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Glass Fracture Mechanism—A Rethinking

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ABSTRACT: Conventional attitudes within the forensic science community concerning the fracturing of glass center around tensile failure of the glass, frequently depicted as a "bending" of the glass. While this is not conceptually incorrect, it represents only one case of a more universal phenomenon in which the tensile failure of glass does not necessarily involve any significant *deflection* of the glass. Tensile failure can be achieved with either quasi-static or dynamic loading of the glass. In quasi-static loading, tensile failure will initiate a fracture at the weakest point (that is, the locus of a *Griffith crack*), but the surfaces of this crack may be in optical contact, and thus no perceptible deformation of the glass would be required before failure. A consideration of dynamic loading is necessary to explain the "cratering" effect observed in moderate- to high-velocity projectile impact. In sharp dynamic loading (for example, a bullet impact) the tensile stress is provided by the reflection and subsequent interference of the compression waves which precede the passage of the projectile; this particular type of stress results in Hopkinson fractures, a multiplicity of which creates a crater. The dimensions and chamfering of projectile craters are a manifestation of the crack velocity propagation, and are not inherently a function of projectile velocity or caliber.

KEYWORDS: engineering, glass, ballistics, glass fracture, impact loading, tensile stress, compressive stress, crack propagation, bullet

In the forensic science literature, the interpretation of glass fracture has been discussed by numerous authors [*1-4*], and has been reviewed by McJunkins and Thornton [*5*]. The classical explanation of the propagation of radial and concentric fractures in glass is that a compressive stress results in a deformation of the glass, with a resultant tensile stress on the opposite side. Since the tensile strength of glass is so much lower than the compressive strength, the glass fails under the tensile stress, with the fracture being initiated on the side away from the compressive force. Radial fractures are formed in this manner. If the kinetic energy transferred to the glass cannot be relieved by radial fractures alone, then concentric fracture may occur. This will happen when a sector of a radial fracture bends away from the compressive force, placing points on the *leading* surface of the glass under a tensile stress. The glass again breaks under tension, this time with the fracture being initiated on the side on which the original compressive force was applied. These mechanisms are depicted in Fig. 1.

There are two defects, or at least shortcomings, with this explanation: It places an emphasis on a *deformation* of the glass which current theory concerning glass fracture does not

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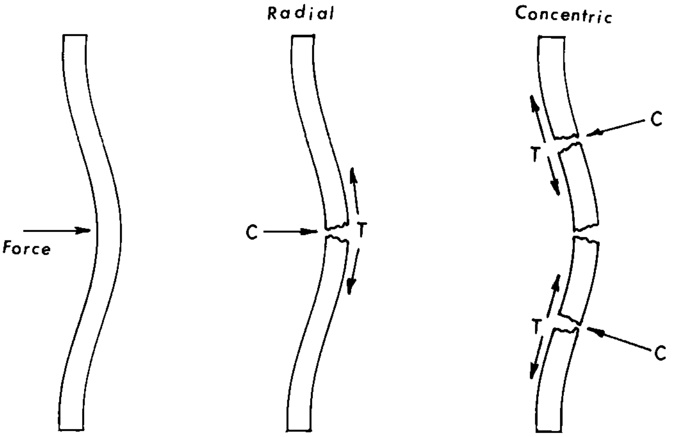

FIG. 1—*Classical means of depicting the breaking of glass under tension. Although this explanation is not incorrect, the fracturing of glass under quasi-static loading does not* require *any significant deformation of the glass before failure.*

hold to be obligatory, and it does not account for the cratering phenomenon observed in glass under conditions of sharp dynamic loading, for example, the impact of a projectile.

The production of craters in glass sheets has received much less attention in the forensic science literature (apart from the obvious issues concerning the interpretation of direction of force) than has the interpretation of the direction of force based on radial and concentric fractures. Even in the 19th century, however, it was speculated that the displacement of glass from the crater was a function of the *velocity* of the missile [*6*]. Precisely what this function is has not been elucidated, although many forensic scientists are generally aware that with a higher-velocity projectile, the size of the crater is diminished. The work of Frye [*7*] did establish, however, that the diameter of the crater was independent of the diameter of the projectile.

Quasi-Static Versus Dynamic Loading

Quasi-static loading is the type of stress that would result from slowly pushing on a glass plate. Dynamic loading is the type of stress that would result from pushing on a glass plate very rapidly. What constitutes "slowly" and "rapidly" here cannot be precisely stated and the two will to some degree overlap. Dynamic loading leading to crater formation will ordinarily represent loading of only a few microseconds, however. The application of force for a few hundreths of a second or less, as in the breaking of glass by a handheld or thrown object, will ordinarily represent a case of quasi-static loading in the interpretation of fracture phenomena.

Quasi-Static Loading

Of the various theories proposed dealing with fracture mechanisms in glass, the one that has proven the most durable over the years is that of Griffith [*8*]. Griffith postulated that all glasses contain on their surface numerous minute flaws which act as stress concentrators. Glass under a static or quasi-static load would then fracture at the locus of one of these Griffith microcracks. Although there were good theoretical reasons for accepting the concept of Griffith cracks [*9,10*], until recently the evidence for them was indirect. Not even electron microscopy had established the presence of these cracks. Recently, however, convincing evidence derived from rather elegant but sophisticated ion exchange [*11*] and pulsed stress [*12*] experiments has been developed to confirm the validity of Griffith's theory; the cracks, although real, are in fact so narrow that *their surfaces are in optical contact*. In glazing quality glass, their average population density is approximately 56 000/cm^2 (868 in.^{2}) [*11*].

The significance of this, from the forensic science standpoint, is as follows: The failure of glass under quasi-static loading is determined not by how strong it is, but rather by how *weak* it is. The initiation of the fracture is always at a surface, and at the locus of a Griffith microcrack. The fracture is then catastrophic in the sense that the fracture propagation phenomenon suddenly overcomes both the scope and the magnitude of the initial motive; the fracture extends through the glass object, with the advancing head of the fracture lying in a plane normal to the tension there. What is required for the initiation of the fracture is the tensile failure of the glass at a Griffith crack. And *since the dimensions of the crack are of the order of a few hundred Angstroms, that is all the displacement that is necessary to initiate the fracture*. Consequently, the glass may break under tension even though the deformation of the glass would not be perceptible to the eye. Stated differently, the glass may fail when it is "stretched" (that is, placed under a tensile stress) by a few hundred Angstroms, rather than by a few millimetres. This does not mean that glass does not break upon being deformed, but rather that an obvious deformation is not obligatory. On the basis of the foregoing, the currently accepted view within the forensic science community of the mechanism of glass fracture should be modified to accept situations where the glass fails under tension, with no deformation of the glass being readily apparent.

Dynamic Loading

In the forensic science literature, cognizance has not been taken of the ability of mechanical waves to fracture glass. The cratering of glass resulting from the impact of a projectile may be explained on the basis of these waves.

When a projectile strikes a sheet of glass, longitudinal mechanical waves are produced, beginning at the point of impact and radiating outward in a series of spherical wavefronts. The wavefronts, which are all in phase, travel through the glass at approximately 5000 m/s (16 400 fps) at a time when the projectile is traveling at only 1000 m/s (3280 fps) (or substantially less).

These waves are known under several appellations—mechanical waves, shock waves, acoustic waves, sound waves, sonic waves, or stress waves. In glass they travel at the speed of sound in glass, approximately 5000 to 6000 m/s (16 400 to 19 680 fps) [*13*]. The pressure of these waves following a bullet impact may be as high as 6.2 MPa (900 psi) [*14*]; glass may in fact be broken by mechanical waves with an overpressure of as little as 6.9 kPa (1.0 psi) [*15*], a very small fraction of the intensity of the mechanical waves that a bullet is capable of producing. Most forensic scientists are of course aware that glass can be broken by short-duration peak overpressures of sonic waves, as in the breaking of glass windows by an explosion, but apparently this phenomenon has not been factored into an explanation of the mechanisms of glass fracture.

Kinetic energy from a projectile may be transferred to a glass object in three ways: (1) by the direct application of force by the projectile, (2) through mechanical waves, and (3) by a transfer of energy in the form of frictional heat. The third mechanism may be dismissed as relatively insignificant. The first mechanism is significant, particularly in connection with quasi-static loading, but lags the mechanical wave production in time by a factor between five and twenty. With a mechanical wave traveling at 5500 m/s (18 040 fps), the wave is traveling approximately 20 times faster than the muzzle velocity of a projectile fired from a Colt .45 Automatic projectile, and approximately 6 times faster than a .308 Winchester. If in fact the mechanical waves are capable of producing pressures greatly in excess of that needed to fracture glass, then more consideration must be given to a wave model as a means of explaining fracture related phenomena.

The longitudinal *compression* stress waves resulting from a projectile impact are reflected from the back side of the glass as *tension waves* [*16*], and are re-reflected from the front side of the glass as compression waves again. The stress distribution of these compression and tension waves is illustrated in Fig. 2; compression is taken as upward and tension is taken as downward. Four stages of the reflection are depicted. When the compression pulse is incident normally on a stress-free boundary (the back side of the glass qualifies in this regard), a tension pulse of essentially the same magnitude and waveform is reflected away from the boundary. In Fig. 2*a* the compression pulse is approaching the free boundary. In Fig. 2*b* a small portion of the compression pulse has been reflected, but the stress is still skewed toward the compressive. In Fig. 2*c*, half the pulse has been reflected and the pulse, moving away from the boundary, takes on the characteristics of a tension pulse. In Fig. 2*d* the pulse has been entirely reflected and a tensile pulse of the same waveform as the original compressive pulse is moving away from the boundary (that is, moving from the back surface of the glass toward the projectile).

The fractures resulting from these compression and tension pulses may be accounted for by consideration of the effects the geometry of the glass has on the interference of the waves. When the compression wave is reflected as a tension wave, interference between the waves may result in such an accumulation of tensile stress that the glass will fracture. The intensity of the tensile stress is a function of both the amplitude and the phase of the wave fronts. When the interference is between waves which are out of phase, the resultant intensity is described by summing the squares of the individual amplitudes; when the waves are in phase, the resultant intensity is described by summing the amplitudes of the individual waves and squaring the sum. This latter case will result in localized accumulations of exceedingly high stress, *far in excess* of that necessary to initiate a single tensile fracture at a susceptible defect.

When a fracture resulting from wave interference of this sort takes place in metal, the metal is said to have "scabbed." The largest scab is at the boundary and successive scabs are smaller; consequently the crater that results from a multiplicity of these scabs is larger on the

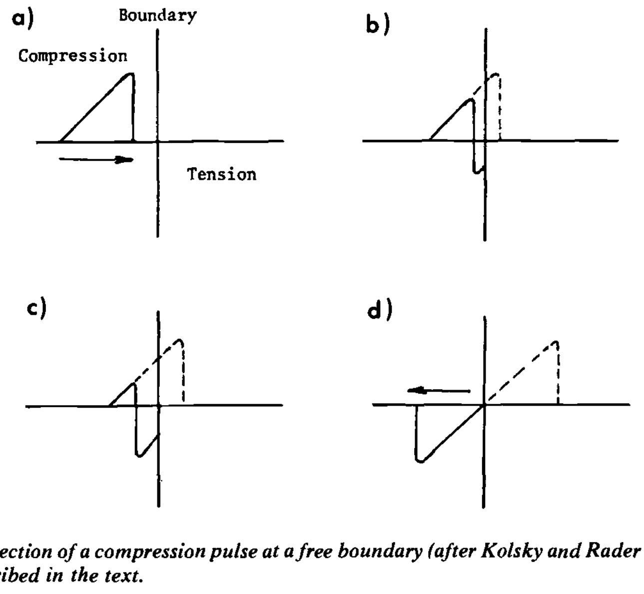

FIG. 2—*Reflection of a compression pulse at a free boundary (after Kolsky and Rader [22]). The four stages are described in the text.*

emergent side; that is, the crater opens in the direction of travel of the projectile. These scabs were first described by Hopkinson [*17*], and are frequently described as *Hopkinson fractures*. The mechanics of Hopkinson fractures have been described qualitatively in a fairly elementary fashion by Rinehart [*18*]. The two most important factors in establishing the character of the Hopkinson fractures are, first, the *form* of the compressive pulse, such as a rapid rise of the pulse and a slower decay, or a slower rise and slower decay; and second, a critical normal fracture stress characteristic of the material. The multiple Hopkinson fractures that manifest themselves in a crater in glass are characteristic of very high stress levels. Geometrical considerations developed by Rinehart and Pearson [*19*] indicate that multiple Hopkinson fractures, that is, cratering, can be expected when the level of stress after interference of the waves is more than double the critical normal fracture stress of the material—in this case, glass.

It should be recognized that these processes will be extant in any brittle solid, not just glass. Cratering is frequently observed in cases of gunshot wounds of the pelvis, scapula, and cranium.

It should also be recognized that *penetration* of the glass is not necessary for crater formation. Once an impulse stress is created by an impact, the Hopkinson fracturing process may proceed in the absence of penetration. As a consequence, it is not uncommon, especially in low-velocity impacts, to observe cratering on the opposite side of the glass and either no hole or a hole smaller than the diameter of the projectile on the front side. This is frequently seen with low-velocity pellet gun impacts.

Interpretation of Crater Form

A mechanical wave of sufficiently large amplitude can present fracture phenomena which differ in several respects from those produced by quasi-static loading. Of these differences, one is important to a forensic science perspective. When a sheet of glass is loaded quasi-statically, the fracture is initiated at the point on the surface representing the "worst flaw." The fracture then traverses the specimen. Under dynamic loading by a projectile, however, the stress wave may initiate a large number of fractures simultaneously, and at a large number of separate loci within the glass. Consequently, since fractures are propagated at approximately 2400 m/s (7872 fps) [*16*] and the stress wave in excess of 5000 m/s (16 400 fps), fractures from sharp dynamic loading progress only a few millimetres before the stress wave has moved on, leaving a stress-free region in which the fractures stop propagating. The practical significance to this is that although the projectile may give up several billion ergs of energy to the glass, the fractures may be confined to a relatively small area; a crater may be observed which at the maximum is only several bullet diameters in size, with no radial fractures observed. (Radial and concentric fractures may be superimposed, however; this is discussed below.)

The general form, that is, dimensions and chamfering of the crater resulting from a projectile impact on a sheet of glass, is *not* a function of the velocity of the projectile, *nor* of its diameter. The chamfering or bevel and the dimensions are instead a manifestation of the *velocity of crack propagation* resulting in the Hopkinson fractures. With conditions of high stress resulting from projectile impact, the maximum velocity of the fracture may be reached within fractions of a microsecond, and in sharp distinction from fracturing resulting from quasi-static loading, the stress caused by the mechanical waves may be sufficient to initiate new subsidiary fractures ahead of the main fracture front [*20*]. The precise crack propagation velocity will be determined by the composite of a number of factors which may or may not be interrelated, including caliber, projectile velocity and kinetic energy, mass, cross-sectional density, hardness of the projectile, bullet form, the angle of approach and the attitude (that is, pitch and yaw) of the projectile upon impact, the thickness of the glass, and the hardness of the glass [stress waves in "soft" glass will travel approximately 5000 m/s (16 400 fps); in "hard" glass the velocity will be closer to 6000 m/s (19 680 fps)]. Given the same caliber, velocity, bullet form, etc., that is, the "same" ammunition, the cratering observed in the glass should be reproducible, within limits, from shot to shot. The "limits" are determined primarily by variation in muzzle velocity, which can vary significantly even within a single lot of ammunition [*21*], and the variation in apparent tensile strength of the glass. Tensile strength measured on supposedly "identical" specimens of glass show considerable variation; mean deviations are typically 10 to 20% [*22*]. Furthermore, tradeoffs in projectile parameters could easily affect the nature of any cratering observed in evidence glass; for example, an expanding point projectile of smaller caliber may mimic the cratering effect observed with full jacketed spitzer ammunition of a larger caliber. Although certain generalizations as to caliber or velocity may be possible through an inspection of the cratering, a detailed analysis would not seem to be particularly feasible.

The authors do not wish to suggest that projectile cratering cannot be interpreted under *any* circumstances. Clearly the cratering will provide much meaningful information in situations where the caliber and type of ammunition are known, for example, a shootout between one individual armed with a .38 Special revolver and another armed with a .223 rifle. But if the caliber and type of ammunition are not already known, it is unlikely that an inspection of the dimensions and beveling of the crater will provide definitive information of this sort.

Superimposition of Hopkinson Fractures Upon Radial and Concentric Fractures

It is not at all uncommon to observe in projectile perforations of glass both cratering and radial fracturing, and even concentric fracturing. This represents a situation where the two processes are superimposed, with the kinetic energy transferred to the glass being partitioned between tensile fracture at the locus of a Griffith crack and tensile fracture at the locus of constructive interference of stress waves. Ignoring for the purposes of this discussion the slowing down of a projectile as it passes through the glass, a projectile will reside in a 4.76-mm ($^3/_{16}$-in.) glass plate for a period of time bounded roughly by 130 to 500 μs; the former would represent a projectile velocity of 1006 m/s (3300 fps) and the latter would represent a projectile velocity of 259 m/s (850 fps). Since the fracture propagation is on the order of 2000 m/s (6560 fps), a radial fracture will have sufficient time during the residency of the projectile to grow to several inches.

If, on the other hand, the energy transferred to the glass is extremely high (kinetic energy being proportional to the *square* of the velocity), then the cratering effect may predominate and radial fractures will not have an opportunity to grow beyond the boundaries of what will eventually be the crater.

Summary

Quasi-static loading of glass will result in its tensile failure at the locus of a Griffith crack, a type of crack that is exceedingly abundant in prosaic sorts of glass. Griffith cracks are real, but, from the standpoint of their conceptualization, are more of a construct of the mind than a true fissure; they do, however, represent discontinuities which are particularly susceptible to tensile stress. In this type of fracture, the initiation of the fracture will involve the separation of the surfaces of a Griffith crack. This separation may involve a displacement of only a few hundred angstroms in object space, after which the fracture continues catastrophically. Radial and concentric fractures resulting from this type of loading may occur even in the absence of any perceptible deformation of the glass.

In sharp dynamic loading characteristic of projectile impact, a crater may form with the greater diameter toward the emergent side of the glass. This is a manifestation of multiple Hopkinson fractures, or "scabs" resulting from very high tensile stresses which in turn are the result of the interference of stress waves in the glass.

The geometry of the crater is determined by the crack propagation velocity, and although *related* to the nature and velocity of the projectile, is not determined by any single identifiable property of the projectile.

In the absence of knowledge as to the caliber and type of ammunition used, or until detailed knowledge is developed concerning the interrelationship of projectile parameters and their effect on crack propagation velocity, any attempt to estimate the caliber or velocity of a projectile from an inspection of the form and dimensions of the crater would seem to be unwise.

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