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Modelling impact fracture and fragmentation of laminated glass using the combined finite-discrete element method

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ABSTRACT

Fracture and fragmentation responses of laminated glass under hard body impact are modelled with the combined finite-discrete element method (FEM-DEM). The method is essentially a discrete element method with finite element mesh be embedded in, yielding more accurate contact forces as well as mass and energy conservation. Failure models of glass, interlayer and glass-interlayer interface are discussed respectively and proven to be reliable in simulating the rupture of laminated glass. Numerical examples are presented and validated with results from different sources, and the advantage of the FEM-DEM modelling on the impact failure of laminated glass over its parent FEM and DEM is demonstrated. The influences of Young's modulus of interlayer are further discussed, showing that a stiff resin can effectively improve the deformation performance at little expense of energy absorption. In general, modelling the impact failure of laminated glass using the combined finite-discrete element method is successful.

1. Introduction

Laminated glass, which is typically composed of glass plies and interlayer(s), is increasingly popular for structural purposes in recent decades [1–2]. Consequently, its fracture and fragmentation responses under impact action attract growing attentions from both academics and practising engineers. Earlier investigations on the performance of laminated glass elements under bending or lateral pressure were conducted experimentally [3–4]. Recently, Zhang et al. [5] presented laboratory test results on the vulnerability of laminated window glass, and concluded that the interlayer thickness plays a crucial role in improving the penetration resistance. Marcon et al. [6] studied the windshield laminated glass experimentally and identified the damage process from the initial micro-crack to catastrophic macroscopic failure.

Since high-speed camera is essential for capturing the transient fracture responses in laminated glass, direct experiments are expensive to perform. In addition, tests could yield some random results and be influenced by unpredictable factors. As an alternative, a variety of novel computational approaches are developed to solve complex fracture and fragmentation. Rabczuk and Belytschko proposed two and three-dimensional cracking particles method [7–9] within the element-free Galerkin (EFG) framework. The method is capable of handling crack branching and fragmentation, and results were validated with numerical and experimental data. Meanwhile, peridynamics was employed to model the rupture of composite laminates [10] under shock-type loading. Further, dual-horizon peridynamics (DH-PD) was developed by Ren et al. [11–12] and used to examine the crack propagation in Kalthoff–Winkler plate as well as crack branching problems..

As for the impact fracture and fragmentation of laminated glass, the finite element method (FEM) is commonly used. In Flocker and Dharani [13–14], linear elastic constitutive relationship was employed to evaluate the fracture of glass plies subject to low velocity missiles based on the maximum tensile stress criteria using an explicit finite element code DYNA2D. They assumed that the interlayer was made out of Polyvinyl Butyral (PVB) and a Hertzian cone was obtained. The laminated glass was assumed to be perfectly bonded without any potential debonding or slipping during impact and only the glass ply in contact with the projectile can be damaged. Du Bois et al. [15] applied two coincided elements (a Belytschko–Tsai shell element for glass and a membrane element for PVB interlayer) in their laminated glass impact investigation. A piecewise linear plastic fracture criterion that allows for a small plastic strain is used for glass failure, and was employed to predict the behaviour of windscreen under a sphere impact. However, the use of coincidental elements assumes that both outer and inner glass plies fail at the same time, which may be unrealistic. Pyttel et al. [16] modelled the crack initiation and propagation in windshield laminated glass subjects to rigid ball impact based on the critical energy threshold and

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local Rankine (maximum stress) criteria using the commercial finite element solver PAM-CRASH. Recently, Chen et al. [17] developed a linear contact algorithm LC-Grid and cohesive model, and coupled them with FEM modelling on impact fracture of laminated glass.

It is understood that although the FEM is capable of predicting the crack initiation and propagation in the laminated glass with reasonable accuracy, possible fragmentation and interactions between fragments are difficult to be simulated due to the natural limitations, i.e. the continuity requirement of the FEM and this cannot be readily resolved by using enhanced shape functions such as XFEM. For the impact fracture and fragmentation analysis of laminated glass, the discrete element method (DEM) can better accommodate the inherent discontinua mechanism. Oda et al. [18] employed the DEM to model the impact behaviour of laminated glass. Later, the approach was extended to laminated glass of bi-layer type [19]. Fragmentation of laminated glass subjects to ball impact was investigated by Zang et al. [20] using rigid spherical discrete elements and a Mohr-Coulomb failure criterion. In the work of Gao [21], spherical discrete elements were also used and qualitative analysis on fracture of laminated glass is performed. Xu and Zang [22] extended the sub-domain concept and attempted to employ the spherical discrete elements for potential fracture region and cubical finite elements for non-fracture region with four-point combined DE/FE algorithm to evaluate the interactions on the DE-FE interfaces. An extrinsic cohesive fracture model is employed for the brittle fracture of glass, while the interlayer is assumed not to fracture during the impact process. Though spherical discrete elements are capable of simulating the post-damage behaviour, crack patterns are usually of low precision and only some non-recognisable cracks can be obtained. Generally, the DEM is good at simulating the fragments and fragmentations of laminated glass under impact, however, precision in predicting crack initiation and fracture patterns is usually unsatisfactory.

To obtain accurate crack initiation and propagation, realistic fracture patterns and practical fragmentation predictions, a novel computational method, i.e. the combined finite-discrete element method (FEM-DEM) [23] is employed in this paper. It overcomes the limitations of the FEM and DEM and best suits for transient computation of discontinua where contact is involved. In the analysis, the structure is fully discretised into a number of individual discrete elements, and each discrete element interacts with those that are in contact with it. Within a discrete element, a finite element mesh is formulated, leading to a more accurate estimate of contact forces, stress distribution and deformation. Fracture models are implemented in the joint interfaces between two adjacent elements. By using the FEM-DEM with an appropriate fracture model, the fracture process of laminated glass under impact can be better represented than its parent FEM and DEM. Unlike some FEM approaches, fragments in the FEM-DEM simulation generated by the impact also take part in the following contact interactions, making the mass and energy comply with the law of conservation.

The combined FEM-DEM was developed by Munjiza and co-workers in 1990s [24–25]. A Munjiza-No Binary Search (NBS) algorithm [26] was proposed by Munjiza and Andrews for contact detection. Later, a combined single and smeared crack model [27] was developed by Munjiza et al. and implemented into the FEM-DEM program “Y” [28]. Issues of mesh sensitivity were discussed and addressed by Munjiza and John [29]. These principles and computational points of the FEM-DEM were systematically summarised in a monograph [23]. The FEM-DEM is still developing and a recent paper [30] proposed a shell FEM-DEM element for the fracture and fragmentation of thin shells. Furthermore, a parallelization solution based on space decomposition is also introduced by Lukas et al. [31]. A newly published book [32] provided ‘down to earth’ illustration of the framework for developing large-strain based nonlinear material laws and the large-strain large-displacement based FEM-DEM. Though there are some applications of the FEM-DEM on fracture considerations, most of them are emphasised on the static or dynamic behaviour of brittle or quasi-brittle civil engineering materials like rock falling [33–34], concrete breakage [35–36] and masonry failure [37–39]. Little attention is given to the impact fracture and fragmentation of glass and laminated glass. The present authors [40] successfully simulated the impact fracture of monolithic glass using the combined FEM-DEM, with the acquisition of a variety of damage modes, e.g. flexural crack, Hertzian cone crack, punching failure and etc. Impact fracture and fragmentation process of laminated glass is highly nonlinear and discontinuous, thus the discontinua-based FEM-DEM approach is appropriate. As was indicated by Rabczuk and Belytschko [7], “for problems with many cracks and less predictability, such as fragmentation, simple methods such as interelement separation may be appropriate.” Since many cracks occur in laminated glass within the impact duration and inter-element separation is employed in the FEM-DEM, the FEM-DEM is suitable for the impact fracture and fragmentation modelling of laminated glass.

Some simple computational issues on the FEM-DEM modelling of laminated glass were addressed in [41–42]. This paper is a substantial extension of [40] and emphasised on the modelling of impact fracture and fragmentation of laminated glass. Following the theoretical background of FEM-DEM, the fracture criteria of glass, interlayer and glass-interlayer interface are discussed respectively. Fracture and fragmentation of laminated glass under hard body impact is simulated using the FEM-DEM program. Results are proven to be reliable by comparing with those from existing literature. A further discussion is presented on the effect of the Young's modulus of interlayer, quantitatively revealing the role of interlayer in the impact fracture and fragmentation mechanism of laminated glass.

2. The FEM-DEM

The combined finite-discrete element method (FEM-DEM) aims at solving large scale transient dynamics where contact and fracture are involved. It considers the solid a combination of both continua and discontinua. Details of the FEM-DEM are found in [23], and some key aspects of the FEM-DEM are addressed in this section.

2.1. Motion of elements

In the FEM-DEM, the stress and deformation are formulated by the standard FEM approach, while the motion and contact forces of elements are considered by the DEM. The translational and rotational motions of a single discrete element i are expressed in terms of Newton's second law as

$$m_i \frac{d^2}{dt^2} r_i = F_i \tag{1}$$

$$I_i \frac{d}{dt} \omega_i = T_i \tag{2}$$

where m_i is the mass of discrete element i; r_i is the position; I_i is the moment of inertia; ω_i is the angular velocity; F_i and T_i are net external force and torque, respectively. Accordingly, velocity and position of an arbitrary discrete element can be determined explicitly at each time step.

2.2. Contact algorithm

Contact algorithm, which can be classified as contact detection and contact interaction, is the central of the FEM-DEM. Contact detection is a particular research domain of DEMs and beyond the scope of this paper. The Munjiza-No Binary Search (NBS) algorithm is employed in the current FEM-DEM so that computational time is linearly proportional to the number of elements involved in the simulation. Full details on the Munjiza-NBS contact detection algorithm can be referred to [23,26].Once contact detection is completed, contact interaction follows where contact forces are defined according to interaction law. In the FEM-DEM, distributed contact force is adopted for two discrete