate strength, U (MPa)	455
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	53
Ductile-brittle transition	53 (lowest measured value; see notes)
Temperature (°C)	10
Criterion	NDT
K_{Ic}/Y ($\sqrt{m}$)	0.23

Operating conditions

Operating stress, σ_o (MPa)	82
Residual stress, σ_R (MPa)	153 (estimated maximum near weld)
Total stress, $\sigma_o + \sigma_R$ (MPa)	235 (est.)
Temperature at failure (°C)	3

Flaw

Size (mm)	Maximum dimension c. 18
Shape	Irregular, mostly subsurface

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	35–40
K/K_{Ic}	0.66–0.75 (see notes)
σ/σ_Y	1.0 (est.)

Notes: Base metal toughness ≈206 MPa$\cdot\sqrt{m}$ was decreased in the laboratory to ≤53 MPa$\cdot\sqrt{m}$ by introducing a weld close to a small flaw. Toughness loss is believed to be caused by strain-aging embrittlement. Actual toughness is believed to be even lower due to higher constraint and more extensive embrittlement in the actual vessel compared to the test specimen.

Source of data: R. E. Mesloh et al., "Failure Investigation of Ashland Oil Tank No. 1338 at Floreffe, Pennsylvania," Battelle Summary Report to Ashland Petroleum Co., June 17, 1988.

Log No. F1* Date: March 31, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Machine housing (see notes)
Section size/shape	997 mm thick/irregular cross section
Material	Cast steel
Operating conditions	Vibrating load
Cause of defect	Fatigue

Material properties

Yield strength, Y (MPa)	280
Ultimate strength, U (MPa)	500–550
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	40
Ductile-brittle transition	
Temperature (°C)	Not reported
Criterion	Not reported
K_{Ic}/Y ($\sqrt{m}$)	0.14

Operating conditions

Operating stress, σ_o (MPa)	52.5
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	52.5
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	997 mm wide × up to 30 mm deep
Shape	Irregular surface

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	18
K/K_{Ic}	0.44
σ/σ_Y	0.14

Notes: This is the second of two case studies reported in this paper; the first case has insufficient information.

Author implies that further operation of housing is risky.

Source of data: M. Maziarz, "Cracking of Large-Size Machine Elements," pp. 352–355, E. Czoboly, Ed., *Failure Analysis Theory and Practice*, EMAS, Warley, U.K., 1988.

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*No failure; analysis of a structure operating safely although containing a defect.

Log No. F2* Date: April 4, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Pressure vessel
Section size/shape	450 mm diam × 35 mm thick/cylinder (see notes)
Material	Carbon steel
Operating conditions	90-MPa pressure, "elevated" temperature
Cause of defect	Weld cracking

Material properties

Yield strength, Y (MPa)	281 (see notes)
Ultimate strength, U (MPa)	465 (see notes)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	65 at 10°C (see notes)
Ductile-brittle transition	
Temperature (°C)	5
Criterion	NDT
K_{Ic}/Y ($\sqrt{m}$)	0.23

Operating conditions

Operating stress, σ_o (MPa)	90
Residual stress, σ_R (MPa)	100–280
Total stress, $\sigma_o + \sigma_R$ (MPa)	190–270

Flaw

Size (mm)	6.4–10.4 (est.)
Shape	Not stated

Fracture-mechanics analysis

Stress intensity, K (MPa•$\sqrt{m}$)	Not stated
K/K_{Ic}	<0.48–1.27 (see notes)
σ/σ_Y	0.68–0.96

Notes: Flaws detected at fillet-weld attachment during in-service inspection. Operating stress is tabulated; investigators suggested that this stress could be maintained safely at elevated operating temperature but recommended lower pressures for cold startup and shutdown. Mechanical properties were measured on steel similar to that in the vessel. K/K_{Ic} was calculated from the square root of actual crack size to critical crack size.

Source of data: O. J. Dunmore and A. J. A. Parlane, "Fracture Mechanics Analysis of a Fillet Welded Attachment in a Pressure Vessel," paper 32, *Fitness for Purpose Validation of Welded Construction*, Welding Institute, Cambridge, 1982.

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*No failure; analysis of a structure operating safely although containing a defect.

Log No. F3[*] Date: April 6, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Pressure vessels (3)
Section size/shape	4 m diam × 40 mm t/cylinder
Material	Carbon steel
Operating conditions	28 bar at 110°C
Cause of defect	Stress corrosion

Material properties

Yield strength, Y (MPa)	Not stated
Ultimate strength, U (MPa)	Not stated
Fracture toughness, K_{Ic} (MPa$\cdot\sqrt{m}$)	70 at −20°C
Ductile-brittle transition	
Temperature (°C)	−16
Criterion	NDT
K_{Ic}/Y ($\sqrt{m}$)	Unknown

Operating conditions

Operating stress, σ_o (MPa)	145 (est.)
Residual stress, σ_R (MPa)	0
Total stress, $\sigma_o + \sigma_R$ (MPa)	145 (est.)
Temperature at failure (°C)	Ambient

Flaw

Size (mm)	<30
Shape	Corner

Fracture-mechanics analysis

Stress intensity, K (MPa$\cdot\sqrt{m}$)	Not stated
K/K_{Ic}	<0.24 (see notes)
σ/σ_Y	Unknown

Notes: Tabulated K/K_{Ic} value based on recommended startup pressure and ratio of largest possible crack size to critical crack size at −20°C.

Source of data: J. D. Harrison, "The Economics of a Fitness-for-Purpose Approach to Weld Defects," paper 45, *Fitness for Purpose Validation of Welded Construction*, Welding Institute, Cambridge, 1982.

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[*] No failure; analysis of a structure operating safely although containing a defect.

Log No. F4* Date: April 7, 1990

FAILURE ANALYSIS CASE STUDIES

Component or structure	Railway drawbar
Section size/shape	Size not stated/rectangular cross section of three-piece welded construction
Material	Carbon steel
Operating conditions	Variable tensile stress
Cause of defect	Weld defects plus fatigue
Material properties	
Yield strength, Y (MPa)	450–500 (dynamic)
Ultimate strength, U (MPa)	490 (static)
Fracture toughness, K_{Ic} (MPa•$\sqrt{m}$)	45
Ductile-brittle transition	
Temperature (°C)	Not stated
Criterion	N.A.
K_{Ic}/Y ($\sqrt{m}$)	0.09–0.10
Operating conditions	
Operating stress, σ_o (MPa)	165 (dynamic)
Residual stress, σ_R (MPa)	100 (est.)
Total stress, $\sigma_o + \sigma_R$ (MPa)	265 (est.)
Flaw	
Size (mm)	8 (maximum allowable, see notes)
Shape	Not stated
Fracture-mechanics analysis	
Stress intensity, K (MPa•$\sqrt{m}$)	Not stated
K/K_{Ic}	0.52 (see notes)
σ/σ_Y	0.53–0.59

Notes: Objective of study was to determine maximum allowable defect size for NDE; worst-case operating conditions were not chosen to determine defect size since they were considered only remotely possible; K/K_{Ic} is square root of ratio of allowable defect size to critical flaw size.

Source of data: R. A. Armstrong and D. F. Cannon, "The Determination of Acceptance Criteria for Flash Butt Welded Railway Drawbar," paper 7, *Fitness for Purpose Validation of Welded Construction*, Welding Institute, Cambridge, 1982.

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*No failure; analysis of a structure operating safely although containing a defect.

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11. ABSTRACT (200 words or less)

Twenty case studies involving the application of fracture mechanics to structural integrity have been reviewed and compared with a similar report published in 1978. Sixteen of the new cases discuss failures, while four are fitness-for-purpose analyses (i.e., evaluation of safe operating conditions of defect-containing structures).

Compared with the earlier study, no significant improvement in accuracy of failure analysis was detected. However, expert opinion suggests that there has been significant improvement in fitness-for-purpose analysis.

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