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Effect of composite covering on ballistic fracture damage development in ceramic plates

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ABSTRACT

This paper describes the damage development in ceramics with and without composite cover during ballistic impact. This is relevant for ceramic inserts in body armor that are often covered with a composite material. To study the effect of the cover on the damage development in the ceramic, projectile impact experiments were performed at sub-muzzle velocities on bare alumina tiles and plates covered with a fiberglass composite. In addition to the experiments, finite element simulations were performed. An atypical formulation was used; Arbitrary Lagrangian–Eulerian (ALE) for the projectile and Lagrangian for the ceramic target. For the ceramic target, an unconventional material model was chosen; the pseudo-geological model 72_R3 in LS-DYNA.

Cracking damage in the recovered plates was characterized in a manner that clearly distinguished between cracking mechanisms and allowed the cracks to be tracked and quantified. In light of the common use of composite cover for ceramics in body armor, an unexpected result was found; that the covered plates showed significantly more damage than the bare plates. The simulations successfully matched details of the cracking patterns and elucidated the damage evolution in the ceramic plates. The simulation results explained the damage observations as the result of restraining effects, i.e. the restraining effect of the composite cover keeps the damaged ceramic in the path of the projectile resulting in increased damage.

1. Introduction and background

Ceramics are attractive tile materials in body armor systems because of their low density and high hardness. The role of the ceramic tile, usually alumina, boron carbide or silicon carbide, is to blunt, shatter, and erode the projectile. The tile is often covered by a composite material, which acts to confine the ceramic fragments and thus improve the multi-hit performance. The ceramic is also often backed with materials capable of absorbing and dispersing kinetic energy. For example, small-arms protective insert (SAPI) plates are often backed with several layers of aramid and/or ultra-high molecular weight polyethylene (UHMWPE) to enhance personal protection.

New designs are continuously sought to improve penetration resistance. Many researchers have performed experiments and developed models in efforts to better understand how ceramic tiles fail, and how failure is affected by a composite cover [1,2,4–16]. The studies do not fully agree on how the performance changes with addition of a composite cover to a ceramic tile. Some studies have shown a positive effect in terms of ballistic performance on an areal density basis of covering ceramic tiles in fiber composites (glass or carbon fibers) or ballistic fibers (aramid or UHMWPE). Sarva et al. studied the ballistic performance of both bare ceramic tiles and tiles with several types of cover material [7]. The study showed significant improvements in ballistic performance and higher projectile erosion (i.e. damage) when adding a front cover and minor additional improvements when also adding a back cover. The increase in performance was attributed to an increased flow of ceramic debris against the projectile due to constraints from the front cover. Contrary to the observations by Sarva et al., Crouch and coworkers [8] have found that adding a composite cover layer to a boron carbide ceramic tile, does not have a significant effect on projectile erosion. This is interesting, since erosion of the projectile is an important mechanism for defeating such threats. In another study, Nunn and coworkers [6] have found a > 40% increase in the ballistic limit, V_{50}, of a boron carbide tile by adding a composite cover that led to an increase in areal density by 9%.

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Crouch has shown that the addition of an aramid fiber based cover to a ceramic plate results in a lowering of the back-face deformation upon multi-hit [16]. In the same study, Crouch observed that the addition of the aramid-reinforced composite cover affected the failure mechanisms of the ceramic - an increase in the number of radial cracks in real-sized ceramic SAPI plates from an average 10.8 without cover to 16 was observed when the ceramic was covered. In another study, Reddy et al. [10] found that the size distribution of the ceramic debris created during impact changed toward smaller fragment sizes when a ballistic fiber front cover was added (the ceramic was backed by fiberglass composite).

Most of the above-mentioned impact studies are performed using regular projectiles, including armor piercing (AP) projectiles, or cylinders of similar size as penetrator and impact velocities around muzzle velocity (800–900 m/s) or at even higher velocities. There is, however, also insight to be gained by studying impact at sub-muzzle velocities. For example, Öberg et al. [17] compared the energy absorption of bare and composite backed ceramic tiles using 8 mm diameter steel spheres at 220 m/s. They found that the composite backing increased the energy absorption and that the effect was more pronounced with higher adhesion between ceramic and composite. In another study, Compton and coworkers [3] were able to identify the sequence of failure modes occurring in a ceramic tile by comparing analytical and numerical studies to impact experiments of metal spheres onto confined ceramic tiles in the velocity range of 250–800 m/s.

To better understand test results and to investigate the effects of composite covers on ceramic armor tiles, finite element analyses have been reported in the literature [8,9,11,12,18–24]. In addition to bare and covered ceramic tiles, layered armors, where two or more different materials form a layered structure, and composite armors have been modeled. Many of these analyses were performed with commercial codes using explicit Lagrangian formulations. To lower computational time, symmetry is often exploited in such analyses, sometimes to the extent where 2D simulations are performed to study the impact dynamics [8,20,22,24]. By performing 2D simulations in LS-DYNA, Feli and coworkers [20] found that when a projectile hits a ceramic/composite target, a ceramic cone breaks from the tile and the semi-angle of the conoid formed in the ceramic decreases with increasing impact velocity. The ceramic was modeled using the Johnson-Holmquist 2 (JH2) material model [23]; one of the most commonly used material models for ceramics.

Due to the non-symmetric nature of damage (cracking patterns) observed in ceramics, a full 3D approach (or applying half/quarter symmetry) is often required to describe the dynamics of the problem. A full 3D geometry was used by Grujicic et al. [21] to study the role of the adhesive interlayer between a ceramic tile and a composite back layer, using the JH2 model for the ceramic. The results showed that by adjusting the material properties of the adhesive, the performance of the hybrid armor can be improved. However, the study also showed that material properties that result in the best single-hit performance not necessarily optimize multi-hit performance. This is in line with results from other studies, showing that optimum thickness of the interlayer is a compromise between lowering either ceramic damage or back plate deformation [12] and that the damage accumulation of the ceramic is affected by the choice of interlayer material [11]. Bürger et al. [18] have also modeled projectile impact on a ceramic/composite target using the JH2 material model for the ceramic. The simulations were able to reproduce ballistic limits, V_{50}, found experimentally. However, the JH2 ceramic model was not able to reproduce the failure mechanics. The simulations showed less damage to the ceramic than what was observed experimentally.

The analyses mentioned above used Lagrangian continuum codes in which material damage was typically modeled by eroding (i.e. removing from the model) elements that have reached full damage. For ceramic armor, eroding elements can have significant effects on the ballistic response of the ceramic because the strength of the ceramic depends on the level of confinement; more confinement gives higher strength. By eroding elements, confinement is reduced and the adjacent elements in the ceramic lose strength and modify the stress field. As a result, fracture patterns observed experimentally are often not accurately reproduced. Alternative formulations have therefore been developed to better capture the response of fractured elements and to capture fracture patterns. Riedel et al. [25] combined commercial and in-house developed codes and material models, including a smoothed particle hydrodynamics (SPH) approach, to analyze fracture patterns and post-fracture loading for different loading histories, as well as failure conditions for edge-on impact experiments in ceramics. Eghtesad et al. [26] developed a corrective smoothed particle method (CSPM) modification of the traditional SPH method to predict fracture and fragmentation in ceramics under hypervelocity impact conditions. Espinosa et al. [27,28] developed an approach using a material model for cracking based on a multiplane plasticity approach that tracks crack initiation and growth in an element combined with a brittle fracture model to form discrete fragments that can interact.

In the present paper, ballistic experiments on bare and covered alumina tiles are described. A fiberglass composite is used for covering the tiles. These materials were chosen as they are commonly

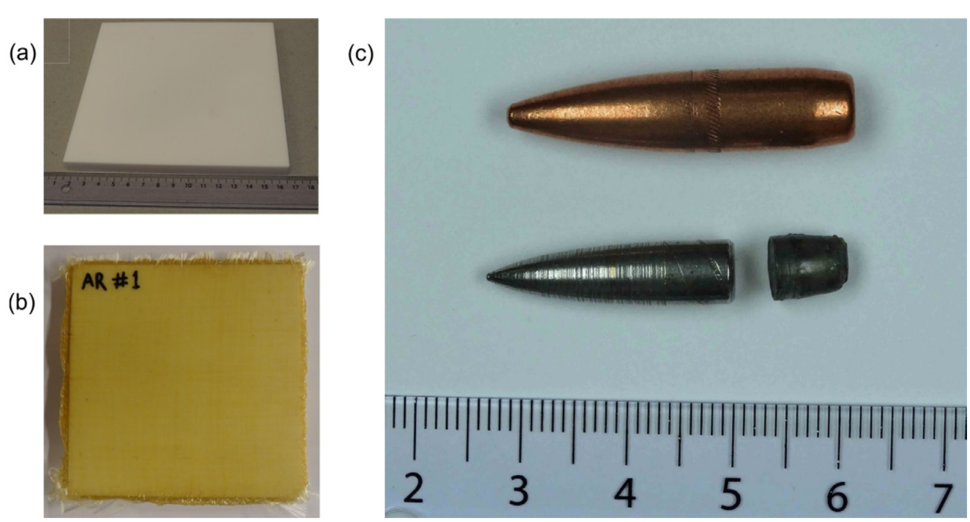

Fig. 1. (a) Bare ceramic tile, (b) ceramic tile covered with fiberglass, and (c) the M61 7.62 mm AP projectile with the steel core and lead filler shown individually.