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Part 1

Introduction to Fracture Mechanics

by E. J. Ripling[1]

"It Ain't Necessarily So"

When structures fracture, it is due either to some combination of improper design, overloads, discontinuities in the structure that concentrate stresses at their edges or to the use of materials with inadequate fracture resistance. Yet when discontinuities are found in the fracture surface of broken members, all other possible reasons for the fracture are ignored, and it is frequently attributed solely to the existence of the discontinuity. Well, "it ain't necessarily so." Until recently, blaming all fracture on discontinuities was expedient since there was no quantitative way of knowing what were the major contributing factors to service fractures. Now, with the advent of fracture mechanics, fractures can be analyzed with a certainty never before possible. The concepts of this new discipline are described in this article.

WHY FRACTURE MECHANICS

Service fractures are almost always associated with a pre-existing crack or crack-like-discontinuity (CLD), see window on page 2. Yet many, if not most, structures contain cracks and/or CLD's that do not interfere with satisfactory operation over long lives, i.e., the CLD's are benign and have no effect on the safety or life of structures.

Obviously then, when a service fracture occurs, a way is needed to determine its main cause: was it the discontinuity, or did overloads, inadequate design or a poor choice of materials play the major role? Classical structural analysis methods can not address this question since they have no way to evaluate the effect of pre-existing discontinuities. They do give realistic predictions of structural stiffness and resistance to permanent deformation since these are not affected by small CLD's.

The best method for analyzing fractures is to use applied fracture mechanics. This is a powerful new tool that teaches us what combinations of CLD sizes and forces acting on the structure will exceed its resistance to cracking. Hence, for any structure and loading condition, it can identify the major contributing factor to fracture. Possibly even more important, it teaches designers and inspectors what size CLD separates a benign behavior from one that leads to fracture. This is especially important to the

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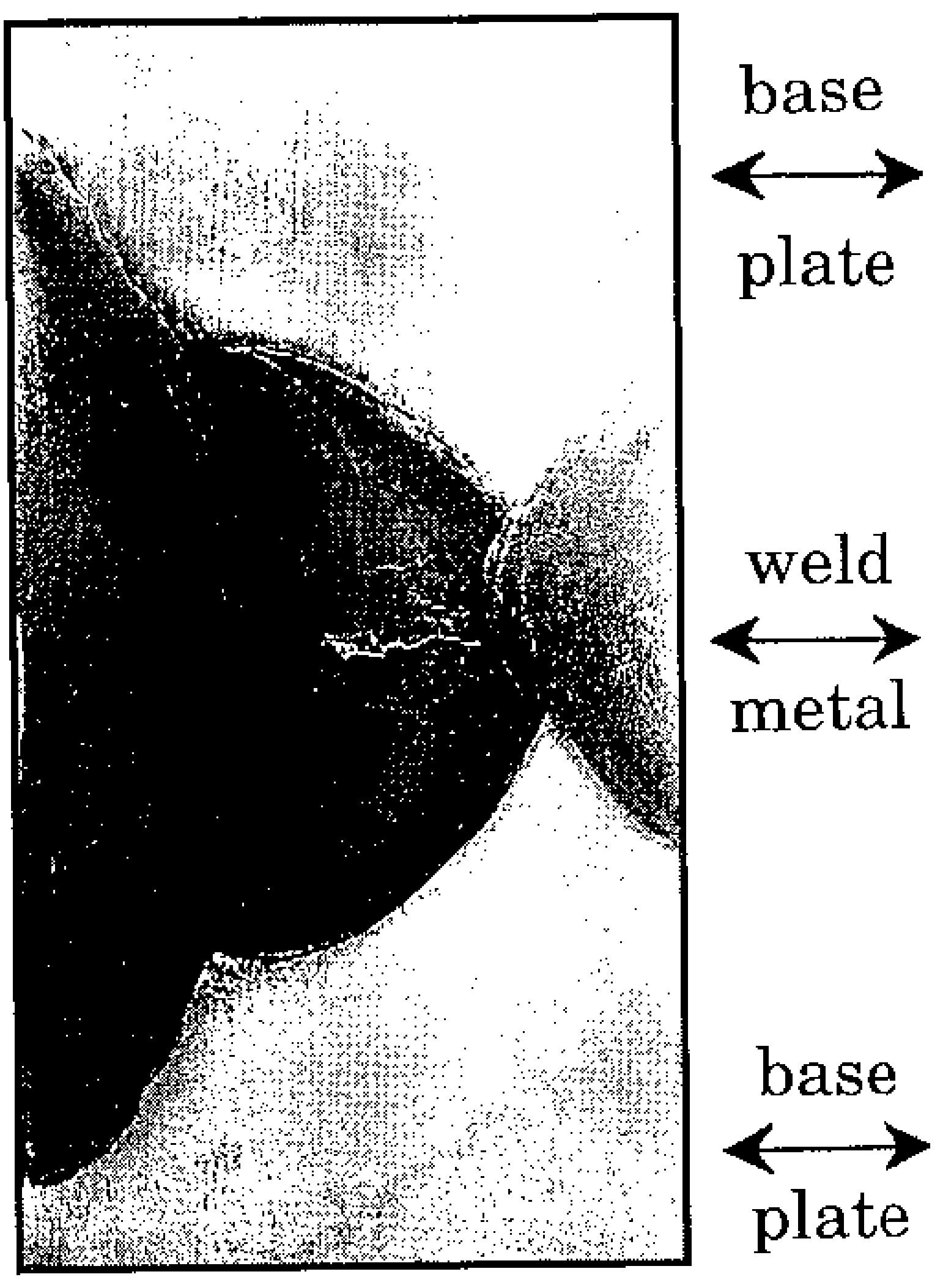
[1] The first article of a series contributed by E. J. Ripling, a leading authority in fracture mechanics. Dr. Ripling is President of Materials Research Laboratory, Inc., One Science Road, Glenwood, Illinois 60425; (708) 755-8760.

inspector: it tells him what size CLD is tolerable so that he can be certain that his inspection equipment has the required sensitivity. In some cases it also tells him at what intervals inspections should be made over the life of the structure.

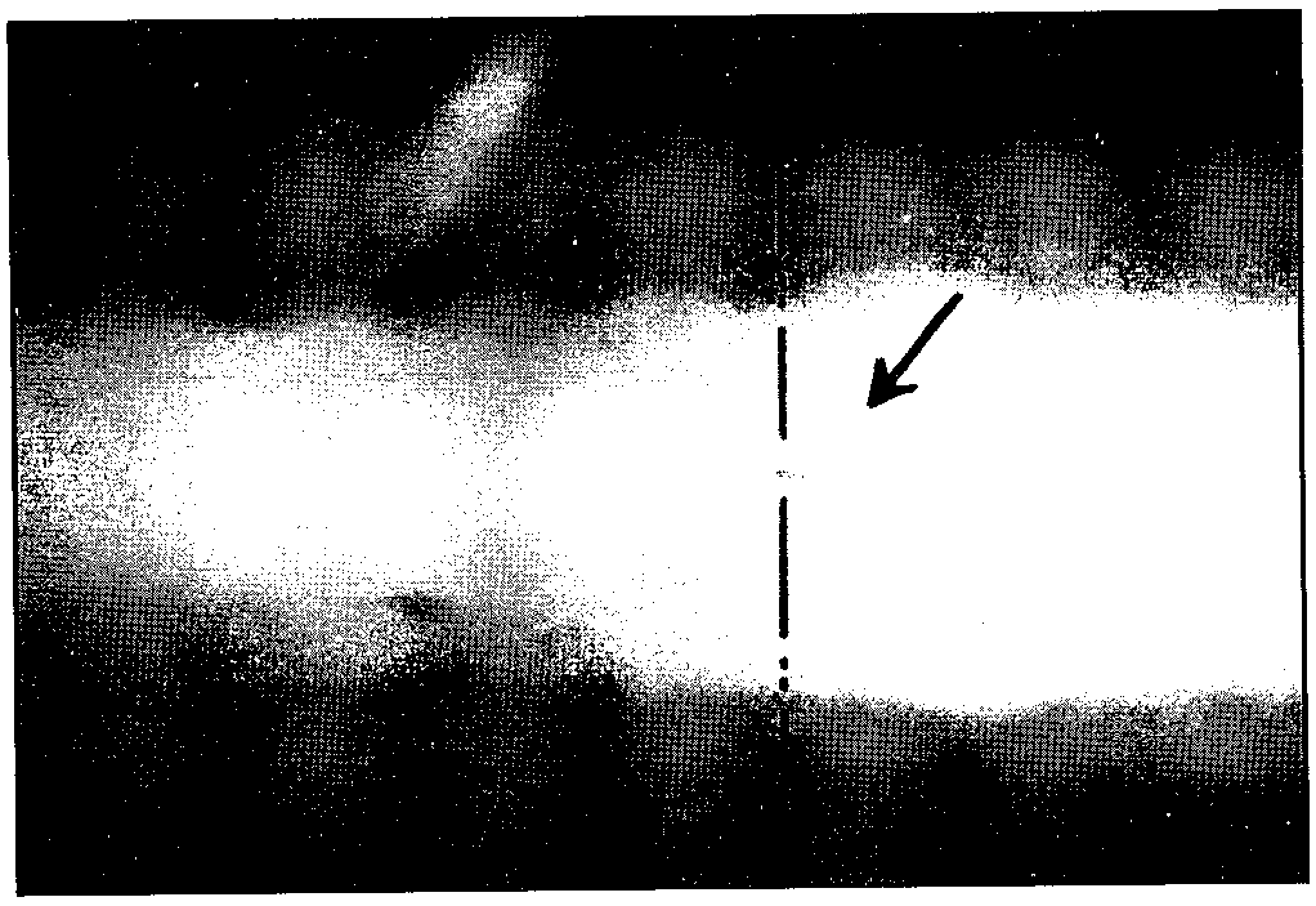
What is Fracture Mechanics?

Fracture mechanics is the newest branch of mechanics and is rapidly becoming one of the most useful. In spite of the fact that it is a relatively new science, its roots go back to work done about seven decades ago by A. A. Griffith, a British scientist, who was concerned with the difference between the actual and theoretically calculated strength of glass. He found that glass contains tiny cracks and when he calcu-

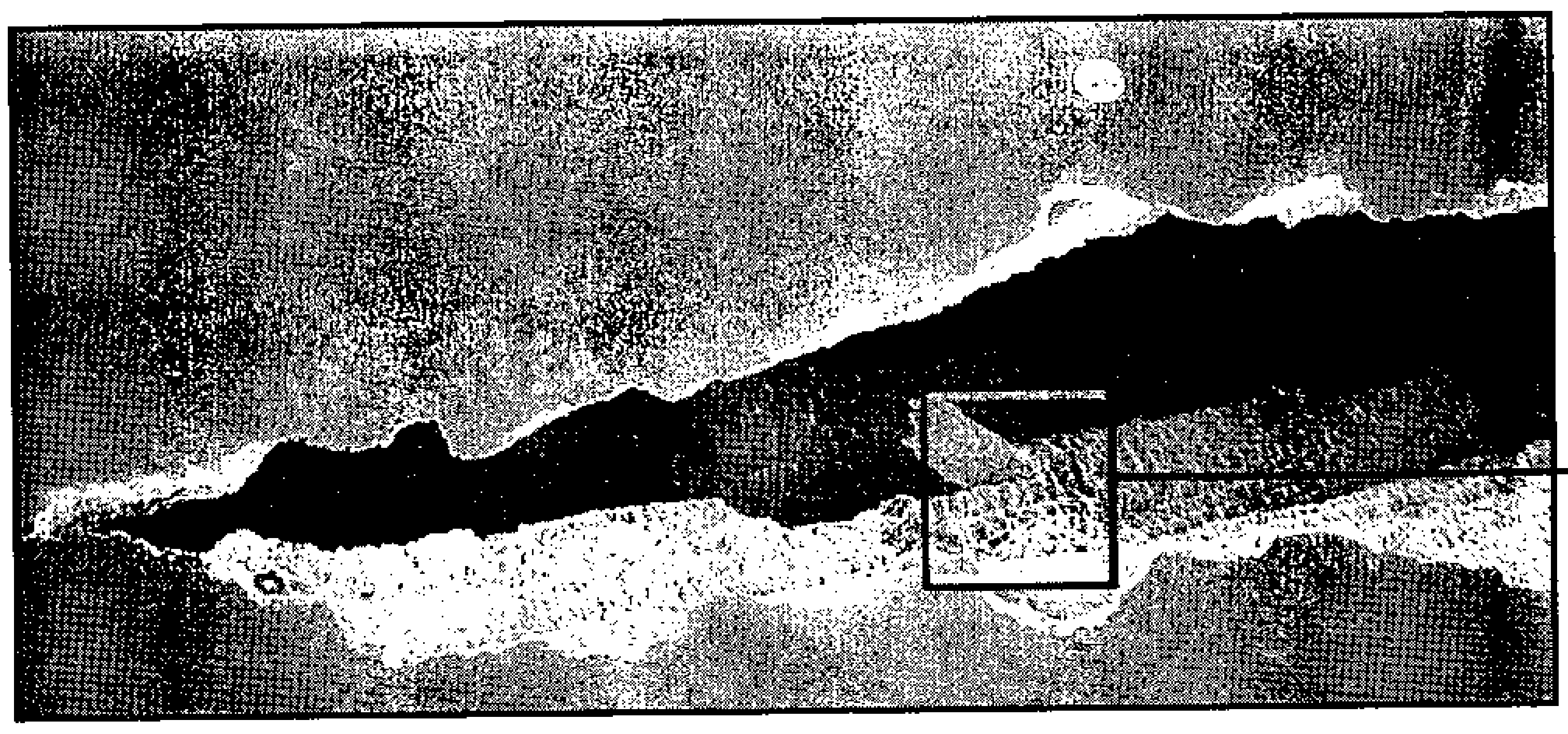
CRACK-LIKE DISCONTINUITIES



Cross-sectional view of weld after section was cut through CLD perpendicular to the weld.



Radiograph of a structural weldment showing a CLD indicated by arrow.



Scanning electron microscope photograph at a magnification of 50x looking down into the CLD.

Enlarged view (500x) of cavity shown in box on bottom left.

When a structure that appears to be operating satisfactorily suddenly breaks with a loud "bang," the fracture does not form instantaneously; rather, it starts in a small area and grows rapidly to form the catastrophic crack. The point at which the fracture started is almost always apparent because the markings on the fracture surface point to it. Examination of fracture surfaces show that the fracture initiator is almost always a pre-existing crack or crack-like discontinuity (CLD) that concentrates stresses at its edges. Some examples of CLD's are laps in forgings, cold-shuts in casting, and lack-of-fusion in weldments. A more complete description of CLD's can be found in handbooks on Fasteners, Forging, Casting and Welding.

Since CLD's are so important in fracturing, some features of a CLD that were found in radiographing a section of a welded structure are described below. A photograph of the radiographic film with the CLD indicated by an arrow is shown in the upper right. In order to find out what caused the CLD, a section containing the weld was cut out of the structure and a cut was then made through the CLD, perpendicular to the weld as shown by the dashed line in the film photograph. The weld cross-section was then polished and treated to make the weld metal conspicuous (top left photograph). The CLD marked with an arrow is the jagged cavity in the center of the weld. To determine what caused the CLD a scanning electron microscope with a magnification of 50X was used to look into the cavity (bottom left). An enlarged view of the boxed-in section of this photograph is shown in the bottom right. The walls of the cavity had an appearance similar to the rows of kernels on a corn cob. This is typical of shrinkage cavities that form when the deposited liquid weld metal changes to a solid. (The liquid, because of its lower density, takes up less space than the solid).

This CLD came out of a structure that performed satisfactorily for twenty years, after which it was dismantled because it was no longer needed. Obviously the CLD in no way interfered with the operation of the structure over its life.

lated its strength, allowing for the strength loss produced by the cracks, his measured and calculated strengths agreed. His work is now considered a classic in the field of fracture; not only did he point out the importance of subtle stress concentrations, in this case due to the small cracks, but he also showed how one can calculate the strength of flawed materials.

It was not until 1948 that two Americans, G. R. Irwin and E. Orowan, independently suggested that the Griffith procedure was not restricted to brittle materials like glass, but could be modified to be applicable to most materials, including metals and plastics. This was an important breakthrough since it was known at the time that fracturing almost always involves the presence of pre-existing cracks or CLD's. In some cases catastrophic cracks extend directly from the CLD. In most cases, however, a small crack extends from the CLD over a period of time. After this crack extends slowly to some critical size, it abruptly jumps ahead causing complete separation of the structure.

Classical methods are satisfactory for calculating the force or load needed to cause a structure to bend or otherwise deform because deformation resistance is dependent only on the stress to which the structure is subjected. (Stress is defined as force per unit of cross-sectional area, i.e., **S = F/A.**) To analyze the deformation resistance of a structure, one calculates the stresses acting in the structure, and compares this with data collected in laboratory tests that show how much stress the material can tolerate before it deforms excessively. If the stresses in the structure are less than the tolerable stress, the structure will not deform excessively during its life; if the reverse is true, it will. This kind of analysis is not significantly affected by the presence of small defects or cracks.

The reason these classical methods cannot be used to analyze flawed structures is that stresses concentrate near the edges of sharp-edged discontinuities or cracks. If one uses classical methods to calculate the magnitude of these concentrated stresses, unrealistically high values are obtained. Indeed, they are so high that even very small cracks would cause structures to break.

Engineers knew that in spite of these calculations many, if not most, structures performed satisfactorily in service even though they contained cracks or sharp-edged discontinuities. The problem they had was one of judging how serious they were. Although some took the viewpoint that the existence of any crack-like defect was sufficient to explain the fracture, the fact that many structures that performed satisfactorily in service contained crack-like defects could not be ignored. Since defects can be benign, it was important to be able to do quantitative calculations of their influence in order to know how material selection, design, fabrication quality and overstressing contributes to failures.

Knowing that fracture mechanics could answer these questions, engineers in the 1950s and 1960s began using it to get a better understanding of why structures break. Two of its first applications were to Polaris motor cases and turbine-rotor generators. Applications grew and broadened rapidly over the 1960s, 1970s and 1980s. At present, fracture mechanics concepts are used for materials selection and safety evaluation of nuclear reactor pressure vessels according to the ASME Code for Boilers and Pressure Vessels, in specifications for aircraft parts, and for many items used by the military, as well as for many structures, including bridges. They are also used to ascertain how proof tests should be conducted and to establish inspection requirements and inspection intervals for structures. Probabilistic fracture mechanics can be of value in making risk analyses.

Many technical societies, including the American Society for Metals, the American Society of Mechanical Engineers, and the Society for Experimental Mechanics, have divisions or other groups working on applying fracture mechanics to their industries. One of the most active committees of the American Society for Testing and Materials has been developing testing standards for measuring fracture mechanics properties of materials since the mid-sixties. Indeed, almost all fractures that result in deaths or injuries or in large amounts of property or environmental damage use the concepts of fracture mechanics in their investigations. The variety of parts on which it can be applied is enormous, from small fasteners to all sorts of vehicles to electric generating equipment.

Fracturing can occur very rapidly or slowly and it is convenient to describe these two types separately. Fast cracking generally leads to catastrophic fractures that occur with a loud noise and generally cause complete separation of the structure. Slow cracking occurs over the life of the structure and is frequently the mechanism by which pre-existing CLD's grow. Fast cracking is described in the remainder of this article and slow cracking will be discussed in a future article.

How Fracture Mechanics is Used to Analyze Fast Cracking

It was stated above that fracture mechanics is a branch of mechanics, and like all branches of this discipline, it is concerned with the reaction of "something" to a driving force. The thing that is driven in this case is the pre-existing crack or crack-like defect. Again like all other branches of mechanics, some way of describing the driving force is needed. One would expect that one component of the driving force is the load or stress acting on the member and it would also be expected that it is easier to extend a large crack than a small one since the amount of stress concentration produced by large cracks is greater than that produced by small ones. Hence, it is intuitively expected that some combination of stress and crack size would make up the driving force. The most common value used for driving force is the **stress-intensity factor**, designated by the letter "**K**". Its formal definition is:

$$\mathbf{K} = \mathbf{Y} \times \mathbf{S} \times \sqrt{\pi \times a}$$

where **Y** = shape factor for the crack and structure

S = stress

a = crack length

Notice that the units of **K** are stress times square root of length. This seemingly awkward dimension is necessary since the crack driving force involves both the stress and crack size. If a structure contains a crack, and the stress and/or the crack size is increased, **K** will increase; when **K** reaches its critical value, K_C, the crack will abruptly propagate. If the driving force in the structure is always less than K_C, the crack will not extend rapidly. K_C is a measure of a materials' crack resistance; it is referred to as the ***fracture toughness*** of the material, and its value is measured by a laboratory test of the material of interest.

Although K_C is the most commonly used parameter for characterizing fracture toughness, it cannot be used for very high toughness materials. Other material characterizations have been developed for these, but their description is beyond the scope of this paper.

The three factors, then, that determine whether or not fast fracturing occurs are the stress acting on the member (**S**), the crack size (*a*) and the material fracture

About the Author

E. J. Ripling is President and Director of Research of the Materials Research Laboratory, Inc. Over more than two decades in this position, he and his associates have helped pioneer the development of fracture mechanics. Dr. Ripling has applied fracture mechanics in the evaluation and improvement of structural safety for the U.S. Army, Navy, Air Force, the Nuclear Regulatory Commission, the Federal Highway Administration, NASA, the Electric Power Research Institute, and the Gas Research Institute. More recently, he has used fracture mechanics for forensic failure analysis. These studies have involved a wide range of structures, varying from small fasteners to rail car parts to large pressure vessels and bridges.

Dr. Ripling earned his Bachelor's degree in Metallurgy from the Pennsylvania State University and his Master's and doctoral degrees from Case Western Reserve University. He was elected a Fellow of the American Society for Metals, "For leadership in research on and intelligent use of fracture mechanics in understanding and solving brittle-material problems with ferrous and aluminum alloys." He was the 34th recipient of the David Ford McFarland Award from Pennsylvania State University, for Achievement in Metallurgy. He is listed in *Who's Who in Engineering*, *Who's Who in Technology*, and *American Men and Women of Science*.

Dr. Ripling has served on a number of advisory committees, including the National Materials Advisory Board Committees on Ship Materials, Fabrication and Inspection and on Materials Information Used in Computerized Structural Design and Manufacturing. He was Chairman of various Blue Ribbon Panels for Projectile Malfunction for the U.S. Army.

Dr. Ripling is co-author of a textbook, *Strength and Structure of Engineering Materials*, published in 1965 by Prentice-Hall, and is the author of more than seventy papers in scholarly journals.

toughness ($\mathbf{K_C}$). These three are simply related so that if two are known, the other can be calculated.

As an example of how a fracture analysis is made, consider a storage tank. Tanks are relatively simple structures having a smooth cylindrical shape; they may be loaded less than a few hundred times during their lives. Assume that the tank contains an initial part- through, fingernail-shaped crack as shown by the cross-hatched half-moon section in the left schematic drawing in Fig. 1. The pressure caused by the product contained in the tank causes tensile stresses to act in the wall of the tank as shown by the arrows acting on the tank wall in the drawing. These act everywhere in the tank wall, including across the plane of the tank containing the defect. As always happens when stresses act across a crack or discontinuity, they concentrate at the crack tip. The higher the wall stresses and/or the larger the crack, the higher is the stress intensity factor, **K**; i.e., the higher is the intensity of these stresses at the crack tip. As stated above, fast crack extension occurs if **K** reaches its critical value, $\mathbf{K_C}$.

As part of the fracture analysis, it is necessary to know $\mathbf{K_C}$ and this is obtained by a laboratory test of the material from which the tank is built. A specimen of the type that might be used for making this test is shown in the right-hand drawing of Fig. 1. In this case, the specimen consists of a rectangular cross-sectioned bar having a crack in it. The bar is pulled on its ends, at the temperature at which the tank operates, until it breaks. The crack size and stress at the moment of fracture are used to calculate $\mathbf{K_C}$ by means of an equation of the type previously shown.

The test specimen in Fig. 1b is schematically shown to be cut out of the cross-section of the tank containing the defect to emphasize that fracture mechanics is a modeling science. Obviously the specimen cannot be taken at this location since the piece is separated, but whenever possible, it is cut out of the structure near the fracture surface. In the storage tank or any other structure containing a crack-like defect, fracturing will or will not occur depending only on the intensity of crack tip stresses; hence, modeling the fracture process in any structure only need model the crack tip and all of the various types of fracture mechanics specimens are designed to do that. The specimen generally does not look like the structure, nor are the crack lengths or stresses the same. So long as the crack length and stress allow for a calculation of $\mathbf{K_C}$ in the specimen, the data are transferrable to the structure. A rather large number of specimen shapes have been developed and promulgated by ASTM Committee E24.

Any value of **K** or $\mathbf{K_C}$ represents an infinite combination of stresses and crack sizes as shown by the above equation. This relationship between stress and crack size for any given value of **K** can be represented by graphs of the type shown in Fig. 2. The two curves represent combinations of stresses and crack sizes that will give two different values of $\mathbf{K_C}$, where $\mathbf{K_C}$(2) represents a higher fracture toughness than $\mathbf{K_C}$(1). If the storage tank had a crack in it whose length was ***a*** and whose wall stress was **S**, the driving force or **K**-value associated with the crack would be given by the circled "**X**" in the graph. This crack would expand rapidly and cause catastrophic cracking if the walls had a fracture toughness of $\mathbf{K_C}$(1), but the crack would be benign if the walls had a toughness of $\mathbf{K_C}$(2). If the crack and/or the stress were larger, even toughness $\mathbf{K_C}$(2) might not have prevented the fracture.

Figure 2 can be used to describe the concept of ***flaw tolerant*** design. If the structure of concern, in this case a storage tank, is never subjected to a stress greater than S, and if after fabrication, the tank is inspected by a method that is certain to find any defects larger than ***a***, the tank is flaw tolerant if it is made of a material having a toughness of $\mathbf{K_C}$(2). If the toughness were given by $\mathbf{K_C}$(1), on the other hand, the tank could not be considered flaw tolerant. Actually, the toughness of materials used in construction varies and so do the stresses and temperatures to which they are subjected. Hence, flaw tolerant design may require the use of probabilistic fracture mechanics.

Although $\mathbf{K_C}$ is a material property, it is thickness dependent. If one tested a set of aluminum alloy plates and another set of steel plates, each set having a range of thicknesses, but all plates within a set being otherwise identical, the thick plates would have lower fracture toughnesses than the thin ones. The toughness of steel (but not most other metals) is also very sensitive to how fast it is loaded and the temperature at which it is loaded. Hence, in fracture toughness testing of steel plates or welds for bridges, the load applied to the test specimen is made to increase from zero to the fracture load in about one-second since this is the fastest loading rate that bridge members experience. Further, the plates are tested at the lowest temperature that is anticipated for the bridge which, of course, depends on where the bridge is located.

There are many uses for fracture mechanics in forensics. Probably the most common use is in postmortem examination of broken parts. It was stated earlier that crack size, *a*, stress, **S**, and fracture toughness, $\mathbf{K_C}$, were related, and if two are known, the third could be calculated. The initial pre-existing crack can frequently be seen on fracture surfaces so that its size can be measured. Likewise, the fracture toughness of the material, $\mathbf{K_C}$, can be measured so that the stress, and in turn, the force acting on the structure can be calculated. This can be used to ascertain whether or not an excessive force was acting on the structure at the time of fracture. The same procedure could be used to determine whether or not the structural material had adequate toughness for its intended service, and whether or not the product was seriously flawed before being put into service.

Another similar use might be for ascertaining which of a number of broken parts found at an accident site is the one that caused the accident and which broke after the accident due to momentary overloading.

SUMMARY

This first paper on Applied Fracture Mechanics pointed out that fracture mechanics is the only realistic way to analyze fracture, introduced some of the concepts of fracture mechanics, defined the crack driving force, K, and briefly described how fractures that occur due to a single load are analyzed. Future papers will discuss fatigue fracturing and stress corrosion cracking as well as fractures surface examination and its importance in understanding fractures. The manner in which postmortem failure analyses are conducted for forensic purposes, as well as some examples on which they have been used, will be discussed.

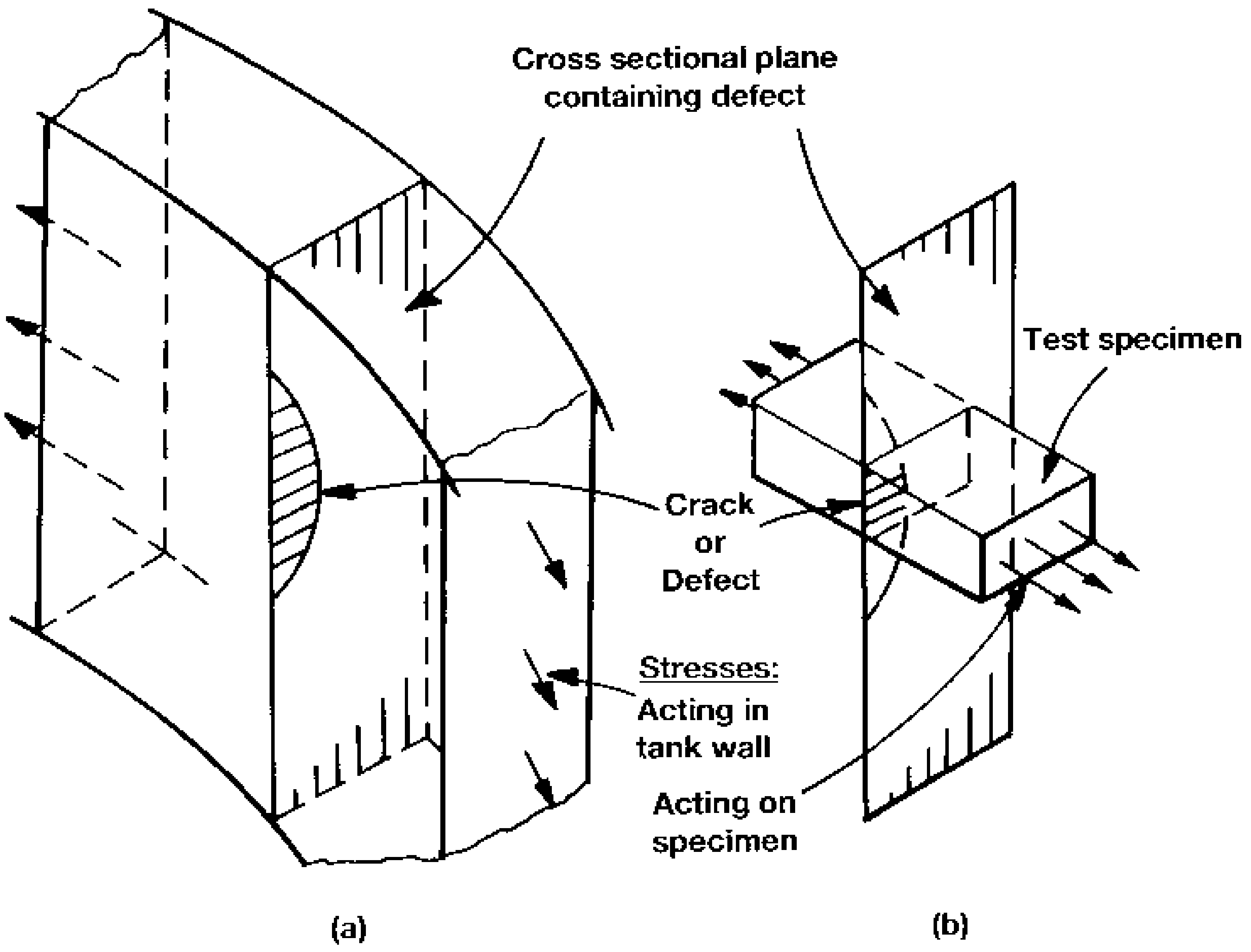


FIGURE 1 (a) Drawing of a section of a storage tank. Cut section shows defect in wall (circular cross-hatched section).
(b) Rectangular cross-sectioned specimen that models crack in tank.

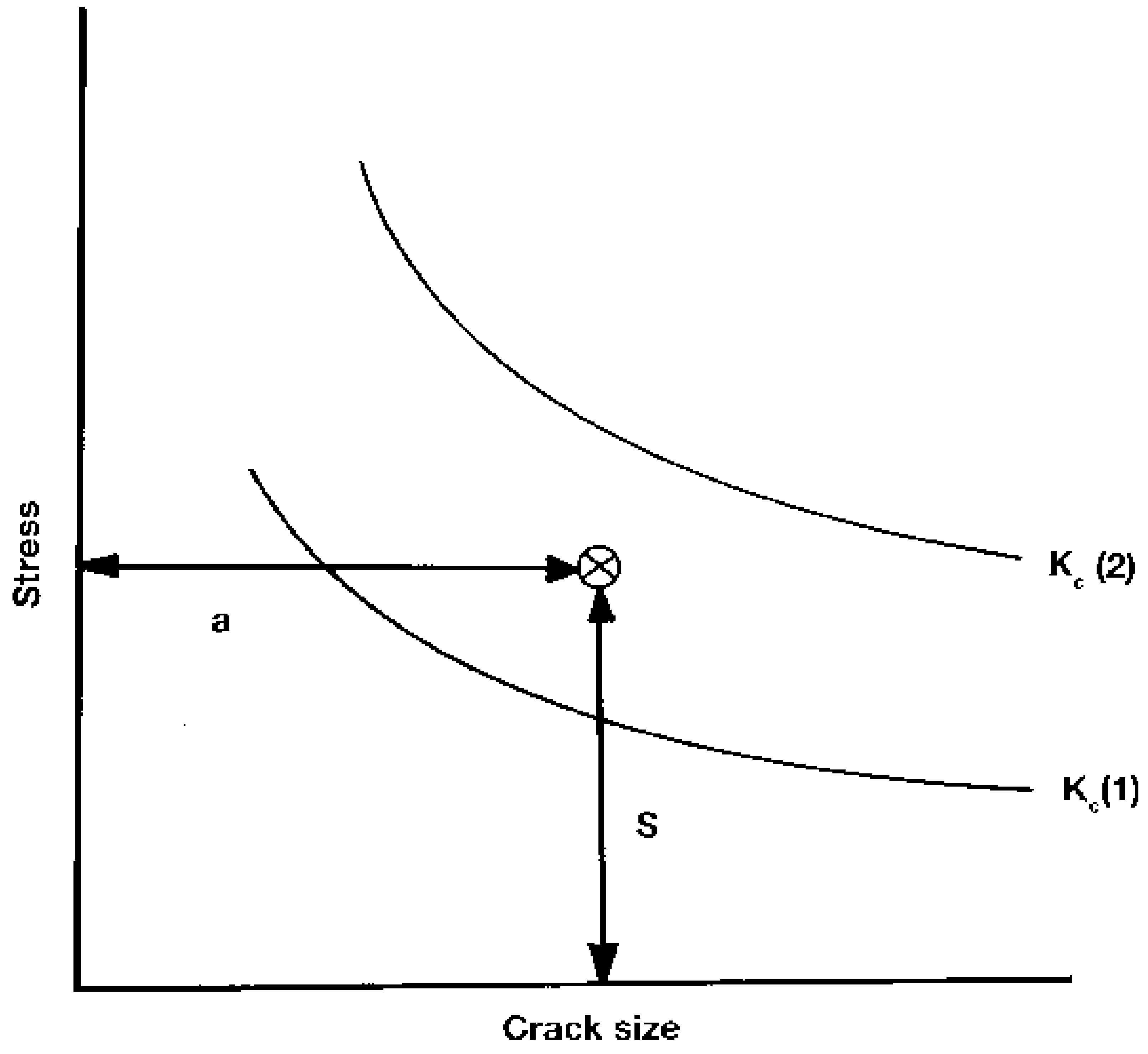


FIGURE 2 Constant K_c curves show all combinations of stresses and crack sizes that cause rapid cracking. $K_c(2)$ is a higher fracture toughness than $K_c(1)$ so that the combination of stresses and crack sizes needed to attain $K_c(2)$ is greater than for $K_c(1)$.

The definition of defective product in a state may be found in the case law of that state. In each issue we explore leading product liability case law from several states. Triodyne relies on the trial bar for selection of the cases cited.

MASSACHUSETTS

Back v. Wickes Corporation [375 Mass. 633, 378 N.E. 2d 964 (Massachusetts 1978)]

In this case the plaintiffs' four decedents died when the motor home in which they were riding caught fire and exploded after hitting a cable fence at the side of the highway. One additional plaintiff, a passing motorist, was injured during a rescue attempt. The plaintiffs brought a product liability action for defective design and breach of warranty against the manufacturer of the motor home (Wickes) and the manufacturer of the chassis (Chrysler).

The court held that amendments to the Massachusetts version of the Uniform Commercial Code make it clear that the legislature intended to transform warranty liability into a remedy fully as comprehensive as the strict liability theory of recovery embodied in the Second Restatement of Torts §402A (1965).

The court held that a merchant seller warrants that his goods are "fit for the ordinary purposes for which such goods are used." The "ordinary purposes" contemplated by M.G.L. c.106, §2-314(2)(c) include both those uses which the manufacturer intended and those which are reasonably foreseeable.

The court further held that a defendant manufacturer is not liable for the consequence of the unforeseeable misuse of a product and that warranty liability is not absolute liability. The manufacturer of a motor vehicle is not obliged to make its product collision-proof.

The court went on to say that in determining whether the design of the motor home was fit for its ordinary purposes, the jury must weigh competing factors much as they would when determining the fault of the manufacturer in a negligence case. The court said that the inquiry must focus on the product characteristics rather than on the defendant's conduct, but the nature of the decision is essentially the same.

In evaluating the adequacy of a product's design, the jury should consider, among other factors:

(1) the gravity of the danger posed by the challenged design;

(2) the likelihood that such danger would occur;

(3) the mechanical feasibility of a safer alternative design;

(4) the financial cost of an imposed design; and

(5) the adverse consequences to the product and to the consumer that would result from an alternative design.

Smith v. Ariens Company [375 Mass. 620, 377] N.E. 2d 954 (Massachusetts 1978)]

In this case the plaintiff was injured while operating a snowmobile manufactured by the defendant when the snowmobile hit a rock which was partially covered by snow. On impact, the right side of plaintiff's face hit a brake bracket which had two unshielded sharp metal protrusions on the handle bar. As a result of the injuries, the plaintiff required hospitalization and surgery.

The plaintiff brought a product liability action based on theory of negligent design and claimed, *inter alia*, that she sustained more severe injuries than she otherwise would have when the collision with the rock occurred.

The court held that a manufacturer has a duty to design products so that they are reasonably fit for the purposes for which they were intended. Such use should include foreseeable participation in collisions. Manufacturers have a duty to design products so that users are not subjected to unreasonable risks of injury in the event of a collision.

The court said "(w)here the injuries or enhanced injuries are due to the manufacturer's failure to use reasonable care to avoid subjecting the user of its products to an unreasonable risk of injury, general negligence principles should be applicable."

Uloth v. City Tank Corporation [376 Mass. 874 384 N.E. 2d. 1188 (1978)]

In this case the plaintiff lost his foot while working on a "refuse body" or trash collection truck. The plaintiff brought a product liability action for negligent design, negligent failure to warn, breach of warranty and strict liability in tort against the manufacturer of the refuse body. The court directed verdicts for the defendants on the warranty and strict liability counts and the case went to the jury on the negligence counts.

The court said "(i)n our view the focus in design negligence cases is not on how the product is meant to function, but on whether the product is designed with reasonable care to eliminate avoidable dangers.

The court went on the say "(w)e reject the suggestion that we adopt a rule that design negligence turn solely on whether a product functions as intended. Such a rule would mean that there would be no liability for negligent design of a product which functioned as intended but which was designed in a fashion more dangerous than need be. Liability, however, would be imposed on a designer who tried to reduce the risk by designing and using safety features which for some reason did not function as intended. Such a rule would discourage designers from attempting to reduce the hazards from machinery. We do not think such a rule is a practical solution to the problems posed by design negligence in product liability cases.

On the issue of warnings the court said, "(A)n adequate warning may reduce the likelihood of injury to the user of a product in some cases. We decline, however, to adopt any rule which permits a manufacturer or designer to discharge its total responsibility to workers by simply warning of the dangers of a product. Whether or not adequate warnings are given is a factor to be considered on the issue of negligence, but warnings cannot absolve the manufacturer or designer of all responsibility for the safety of the product." "However, in some circumstances a warning may not reduce the likelihood of injury. For example, where the danger is obvious, a warning may be superfluous. A designer may have no duty to warn of such dangers."

"Moreover," the court said, "a user may not have a real alternative to using a dangerous product, as where a worker must either work on a dangerous machine or leave his job. Further, a warning is not effective in eliminating injuries due to instinctual reactions, momentary inadvertence or forgetfulness on the part of the worker. One of the primary purposes of safety devices is to guard against such foreseeable situations."

Maldonado v. Thomson National Press Company [6 Mass. App. Ct. 901, 911 (1983)]

In this case the plaintiff injured his right hand while attempting to clear a jam in a platen press. On the press, facing the operator (plaintiff) was a bright yellow card on which was printed in large letters "WARNING, STOP MACHINE BEFORE CLEARING JAMS OR REPAIRING." Despite the plaintiff's acknowledgement that he had read and understood the warning sign, the jury found that the manufacturer did not adequately warn the plaintiff of the machine's characteristics and the risks associated with its use. The Massachusetts Appeals Court reversed and entered judgment for the defendant.

The court said "a manufacturer's duty to warn purchasers and expected users of its product refers to latent dangers in the normal and intended use of the product. The duty to warn "is not imposed by law as a mindless ritual." Killeen v. Harmon Grain Products, Inc., Mass. App. Ct. Adv. Sh. (1980) 2165, 2169. The duty to warn assumes some reason to suppose a warning is needed, and, therefore, has application in the context of dangers which are concealed or less than obvious. It may be supposed, for example, that the person who wields an axe does not require a warning that he should avoid bringing the axe down on his foot and that, should he do so, the consequences will be unpleasant" (citation omitted). "When as here a dangerous condition is fully obvious and generally appreciated, nothing of value is added by a warning."

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MICHIGAN

Prentis v. Yale Manufacturing Company [421 Mich 670; 365 NWed 176 (1984)]

Plaintiff John Prentis sustained an extensive hip injury while operating a standup/walking type model forklift (also known as a Walkie Hi-Lo model) manufactured by defendant Yale Manufacutring Company.

The forklift weighed approximately 2,000 pounds and was equipped with a hand-controlled deadman switch which prevented movement of the forklift without the operator holding the handle of the controls. The artifact forklift had, by Mr. Prentis own testimony, experienced previous problems with power failures and surges and with erratic operation when the battery ran low at the end of each workday. Mr. Prentis testified that when this erratic operation began, he often played the handle back and forth to get the forklift to operate. At the time of the injury in this case, Mr. Prentis testified that it was late in the day and, while moving a heavy object, the forklift experienced a power surge, knocking Mr. Prentis to the ground. He suffered injuries as a result of the fall, but was not run over by, nor did he make contact with, the forklift.

Plaintiff filed suit alleging negligence, failure to warn, and breach of implied warranty. The focus of his proof at trial was an alleged defect in design. The plaintiff claimed that the defendant failed to incorporate the operator as a "human factor" into the design of the forklift. He alleged that the forklift should have been designed with a platform or seat for the operator to ride during operation.

The trial court refused to instruct the jury on breach of warranty, but properly instructed on the theory of negligent design, and entered judgment for the defendant upon a jury verdict of no cause for action. The Court of Appeals held that the refusal to instruct on breach of warranty was an error requiring reversal. The defendant appealed and the Michigan Supreme Court ruled that, in a products liability action against a manufacturer on theories of defective design of a product and upon breach of implied warranty, there was no error in refusing to instruct the jury on breach of warranty where the jury was properly instructed on the theory of negligent design. The Court ruled that in such situations jury instructions on breach of warranty would have been repetitive and could have created jury confusion and prejudicial error. Jury instructions could have mislead the jury into believing that recovery on the warranty theory could have been had even if no defect in the design was found. Also, the Court noted that recovery under either theory required a determination that the product was defectively designed. In ruling on the jury instructions, the Court elaborated upon what constitutes a "defect" under Michigan law.

The Court began by noting that for a product to be "defective" there must exist a casual connection between the alleged defect and the injuries sustained. The product itself must be actionable, and the plaintiff must prove this. Two kinds of defects were defined and distinguished by the Court. First a "manufacturing defect" exists if one particular item is not the same as the rest of the manufacturer's product line. In such cases, the Court noted that it is fairly easy to determine whether or not a defect exists by simply evaluating the individual item in relation to the manufacturer's own production standards for that particular product line. In the case of a "design defect," no simple test exists. In these cases, for a defect to exist, it must be shown that intentional design decisions of the manufacturer were not sufficiently safe. The Court is then called upon to supply the standard of defectiveness.

The Court also described and discussed four general categories of design defect tests which have been applied at various times in the Trial Courts and Appellate

Courts of the State of Michigan. First, the negligence risk-utility analysis focuses upon whether a manufacturer would be judged negligent if it had known of the product's dangerous condition at the time of marketing. Second, at times various courts have compared the risk of harm with the utility of a product at the time of trial. The third test focuses on consumer expectations of a particular product. The fourth test combines a risk-utility analysis along with consumer expectation tests.

For a number of reasons, the Court adopted a pure negligence standard for design defect cases. In other words, the Court chose a risk-utility test in products liability actions where that liability is based upon defective design. The Court articulated its reasoning for choosing this test as the most desirable, simple, and clear test for design defects. First, by focusing on design decisions, the plaintiff is well equipped to examine the choices made by a manufacturer through liberal modern discovery rules and can analyze technical decisions through the use of expert witnesses. Second, the negligence standard rewards carefulness and punishes carelessness on the part of manufacturers as a whole. Third, a verdict for the plaintiff in a design defect case is a determination that an entire product line is defective. Finally, the Court noted that this fault system incorporates greater fairness as careful manufacturers do not bear the burden of paying for negligence by various sellers.

In making its design decisions, the manufacturer has a duty to design its product so as to eliminate any unreasonable risk of foreseeable injury by a user. Owens v Allis-Chalmers Corporation, 414 Mich 413, 425; 326 NW2d 372 (1982). A product is "unreasonably dangerous" if it creates unreasonable risk of foreseeable injury. Dooms v Stewart Bolling & Company, 68 Mich App 5, 14; 241 NW2d 738 (1976), lv den 397 Mich 862 (1976). To find a manufacturer negligent, the risk of harm due to the operation of a particular product must outweigh the utility of the particular design "defect." Here, the trier of fact must consider alternatives and risks that were faced by the manufacturer at the time of design decisions were made and must decide whether the manufacturer used reasonalbe care in making its decisions. The tort is a matter of negligence, with the liability of the manufacturer resting upon a departure from proper standards of care.

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