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A ballistic material model for starphire®, a soda-lime transparent-armor glass

M. Grujicic[a,*], B. Pandurangan[a], N. Coutris[a], B.A. Cheeseman[b], C. Fountzoulas[b], P. Patel[b], Elmar Strassburger[c]

[a] International Center for Automotive Research CU-ICAR, Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, United States
[b] Army Research Laboratory-Survivability Materials Branch, Aberdeen, Proving Ground, MD 21005-5069, United States
[c] Fraunhofer Ernst-Mach-Institut (EMI), Efringen-Kirchen, Germany

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ABSTRACT

Experimental observations pertaining to the damage evolution in Starphire®, a soda-lime transparent-armor glass, made in the recent work of Strassburger et al. [E. Strassburger, P. Patel, J.W. McCauley, C. Kovalchick, K.T. Ramesh, D.W. Templeton, Proceedings of the 23rd International Symposium on Ballistics, Spain, April, 2007; E. Strassburger, P. Patel, J.W. McCauley, D.W. Templeton, Proceedings of the 23rd International Symposium on Ballistics, Spain, April, 2007] in a series of edge-on-impact (EOI) tests and other open literature experimental findings are used to construct a (high strain-rate, high-pressure, large-strain) ballistic constitutive model for this material. The basic components of the model are constructed in such a way that the model is suitable for direct incorporation into typical transient non-linear dynamics finite element-based software packages like ANSYS/Autodyn [ANSYS/Autodyn version 11.0, User Documentation, Century Dynamics Inc. a subsidiary of ANSYS Inc., 2007] or ABAQUS/Explicit [ABAQUS version 6.7, User Documentation, Dessault Systems, 2007]. To validate the material model, a set of finite element analyses of EOI tests was carried out and the computational results compared with their experimental counterparts. It is found that front-shapes and propagation velocities of the longitudinal and transverse waves are quite well represented by the model. The same was found to be the case for front-shapes and propagation velocities of the "*coherent-damage*" zones but mainly at shorter post-impact times. Discrepancies at longer post-impact times are attributed to the effects of damage-promoting target-fixturing-induced stresses and cutting/grinding-induced flaws.

1. Introduction

Recent experiences of the U.S. military forces in the Operation Iraqi Freedom have clearly demonstrated the critical importance of transparent-armor. With continuing escalations in the number and variety of threats, the needs for rapidly deployable threat-specific weight/cost-performance-optimized transparent-armor and armor systems have greatly increased. There are numerous efforts by the researchers in the U.S.A. and elsewhere around the world, to help accelerate the development of transparent-armor systems. For example, the Army Research Laboratory at the Aberdeen Proving Ground, MD and the U.S. Army Tank Automotive Research Development and Engineering Center in Warren, MI, have established a partnership with The Ernst-Mach Institute (EMI) of Efringen-Kirchen, Germany, to utilize the unique, fully instrumented "*Edge-on-Impact*" facility at the EMI, modified for dynamic photo-elasticity. This facility is being used to quantify stress wave propagation as well as damage nucleation and propagation during high-velocity impact of a hard projectile onto the side face of a transparent-armor plate. The results of these experimental investigations provide the required short post-impact data and insight into the role of different wave-mechanics, deformation and fracture phenomena within the armor materials and along material interfaces. These are, in turn, used to corroborate and further refine existing high deformation-rate, large-pressure, large-strain material models for transparent-armor and transparent-armor systems and are expected to eventually guide the design of armor materials as well as inter-layering and laminating armor systems.

The current development of armor systems is guided by the "*fire and maneuver*" doctrine which calls for light-weight solutions that enable soldiers and vehicles to be highly mobile, destroy their targets, and return home safely [5]. The armor must provide pro-

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[*] Corresponding author at: 241 Engineering Innovation Building, Clemson University, Clemson, SC 29634-0921, United States. Tel.: +1 864 656 5639; fax: +1 864 656 4435.
E-mail address: mica.grujicic@ces.clemson.edu (M. Grujicic).

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tection from a wide variety of threats, and must not interfere with the soldier's ability to do their job. Relative to conventional armor, transparent-armor has an additional requirement in that it must be transparent and must remain transparent to visible light after being impacted by a projectile. These transparency and multi-hit capability requirements dramatically limit the material choices for transparent-armor systems. Traditionally, transparent-armor is made of monolithic glass or transparent-elastomer inter-layered glass laminates. Among the new transparent-armor materials and technologies available today, the following have received most attention: crystalline ceramics (e.g. aluminum-oxinitride spinel, AlON [6]), new transparent polymer materials (e.g. transparent nylon [7]), and new interlayer technologies (e.g. polyurethane bonding layers [1]), and new laminate designs, e.g. [8].

Transparent-armor is commonly used in the following military applications: ground-vehicle protection, air-vehicle protection, personnel protection, and protection of equipment such as sensors and communication devices. Among the typical commercial applications requiring transparent-armor are the items such as riot gear, face shields, security glass, armored cars, and armored vehicles. One of the largest application areas for transparent-armor are windshields and side windows on ground military vehicles like high-mobility multi-wheeled vehicles (HMMWVs), tankers, trucks, and resupply vehicles. The following general requirements are typically placed on transparent-armor when used in these applications [7]: (a) the armor must be able to withstand multiple hits since most threat weapons are automatic or semi-automatic; (b) the windows must be full-size so that the vehicle can be operated without reducing the driver's field of view; (c) the use of transparent-armor must not give rise to an excessive increase in weight, since the added weight, when significant, can often require enhancement of the suspension and drive train, in order to maintain the vehicle performance and payload capacity; (d) thinner armor systems are also preferred to increase the cabin volume of the vehicle; and (e) The armor system must also be compatible with night vision goggle equipment and offer laser protection.

Due to their large size and curved shape, the majority of armor windows are still being constructed using glass. While ever increasing demands for reductions in weight and for improvements in ballistic-protection performance of transparent-armor are calling for the use of new transparent materials (e.g. transparent crystalline ceramics, advanced transparent polymeric materials) and advanced technologies (e.g. multi-material functionally graded laminated transparent-armor), glass (as well as glass ceramics) continue to remain important material choice in ground-vehicle transparent-armor applications. Compositional modifications, chemical strengthening, and controlled crystallization have demonstrated to be capable of significantly improving the ballistic properties of glass [7]. Glass windshields and windows can also be produced in large sizes with curved geometries, and can be produced to provide incremental ballistic performance at incremental cost.

The main objective of the present work is to utilize some of the soda-lime glass experimental data generated by Strassburger et al. at the EMI [1] in order to develop a high deformation-rate, large-pressure, large-strain model for this material. Such model can then be used in transient non-linear dynamic simulations of the tests typically employed to quantify the ballistic performance of glass-based transparent-armor. While there is a number of soda-lime glass material models in the open literature, e.g. [9,10], our preliminary investigation has shown that these models either do not realistically predict the response of glass under ballistic impact conditions (e.g. the model proposed by Brajer et al. [11] does not account for the formation of crack centers ahead of the damage-zone front) or rely on the use of interfacial-element activation algorithms, e.g. [12] which cannot be readily incorporated into commercial transient non-linear dynamic codes like ANSYS/Autodyn [3] or ABAQUS/Explicit [4]. A more detailed discussion regarding the relationship between the current material model for glass and the existing glass material models is provided in Section 5.

The organization of the paper is as follows: a brief description of the edge-on-impact (EOI) tests and real-time recording of the wave and damage propagation using a Cranz–Schardin photographic technique based on shadow-graphs and photo-elastic effects as well as a summary of the main results is presented in Section 2. The development of a high deformation-rate, high-pressure, large-strain material model for soda-lime glass which can account for the experimental observations made in the work at EMI is presented in Section 3. A description of the finite element analysis of EOI test is presented in Section 4. The computational results obtained are presented and compared with their experimental counterparts in Section 5. A brief discussion of the relationship between the proposed material model for glass and the existing material model for the same material is given in Section 5. A brief summary and a list of conclusions resulting from the present work are presented in Section 6.

2. Edge-on impact (EOI) tests and results

2.1. Edge-on impact test set-up and procedure

Edge-on impact (EOI) tests are frequently used to study deformation and damage of (non-transparent) conventional structural ceramic armor systems. Most of these studies involve real-time, reflection-mode, optical monitoring of armor deformation and damage during impact. In the work carried out by Strassburger et al. [1], the EOI method is coupled with a high-speed 0.10 μs-resolution Cranz–Schardin camera (originally developed at the Fraunhofer-Institute for High-Speed Dynamics, EMI). This test set-up was utilized in a number of studies to visualize damage propagation and dynamic fracture in structural ceramics. In the work of Strassburger et al. [1], the test set-up was reconfigured in order to record photographically the propagation of damage in transparent-armor systems using the plane-light shadow-graphs transmission mode ("*the shadow-graphs mode*"). In addition, the test set-up was modified by adding crossed polarizers to visualize the propagation of stress waves using a dynamic photo-elasticity technique ("*the photo-elasticity mode*"). A schematic of the edge-on impact test set-up with the added crossed polarizers is displayed in Fig. 1, while Fig. 2 provides a close-up view of the projectile/target interaction and a schematic of the resulting damage and wave swept zones.

Within the EOI tests used by Strassburger et al. [1], the projectile strikes one side face (generally referred to as an "*edge*") of a plate-like specimen/target and damage formation and fracture propagation is recorded by photographing (in transparent mode) the broad faces of the target during the first 20 μs following the impact. Plate-shape 100 mm × 100 mm × 10 mm test specimens/targets are typically impacted using either solid cylinder-shape steel projectiles (30 mm diameter, 23 mm length) or using 16 mm-diameter solid sphere-shaped projectiles. The impact velocities used are normally in a range between 270 m/s and 925 m/s. In the shadow-graph mode of the optical set-up, the target is placed between the condensing lens and the camera. In the photo-elasticity mode of the optical set-up, two sheet polarizers (one on each side of the target) are attached to the transparent sides of the target chamber so that broad polarizers' faces are parallel with the broad target faces (Fig. 1).

For the velocities below 400 m/s, a gas gun was used for the acceleration of the projectiles. The projectile velocity was mea-