Analysis of cracking in glass by using an edge-on-impact configation.

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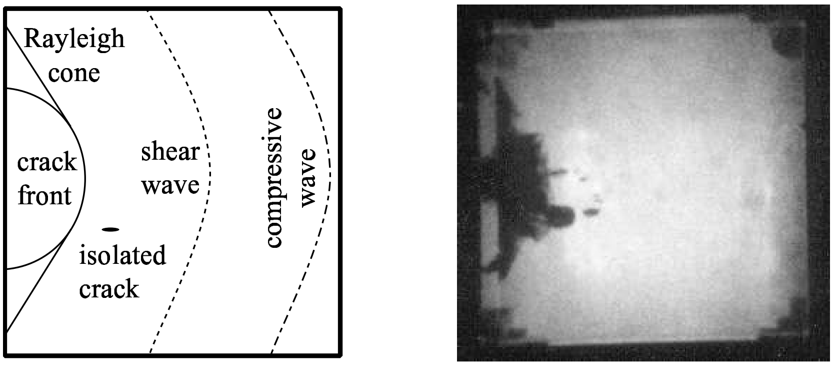
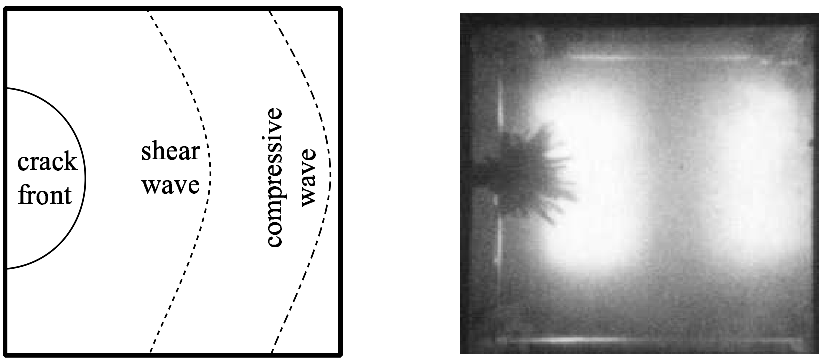
The use of brittle materials in armors requires studies on their response to impact. For example, glass can be used against ballistic threats (e.g., in windshields). Furthermore, multi-layered armor materials are used (with polycarbonate, PC, as back layer and polyurethane, PU, between glass plies) to optimize the ballistic performance. The use of PU and PC is essential to maintain the fragments when glass is impacted, especially for the back layer that ensures the structural integrity and absorbs the impact energy. The results reported herein are a first step towards the modeling of these complex multi-layered materials. The present study is therefore restricted to the dynamic fracture patterns of soda-lime glass alone and completes earlier studies [4]

To visualize damage, a so-called Edge-On-Impact configuration is used [1].This configuration allows the user to observe the cracking pattern. Bullets are fired by a gas gun and impact a float glass target of size 100 x 100 x 10mm^3. The projectile speed is measured by two optical cells one meter apart. Two different impactors are used in an "open" configuration enabling for in-situ observations by utilizing a high-speed camera. The interframe time can be as low as 0.5µs. In the present case, an interframe time of 3.3µs was used. When the bullet reaches the second cell, flashlights are triggered. When the bullet impacts the target, it activates the camera to take pictures. A so-called BR4 bullet (i.e., magnum 44) traveling at a speed of 430m/s and a BR7 bullet traveling at a speed of 820 m/s are used. BR4 bullets have a core made of lead and an envelope of brass wire, which classify them as soft. BR7 bullets have a core made of steel, an envelope of brass wire and a small head of lead (i.e., a "hard" bullet). Contrary to quasi-static experiments, the overall damage pattern is reproducible under dynamic loading conditions. Yet, it depends on the type of bullet (Fig. 1). On the one hand, impacts with BR7 bullets show mainly a circular cracking front, the speed of which has a constant value V_c of the order of 1500m/s. This result indicates that numerous radial cracks propagate from the impact zone; this explanation is confirmed by post-mortem examinations (that revealed mainly radial cracks propagating from the impact zone). On the other hand, other phenomena occur with BR4 bullets. Post-mortem observations reveal that there is a comminuted zone just under contact. Far from the impact area, we can observe long cracks. In particular, a Rayleigh cone appears due to tension on the surface [3] with BR4 bullets. The Rayleigh cone is caused by multiple nucleation of surface cracks induced by the so-called Rayleigh wave. This wave is created when the bullet impacts glass and propagates at a speed C_R of the order of 3300 m/s for glass [3].The theoretical angle of the cone is expressed as $\tan\theta = V_c / C_R$, $\theta \approx 25°$ and a value of 28° is found experimentally. This phenomenon is not observed with BR7 bullets. A finite element (FE) simulation with the explicit code Pamshock (all materials are supposed to be elasto-plastic) shows that tensile stresses are higher for BR4 impacts (Fig. 2). Consequently, the stress levels become too low for cracks to initiate close to the surface and cracking induced by the Rayleigh wave cannot develop when the target is impacted by a BR7 bullet. This is confirmed by using an anisotropic damage model [2].



BR4 BULLET



BR7 BULLET

Fig 1. Comparison of cracking patterns 10ms after impact

We can also observe nucleation of cracks ahead of the main circular front, especially with a BR4 bullet. This event is not observed when glass is tempered or impacted with BR7 bullets [1]. This damage seems to be independent of the damage front. The main crack front is caused by flaws that are located in the vicinity of the impact point. These flaws nucleate cracks that propagate at a constant velocity V_c. The FE simulation (Fig.2) shows that the level of tension is too small to nucleate cracks on the external surface of glass when impacted with BR7 bullet or when glass is tempered. When cracks nucleate ahead of the main front, an apparent speed greater than 1500 m/s is observed. This tendency can also be explained by the fact that numerous cracks can be formed ahead of the main front. The measured speed is an apparent speed caused by the coalescence of cracks in the zone of high stresses. This type of speed is bounded by the tensile stress rate induced by the compressive wave. The apparent speed can reach up to 3500 m/s, which corresponds to the compressive wave speed of glass.

To confirm the previous hypothesis, an impact is carried out with a glass tile with a scratch on its surface (Fig.3). The same phenomenon is observed, i.e., the scratch induces a propagating crack ahead of the main cracking front. Therefore, flaws located in the vicinity of the surface of glass constitute initiation sites.

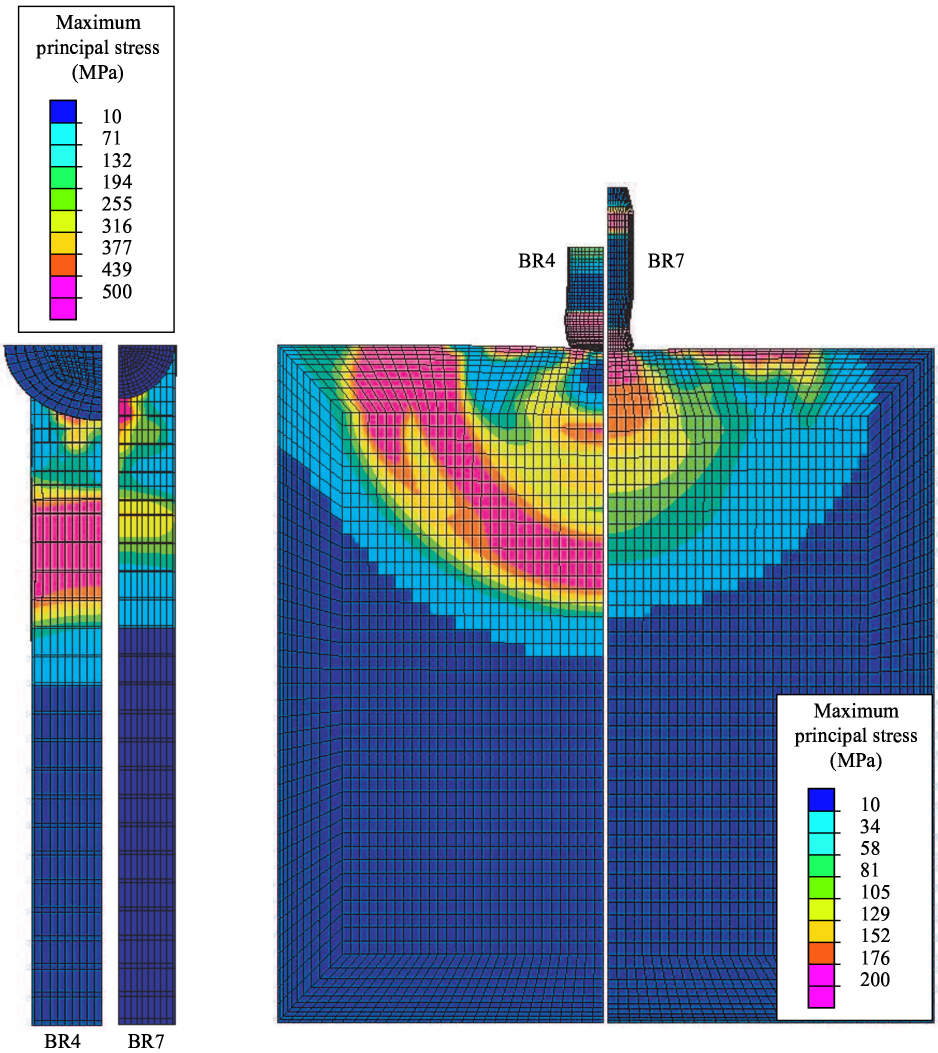


Fig 2 FE simulations showing tension level.

Fragmentation of impacted glass is mainly caused by the growth of cracks nucleated close the impact zone or the surface hit by the projectile. Differences observed between soft and hard bullets corroborate this hypothesis. Furthermore, BR4 bullets have a flat end whereas BR7 bullets have a piercing end. Soft bullets crash on the glass surface and are stopped whereas hard bullets penetrate glass. The population of defects is an important parameter that governs the cracking pattern. The estimation of the scatter in strength is the key to understanding the nucleation stage. Far from bullet impact, propagation of long cracks has been observed.

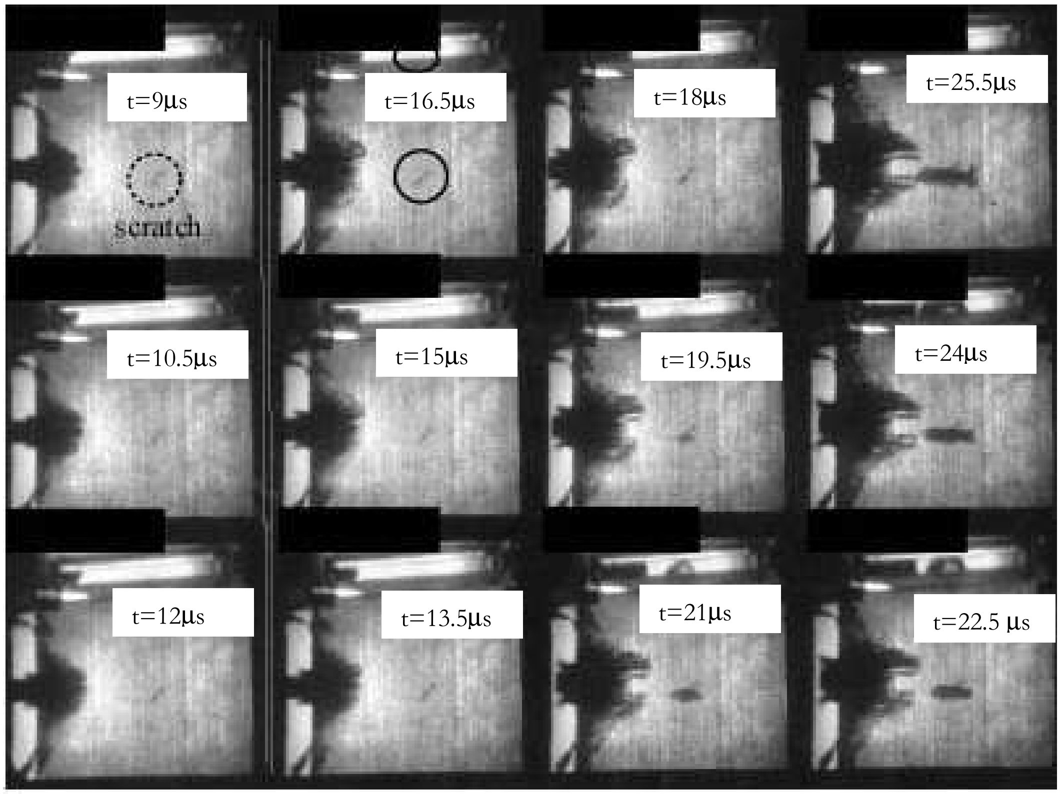


Fig 3 Cracking patterns of a glass tile with a scratch. A crack propagates ahead of the main cracking front 16.5µs after impact

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