FRACTURE MECHANICS AND TOUGHNESS MEASUREMENTS

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Keywords: Fracture Mechanics, toughness, cracks, structural defects, damage tolerance

Contents

Summary

This chapter presents a compact but clear revision of the fundamental concepts required to analyze the effect of crack like defects on the resistance of structural components.

1. Introduction

Toughness means resistance to crack propagation, and Fracture Mechanics is the tool used to model cracks, which are very sharp notches whose tip radius $\rho \to 0$. Cracks are common defects in structural components, especially in large welded structures. They can be caused by several mechanisms during material manufacturing (e.g., by rolling without welding or brazing inclusions or pores, by excessive lamination or forging deformations, or by quenching-induced thermal stresses); during the component or structure manufacturing (by incomplete penetration in welding, by residual stress generated during welding or thermal treatment, by interference or excess pressure, by abusive grinding, etc.); or during the structure service (by overloads, fatigue, wear, creep and/or corrosion induced damage).

The classic linear elastic (LE) stress analysis around an elliptical hole in a large plate conducted by Inglis in 1913 justifies the great practical importance of cracks in real life: if a and b are the semi-axes of the elliptical hole, with a perpendicular to nominal

stress σ_n; σ_{max} is the greatest stress induced by σ_n on its edge; and $\rho = b^2/a$ is the tip radius of the elliptical hole at the extremes of its axis $2a$, see Figure. 1, the Inglis stress concentration factor is thus given as:

$$K_t = \frac{\sigma_{max}}{\sigma_n} = 1 + 2\frac{a}{b} = 1 + 2\sqrt{\frac{a}{\rho}} \qquad (1)$$

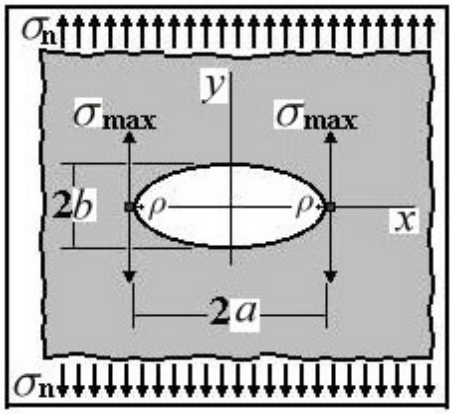

Figure 1. Plate with an elliptical hole

Since cracks can be approached by the sharp elliptical (or semi-elliptical) notches that surround them, and since the tips of ideal cracks have such a small radius ρ that one can and should suppose that $\rho \to 0$, such ideal cracks have $K_t \to \infty$, and thus singular LE stresses at their tips. In other words, in any such crack, $\sigma_n > 0 \Rightarrow \sigma_{max} = \sigma_y(x = \pm a) \to \infty$. That is why cracks are particularly damaging structural defects. But even the most fragile cracked pieces (such as those made of glass, e.g.) have some residual resistance and tolerate nominal stresses $\sigma_n > 0$, whose magnitude should be predicted when brittle pieces are used in structural applications. However, as the stresses are always singular at the tips of ideal cracks for any $\sigma_n > 0$ (even when σ_{max} is considered elastic-plastic), the traditional stress analysis *cannot* be used to predict the residual resistance of cracked pieces, because singular stresses cannot be compared to the material's resistances (like yielding S_Y or ultimate S_U strengths, e.g.).

Therefore, the structural effect of cracks should be handled with a specific mechanics, known as Fracture Mechanics. In reality, Crack Mechanics would be a more appropriate name for its practical purpose: to model cracked structures that, because they have yet to break, work in a partially damaged mode. Indeed, ductile structures normally spend a great part of their useful life generating and/or propagating cracks in a stable and gradual manner (by fatigue, for example), and most of them are removed from service before fracturing. Thus, in order to distinguish the various physical processes associate with crack growth, it is best to call *fracturing* the unstable and *tearing* the stable (that requires increasing loads to progress) fracture process, and *cracking* the stable and gradual crack propagation process (under cyclical loads, e.g.).

Since the safety of cracked structures decreases over their lifetime as the cracks grow, the objectives of Fracture Mechanics are to quantify:
1. The greatest load (or the critical load) a cracked structure can support in service;
2. The size of the largest crack (or the critical crack) that can be tolerated by a structure in service; and
3. The residual life of cracked structures under real service loads.

A structure can only be considered safe when it is possible to guarantee it will resist all possible service loads throughout its operational life, in a predictable and repetitive manner, even in the presence of the largest crack that may not have been detected during the last inspection of the structure. This so-called defect-tolerant structural design philosophy, despite its evident logic, only began to be required in the 1970s. However, today it is an indispensable engineering practice.

Indeed, since the total absence of defects *cannot* be guaranteed in real structures, structural engineers can only suppose that it is improbable for them to have defects greater than the detection threshold of the method used in their inspection. This must be emphasized: if the effect of cracks is not considered in the design or management of a structure, its safety can only be guaranteed when it is truly free of such defects. In all other cases, structural safety can only be guaranteed if a defect, which may not have been detected at a given inspection, cannot grow until reaching its critical size before being discovered and corrected at a subsequent inspection.

2. Defect Inspection Methods

The main non-destructive inspection (NDI) methods used to find cracks in practice are:

1- Visual Inspection (VI): requires good vision, very good illumination, cleanliness, attention to details and knowledge of what to look for. Since VI is indispensable for assessing the real state of a structure, it should always be included in any structural integrity analysis (SIA) service. VI resolution can be improved by optical equipment such as lenses, endoscopes, microscopes and/or video cameras, as well as by other superficial NDI techniques. VI procedures can be quite elaborated, but are difficult to standardize because they require subjective judgments. Therefore, VI results depend on the experience and good sense of the inspector (actually, the maxim “do not entrust an important machine to an inexperienced pilot” is particularly wise in SIA). However, a good photographic documentation, a most important VI complement that nowadays can be redundantly used due to the widespread availability of good and affordable digital cameras, can be used to minimize at least in part the inspector experience requirement.

2- Penetrating Liquid (PL): is a simple and reliable technique which does not require special equipment and can be applied in a safe and economic manner in virgin or used pieces made of a great variety of metallic and non-metallic materials, in cast, forged, welded, machined, heat-treated, whatever state. The part of the piece to be tested must first be degreased and have all paint traces chemically or mechanically removed from their surfaces. The cleaned part must then be soaked in a high capillarity and highly visible dye, generally red or fluorescent under ultraviolet light (in this case, usually greenish-yellow). After the time needed for the dye to penetrate into the defects (typically 10 to 120 minutes), the piece should be dried

and covered by a special paint (generally white) that absorbs the liquid that penetrated the cracks, or else be placed under ultraviolet light, to highlight the visual location of the cracks (see ASTM standards E165, E433, E1417, E1418, E1135, E1208, E1209, E1210, E1219, E1220, E2297, etc.).

3- Magnetic Particles (MP): cracks perturb the magnetic field caused by a high electrical current flow in ferromagnetic pieces, and form opposing poles causing a leak in the local field that attracts MP, iron shavings applied on the cleaned (degreased and sanded, if necessary) piece surface, using a dry or wet, fluorescent or not, recover technique. The concentration of these MP is much more visible than the crack, and facilitates its location (see ASTM E709 and E1444).
4- Eddy Currents (EC): a versatile technique based on the distortion of a magnetic probe field, generally a coil excited by an alternate current, by the parasite currents it induces in the piece (that must be an electric conductor), which concentrate around the superficial or internal defects and are detected by the variation in the probe impedance or in the impedance of another sensor placed on the piece. The probes are adaptable to countless geometries, and the inspection process can be automated for use in production lines (ASTM E215, E243, E566, E571, E690, E1606).
5- Ultrasound (U): detects superficial or internal defects on metallic or non-metallic pieces using the reflection and/or refraction of high frequency mechanical waves generated by a special head that normally contains the transducer that induces the waves and the receiver that measures them, both of which are usually piezoelectric crystals. The head is rubbed over the piece's surface to introduce pulse bursts of well-known amplitude and duration. The inspected surface must first be well cleaned and then generally covered by a liquid or gel to improve the transmission and reception of the mechanical pulses. The attenuation and distortion of these pulses are read on the screen of an oscilloscope and are listed with the type, shape and position of the defects. Modern ultrasound scanners can use multiple heads to create three-dimensional (3D) maps of the inspected areas, increasing the resolution and the defect mapping speed, using digital image techniques and dedicated software. This technique is versatile, but requires well-trained inspectors (see ASTM E127, E1441, E1454, E1495, E1736, E2001, E2192, E2223, E2580, etc.).
6- Radiography (R): uses x or γ rays (in the latter case, it is galled gammagraphy), depending on material thickness and permeability, to detect internal and superficial defects in most materials. Small pieces can be inspected using 3D scanners. However, the radioactive sources can be very dangerous and their handling requires qualified and especially trained inspectors, as well as rigorous protection practices, which in the case of gammagraphy may include the complete evacuation of the industrial plant during testing (see ASTM E94, E748, E545, E592, E801, E999, E1030, E1032, E1255, E1391, E1496, E1742, E1814, E2007, E2141, E2445, etc.).

Besides these 6 methods, there are other NDI techniques that can be used in structural integrity management. Acoustic emission (AE) stands out among them. It can be used to identify and locate cracks by analyzing the noise generated by the elastic waves caused by dislocation displacement or by the propagation of fatigue cracks during structure loading in service or in test (ASTM E596, E650, E749, E750, E1319, E1392, E1962, E2191, E2076, E2374, etc.). However, AE performance in crack size measurements

tends to be less robust and reliable than the performance of the standard 6 methods listed above.

Other methods that deserve mention are: spectral analysis (cracks affect the rigidity and thus the natural frequencies of a structure); thermography (which detects defects measuring small variations in the temperature around them during structure loading); and the various techniques used for experimental strain analysis such as extensometry, holographic interferometry or photoelasticity, whose main use is not to detect or measure cracks. It is also worth mentioning that several NDI techniques can also be used to detect porosities, inclusions or corrosion, measure wall or coating thicknesses, density, electric conductivity, etc.

In actual field applications, all of the aforementioned NDI methods have high probability of detecting cracks greater than 10mm, if the inspector is well qualified and the access to the inspected areas is adequate, but none of them reliably detects cracks smaller than about 0.1mm Thus, they all may *not* detect cracks that measure about 1mm, see Figure. 2.

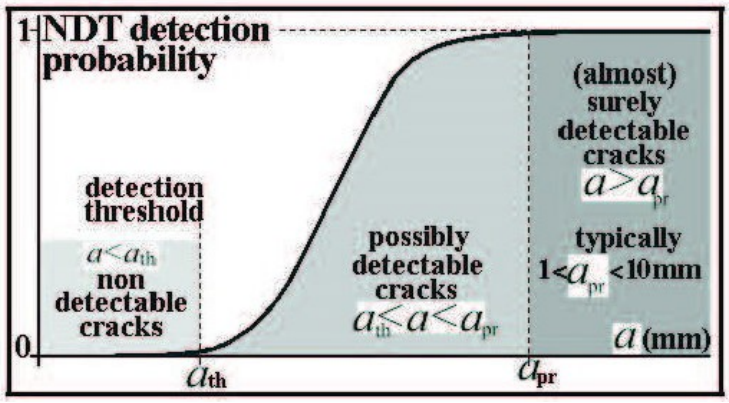

Figure 2. The probability of detecting cracks depends on crack size, and each NDI method has a detection a_{th} and a probable detection a_{pr} threshold.

Detection and measurement of cracks smaller than 100μm is possible in well-controlled laboratory environments, when the crack location is known beforehand and the work conditions are ideal, with well-polished, clean and thoroughly illuminated surfaces. Stereo microscopes (which have a greater depth of view than traditional microscopes), or confocal laser scanning microscopes (which maximize the focus depth since they focus on a single point and not on an area), can be used in these cases. In the most sophisticated experiments, the cracks can be observed by electronic scanning microscopy (if they fit inside the microscope's vacuum chamber). Table 1 lists the smallest crack sizes probably detectable by experienced inspectors properly trained in the various NDI techniques, according to NASA's data: eddy currents (EC), penetrating liquid (PL), magnetic particles (MP), radiograph (R) and ultrasound (U). Dimensions a and c of 2D cracks, which appear in this table, are defined in Figure 3.

Crack geometry	**Inspection technique**	**Thickness of piece** t (mm)	**Crack size** a (mm)	c (mm)
passing crack on the external surface of a plate, sphere or cylinder	EC PL PL MP	$t \le 1.3$ $t \le 1.3$ $1.3 < t \le 1.9$ $t \le 1.9$	1.3 2.5 $3.8-t$ 3.2	- - - -
lateral passing crack on a plate	EC PL MP	$t \le 1.9$ $t \le 2.5$ $t \le 1.9$	2.5 2.5 6.4	- - -
passing crack exiting a hole in a plate, ear, flange or cylinder	EC PL MP	$t \le 1.9$ $t \le 2.5$ $t \le 1.9$	2.5 2.5 6.4	- - -
internal crack (two-dimensional, 2D) on a plate	R R U	$0.6 \le t \le 2.7$ $t \ge 2.7$ $t \ge 7.6$	$0.35t$ $0.35t$ 1.7	1.9 $0.7t$ 1.7
2D corner crack on a rectangular plate	EC PL MP U	$t > 1.9$ $t > 2.5$ $t > 1.9$ $t > 2.5$	1.9 2.5 1.9 2.5	1.9 2.5 6.4 2.5
2D corner crack exiting a hole in a plate, ear or flange	EC PL MP U	$t > 1.9$ $t > 2.5$ $t > 1.9$ $t > 2.5$	1.9 2.5 1.9 2.5	1.9 2.5 6.4 2.5
2D superficial crack in a rectangular plate or spherical pressure vase (external surface), or exiting a hole in a plate, ear or flange	EC PL MP R R U	$t > 1.3$ $t > 1.9$ $t > 1.9$ $0.6 \le t \le 2.7$ $t > 2.7$ $t \ge 2.5$	0.5 to 1.3 0.6 to 1.9 1.0 to 1.9 $0.7t$ $0.7t$ 0.8 to 1.7	2.5 to 1.3 3.2 to 1.9 4.8 to 3.2 1.9 $0.7t$ 1.3 to 1.7
2D surface crack on the external or internal walls of a pipe	EC (ext. and int.) PL (external) MP (external) R (ext. and int.) R (ext. and int.) U (ext. and int.)	$t > 1.3$ $t > 1.9$ $t > 1.9$ $0.6 \le t \le 2.7$ $t > 2.7$ $t \ge 2.5$	0.5 to 1.3 0.6 to 1.9 1.0 to 1.9 $0.7t$ $0.7t$ 0.8 to 1.7	2.5 to 1.3 3.2 to 1.9 4.8 to 3.2 1.9 $0.7t$ 1.3 to 1.7
circumferential crack on the external or internal walls of a pipe	EC (ext. and int.) PL (external) MP (external) R (ext. and int.) U (ext. and int.)	$t > 1.3$ $t > 1.9$ $t > 1.9$ $0.6 \le t \le 2.7$ $t \ge 2.5$	0.5 0.6 1.0 $0.7t$ 0.8	– – – – –
2D radial surface crack on an r radius axis	EC PL MP	– – –	$r \cdot [1 + \tan(c/r) - \sec(c/r)]$	1.3 1.9 3.2

Table 1. Crack sizes probably detectable by the various NDI techniques

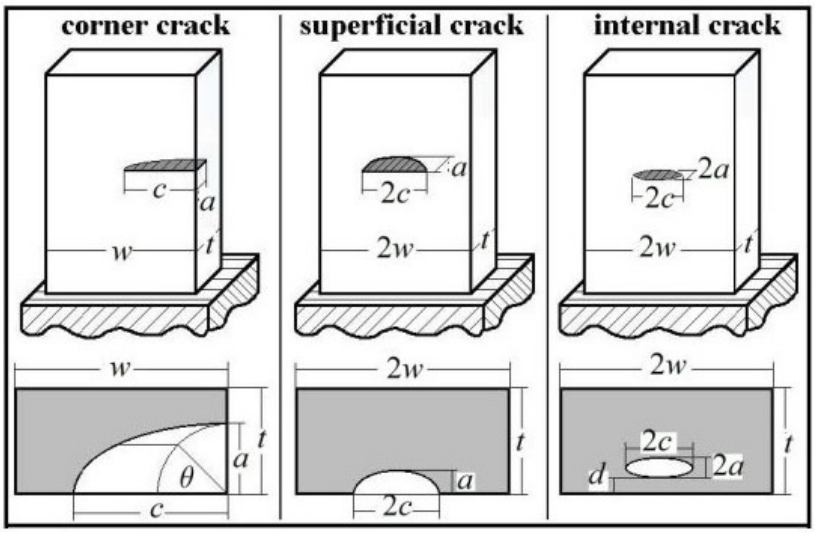

Figure 3. Basic types of elliptical of 2D cracks.

3. Griffith's Energy Balance

Inglis demonstrated that elliptical (or similar) notches have a stress concentration factor K_t proportional to $\sqrt{(a/\rho)}$, but he did not explain why cracked pieces *do not* break under small loads, since $K_t \to \infty$ when $\rho \to 0$. It was then up to a (at the time) young man named Griffith to have in 1920 the genial insight that resulted in Fracture Mechanics, by not allowing himself to be intimidated by the singular stresses projected by the Inglis model at the crack tips, because he knew this was a characteristic of the model (that assumed tip radii $\rho = 0$ and linear elastic stresses), not of the real cracks. Griffith solved this problem using a much stronger principle: he supposed that the crack propagation, like any other physical phenomenon, can only take place if it obeys the conservation of energy *law*. In other words: a crack can only grow, increasing by δA its area, when the increment of work δW supplied to the cracked piece is at least equal to the variation δE_s of strain energy stored in the piece plus the increment of absorbed energy during that crack growth step:

$$\delta W \geq \delta E_s + \mathcal{T} \cdot \delta A \qquad (2)$$

where $\mathcal{T}$ is the toughness, or the energy needed to grow the crack area by one unit (in J/m^2), and δA is the increase in crack area, in m^2 ($\delta A = t \cdot \delta a$ when the through crack can be characterized by its length a and piece thickness t is constant). Since tensile stresses cannot be transmitted across crack faces, the material around them must remain unloaded. Thus, the amount of unloaded material in the cracked piece grows when the crack increases. Therefore, the crack increase tends to relieve the deformation energy E_S stored in the piece, reducing the loaded system potential energy E_P:

$$E_P = E_S - W \qquad (3)$$

where W is the work carried out by the forces applied on the cracked piece. This effect can be quantified by the so-called potential energy release rate per unit of crack area:

$$\mathcal{G} = -\partial E_{\mathrm{P}} / \partial A \tag{4}$$

The negative sign in this definition makes the energy release rate $\mathcal{G}$ a positive number, since the energy stored in a cracked piece tends to decrease when the crack increases.

In his original work, Irwin named $\mathcal{G}$ the force (needed) for crack extension, a less clear term, denoting it with the handwritten letter $\mathcal{G}$ (to avoid confusion with $\mathbf{G}$, the shear module) in honor of Griffith. But, before using $\mathcal{G}$ to quantify cracks, it is necessary to prove that the energy release rate is indeed a property of the cracked structure. Thus, let a cracked piece (see Fig. 4) be loaded by a force P through a spring of compliance $C_{\mathrm{M}} = y_{\mathrm{M}} / P$ (to represent the finite stiffness of any machine or structure used to load the piece), where $y_{\mathrm{M}} = y_{\mathrm{T}} - y$ is the spring displacement along force line, and y_{T} and y are total displacements of the force P and of its application point on the piece (by the spring). Let the load P be generated by a prescribed fixed displacement $y_{\mathrm{T}} = y + y_{\mathrm{M}} = y + C_{\mathrm{M}} P = y\left(1 + C_{\mathrm{M}} / C\right)$, where $C = y/P$ is the compliance of the cracked piece, which depends on the crack size a. Since the potential energy stored in the system (spring + piece) is given by $E_{\mathrm{P}} = \left[y^2 / C + \left(y_{\mathrm{T}} - y\right)^2 / C_{\mathrm{M}} \right] \Big/ 2$, and since the force P does not produce work when the crack size a varies (because y_{T} remains fixed), the energy release rate is then given by:

$$\mathcal{G} = -\frac{1}{t}\frac{dE_{\mathrm{P}}}{da}\bigg|_{y_{\mathrm{T}}} = -\frac{1}{t}\left\{\left[\frac{y}{C} - \frac{(y_{\mathrm{T}} - y)}{C_{\mathrm{M}}}\right]\frac{dy}{da} - \frac{1}{2}\frac{y^2}{C^2}\frac{dC}{da}\right\}\bigg|_{y_{\mathrm{T}}} \tag{5}$$

Note that the cracked piece thickness t is assumed constant in this equation, for simplicity. Since $y/C = y_{\mathrm{M}}/C_{\mathrm{M}} = P$ (because the force passes through the spring) the energy release rate does not depend on the test machine stiffness (at least in this case), thus it is given by:

$$\mathcal{G} = \frac{P^2}{2t}\frac{dC}{da} \tag{6}$$

Now let the same cracked piece be loaded by a force P kept constant, applied (e.g.) by a dead weight) through a spring of compliance C_{M}. The spring displacement $y_{\mathrm{M}} = y_{\mathrm{T}} - y$ in this case remains constant, but the force P can move, producing work $W = P \cdot y_{\mathrm{T}}$. Therefore, the potential energy of the (piece + spring) system in this case is given by:

$$E_{\mathrm{P}} = E_{\mathrm{D}} + \frac{y_{\mathrm{M}}^2}{2} C_{\mathrm{M}} - W = \frac{y^2/C + y_{\mathrm{M}}^2/C_{\mathrm{M}}}{2} - P \cdot y_{\mathrm{T}} \tag{7}$$

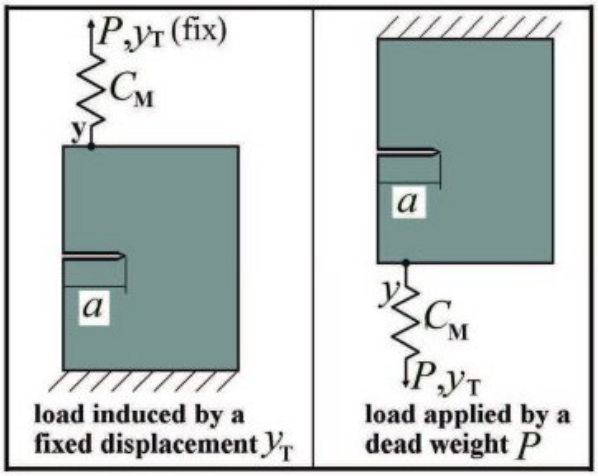

Figure 4. Load P applied to a cracked piece using the flexibility spring C_{M}.

Since the energy release rate is $\mathcal{G} = -dE_{\mathrm{P}}/d(a \cdot t)$, supposing t is constant and knowing that y_M is fixed (since P does not vary), with $dy_{\mathrm{T}}/da = dy/da$, and $P = y/C$, we get:

$$\mathcal{G} = -\frac{1}{t}\left\{\frac{y}{C}\frac{dy}{da} - \frac{1}{2}\frac{y^2}{C^2}\frac{dC}{da} - P\frac{dy_{\mathrm{T}}}{da}\right\}\Bigg|_P = \frac{P^2}{2t}\frac{dC}{da} \tag{8}$$

This is exactly the same rate obtained in (6), proving that it does not depend on how the load is applied. Therefore, $\mathcal{G}$ is indeed a property of the cracked piece. The interesting graphic interpretation of $\mathcal{G}$ shown in Fig. 5 is educational and indicates how it can be measured. In this figure, $\mathcal{G}$ is proportional to the gray area between the force × displacement curves used to quantify the stiffness of a cracked piece at two moments, the first when the crack size is a, and the second after it grows to $a + \Delta a$. Note that the displacement of the force application point in the cracked piece is called x in this figure, thus its compliance is $C = x/P$, and that its thickness t is assumed constant. The load P on right side is supposed fixed, applied (for example) by a dead weight, whereas the load $P(a)$ on the left is applied by a fixed displacement and diminishes as the crack increases from a to $a + \Delta a$. However, when $\Delta a \to 0$ the two gray areas tend towards the same value, graphically proving that $\mathcal{G}$ does not depend on how the load is applied, and that it can be measured by the variation in piece compliance dC/da as the crack increases. This technique for measuring the flexibility (or the stiffness) variation of a cracked piece as the crack grows is used for measuring crack size during fatigue tests, as described further ahead, after discussing the fracture process in a little more detail.

There are 3 basic ways to propagate a crack, called mode I (traction), mode II (shear) and mode III (torsion), see Fig. 6. Cracks can be loaded by a combination of these 3 modes, but they prefer to grow in mode I, changing their path if necessary to avoid the intrinsic friction between their faces induced by the shear and torsion modes.

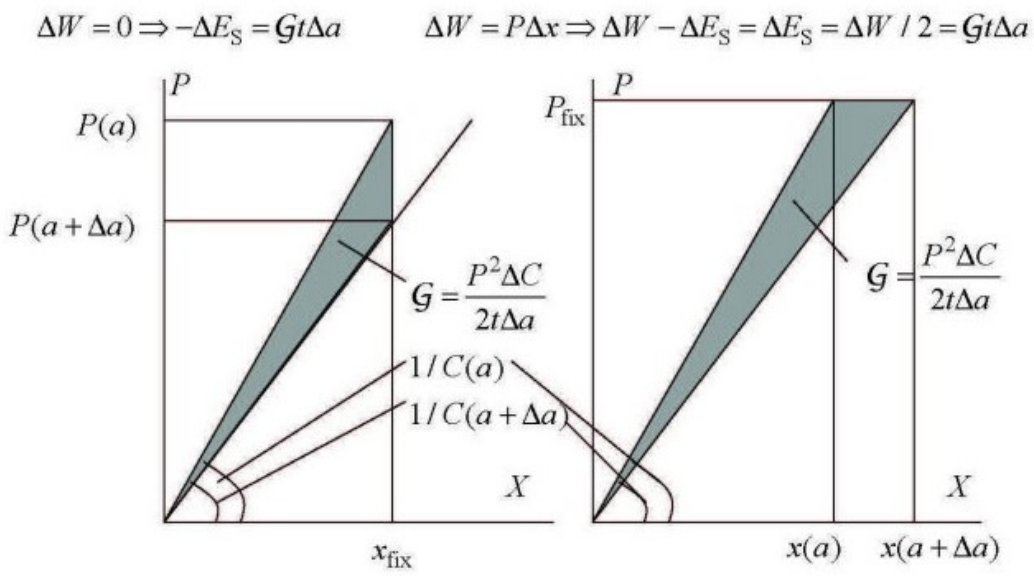

Figure 5. Graphic interpretation of $\mathcal{G} = -\partial E_P / \partial A \cong \left(\delta W - \delta E_S\right) / \delta\left(t \cdot a\right)$.

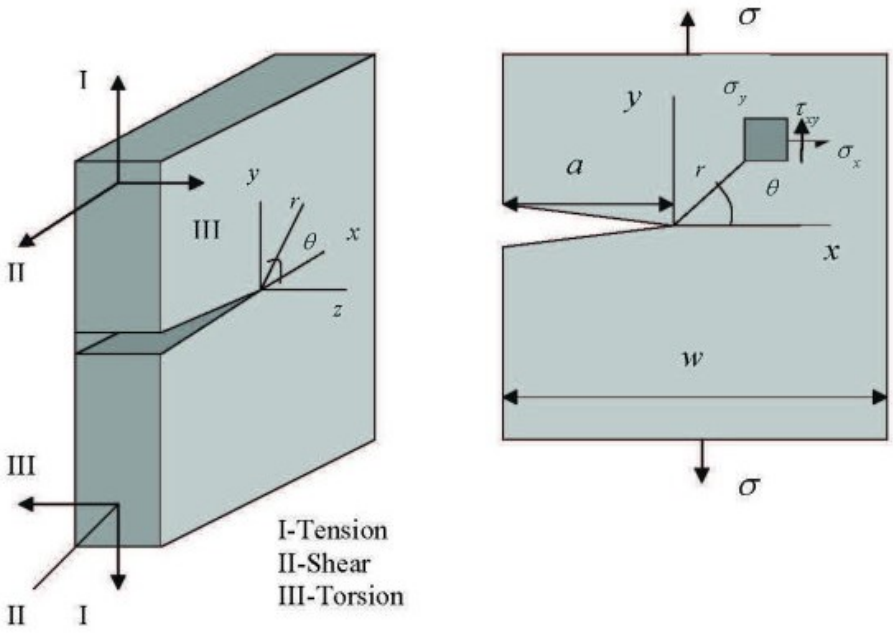

Figure 6. The 3 basic modes to obtain cracks: mode I (traction), mode II (shear) and mode III (torsion); and the notation used for the stresses around the crack tip.

If a crack requires $\mathcal{G}_{IC}$ (J/m^2) for its area to grow from A to $A + \Delta A$ in mode I (when the toughness $\mathcal{T}$ is constant and does not depend on the crack length a and increment Δa, a typical brittle behavior), then by the conservation of energy law, the crack can only propagate when:

$$-\partial E_P / \partial A = \mathcal{G}_I \geq \mathcal{T} = \mathcal{G}_{IC} \qquad (9)$$

$\mathcal{G}_{IC}$ (read "gee-one-cee") is the critical release rate of the potential energy stored in the cracked piece that induces fracture in mode I (in brittle materials). As the crack remains stable while its release rate $\mathcal{G}_I < \mathcal{T} = \mathcal{G}_{IC}$, this critical release rate can be used to measure the resistance to fracture caused by crack propagation, or the material toughness in mode I under predominantly elastic conditions. Ideally elastic materials are very brittle because all the energy $\mathcal{G}_{IC} \cdot dA$ needed to propagate the crack is spent to form its new surfaces, in an abrupt and unstable fracture. Actually, that is why Griffith, who knew how to estimate the surface energy of glass, used small fibers of this material (extremely brittle and almost ideally elastic) to experimentally prove his theory.

The abrupt fracture of brittle structures generally occurs at very high speeds, around the material's shear wave propagation speed, typically from 2 to 3km/s in most metals and ceramics (for comparison purposes, the speed of sound in the air is 325m/s at -10^oC or 349m/s at 30^oC). Furthermore, they generally do not generate clear warnings of imminent failure. Therefore, brittle fractures are almost instantaneous in practice: there is simply not enough time to take any corrective measure to stop them, so their consequences can be catastrophic, and must be avoided in all structural applications.

Sudden brittle fracture is generally the predominant mechanical failure mechanism in high strength metallic alloys, ceramics, vitreous polymers, and in ferritic and martensitic steels (and other body-centered cubic metals) below their brittle-ductile transition temperature, Θ_{BD}. In other words, ceramics are brittle, metals and composites are generally tough, and thermoplastic polymers are brittle below Θ_V, their vitreous transition temperature. However, there are notable exceptions to this general rule. In particular, it is important to mention low carbon steels, by far the most used structural alloys, which are generally ductile and very tough materials, since they can have $\Theta_{BD} \cong 0°C$. Thus, it is necessary to take care with low carbon steel structures in very cold climates!

However, there is no such thing as a perfectly elastic or ideally brittle material, because the fracture of real structural alloys is always accompanied by some plasticity (or other types of inelastic deformation). In this case, the energy required for crack propagation also includes the amount spent to generate the plastic strains around the crack tip during the fracture process, which can be much bigger than the energy required to create the new crack surfaces: indeed, more plasticity means greater toughness. Actually, any other mechanism that absorbs energy during fracture, such as micro cracking in ceramics, the formation of fine fibrils in vitreous thermoplastic polymers (crazing), or the pulling out of the fibers in composites, also contributes to increase the material toughness.

When the fracture occurs under gross plasticity, the elastic toughness $\mathcal{G}_{IC}$ cannot predict well the fracture initiation, which needs then to be modeled by more elaborated Elastic Plastic Fracture Mechanics (EPFM) concepts. Since most structures are purposely made of materials that are as tough as possible, it may seem that investing time in studying Linear Elastic Fracture Mechanics (LEFM) is a waste of time. But a simple analysis of the competition between plastic collapse and fracture based on LEFM concepts can be

used to properly model failure in many practical cases, as studied further ahead. Moreover, LEFM is indispensable for modeling the propagation of fatigue cracks. Typical toughness values of some structural materials are listed in Table 2. The K_{IC} values, another way of measuring toughness, which are also listed in this table, will be studied further ahead, but it is important to mention here that the higher $\mathcal{G}_{IC}$ and K_{IC} values must be measured using EPFM techniques.

Material	$\mathcal{G}_{IC}$(kJ/m^2)	K_{IC}(MPa$\sqrt{m}$)
pure ductile metals	100-1000	100-450
low C steels	100-300	140-250
high strength steels	10-150	45-175
Ti alloys	25-115	55-115
Al alloys	6-35	20-50
GFRPs	10-100	20-60
CFRPs	5-30	32-45
wood, $\perp$ to fibers	8-20	11-13
polypropylene (PP)	8	3
polyethylene (PE)	6-7	1-2
reinforced concrete	0.2-4	10-15
cast iron	0.2-3	6-20
wood, // to fibers	0.5-2	0.5-1
acrylic (PMMA)	0.3-0.4	0.9-1.4
granites	~0.1	1-3
Si_3N_4	0.1	4-5
cement	0.03	0.2
glass	0.01	0.7-0.8
ice	0.003	0.2

Table 2. Fracture toughness of some materials

Toughness expressed in terms of the energy absorbed to propagate one unit of crack area has a very clear physical interpretation, and values that cover several orders of magnitudes. For example, on the low toughness extreme of Table 8.2, ice, which only absorbs around 3J to form 1m^2 of crack, is an extremely brittle material. On the other extreme, pure copper, which needs nothing less than 1MJ to form 1m^2 of crack, is extremely tough, and almost never fractures in a brittle manner. This means that pure Cu structural components practically ignore cracks, which only influence their fracture because they reduce the resisting area, without introducing any major additional stress concentration factor. On the other hand, this concentration effect is the main cause of brittle fracture.

A note of caution is needed here: the word brittle is used as the opposite of both ductile and tough, two completely different concepts. A material is ductile when it tolerates large plastic strains before fracturing (ductility can be measured by the elongation or by the area reduction of a normalized specimen after a tension test). A material is tough when it tolerates cracks (toughness can be measured by the energy required to propagate them). Ductile materials are generally tough as well, but ductility cannot be confused with toughness. These properties are clearly different, because not all materials are tough and ductile. For example, wood is a generally tough material that does not care much about cracks (most woods can be nailed without any problem), but it certainly is not ductile (wood cannot be plastically conformed at room temperature).

Plastic deformation absorbs much energy, and that is why ductile materials tend to be tough. In ductile metals, energy is absorbed by propagating and multiplying dislocations, whose density in the annealed state is around 10^8-10^{10} m/m^3, but may reach up to 10^{14}-10^{16} m/m^3 when the metal is completely strain hardened. Since the toughness of metallic alloys is strongly dependent of their ductility, it generally increases with temperature Θ and tends to decrease with the increase in yield strength S_Y and load rate $d\varepsilon/dt$. In particular, the toughness of BCC metals, which fail by cleavage at low and by ductility exhaustion at high temperatures, can vary two orders of magnitude with temperature, as already mentioned above (some low C steels, from 3kJ/m^2 below Θ_{BD} to 300kJ/m^2 well above it, for example).

But plastic deformation is not the only mechanism that can absorb energy during fracture and contribute towards toughness increase. Glass fiber reinforced polymers (GFRP) used in boats, cars and surf boards, e.g., is a tough engineering material, despite being made of brittle glass fibers bonded by a polyester resin that is even more fragile than the glass. GFRP typically have $\mathcal{G}_{IC} \cong 30$ kJ/m^2, much more than the glass $\mathcal{G}_{IC} \cong 10$ J/m^2, because the composite materials absorb a lot of energy to unglue and pull off the fibers from the matrix.

Despite the clear physical interpretation of the toughness measured by $\mathcal{G}$ in J/m^2, the energy balance is not practical for most local analyses of fracture problems in cracked pieces. The stress intensity factor is much easier to use in these cases, as discussed below.

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Bibliography

Anderson,TL. *Fracture Mechanics*, 3rd ed., CRC 2005 [a general purpose erudite text].

ASTM Standards v.03.01, current edition [for the normalized test procedures].

Barson,JM; Rolfe,ST. *Fracture and Fatigue Control in Structures*, 3rd ed., ASTM 1999 [a good introductory text, focused on structural applications].

Broek,D. *The Practical Use of Fracture Mechanics*, Kluwer 1988 [a text that really deserves its name].

Dally,JW; Riley,WF. Experimental Stress Analysis, 4th ed., College House 2001 [for learning more about experimental stress intensity measurement methods - and about strain gages].

Epstain,JS, ed. *Experimental Techniques in Fracture*, Wiley 1993 [11 chapters on different experimental methods written by experts].

Gordon,JE. *The New Science of Strong Materials*, Princeton 1984 [a delicious romanticized description of the fracture problem].

Kobayashi,AS ed. *Handbook on Experimental Mechanics*, 2nd ed., Wiley 1993 [a classic].

Kobayashi,AS ed. *Experimental Techniques in Fracture Mechanics*, v.1 e 2, SESA 1975 [each volume has 5 chapters on different experimental methods written by specialists].

Sanford,RJ. *Selected Papers on Linear Elastic Fracture Mechanics*, SEM 1997 [a compilation of the fundamental papers in this field].

Sanford,RJ. *Principles of Fracture Mechanics*, Pearson Education 2003 [another general purpose erudite text].

Sharpe,WN, ed. *Springer Handbook of Experimental Solid Mechanics*, Springer 2008 [a more recent handbook].

Tada,H; Paris,PC; Irwin,GR. *The Stress Analysis of Cracks Handbook*, 3rd ed., ASM 2000 [the most popular collection of stress intensity factors].

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