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On the impact fracture simulations of automotive laminated glass

ShunhuaChen[1], MengyanZang[1]
[1]*South China University of Technology, Guangzhou, China, 510641*
Email:chenshunhuascut@gmail.com;myzang@scut.edu.cn

Abstract:

***Background*:**Laminated glass which is comprised of two soda-lime glass sheets bonded with a plastic interlayer, polyvinyl butyral (PVB), is widely used in the automotive and architectural industries. As a windshield glazing, laminated glass possesses good energy absorption capability, which is helpful to reduce the head injury of the pedestrian during its impact with the windshield glazing in a pedestrian-vehicle accident. In addition, the adhesion between PVB and glass is conductive to bond the glass fragments to reduce the possible risk of injury by the flying glass shards.

***Objective*:**In this work, we review three kinds of numerical algorithms, namely the discrete element method (DEM), the coupling discrete element and finite element method (DEM/FEM) and the cohesive zone model (CZM), for the impact fracture simulations of automotive laminated glass. Based on the non-continuum theory, the DEM is capable of modeling the impact fracture phenomenon. However, this method is very time-consuming. To remedy this shortcoming, we have been devoted to combining the discrete element method and the finite element method. Another notable work is to simulate the impact fracture behaviors by using the CZM. Some future works concerning this research aspect are also presented.

Keywords:PVB laminated glass, Coupling DEM/FEM, Cohesive zone model, Impact fracture

1 Introduction

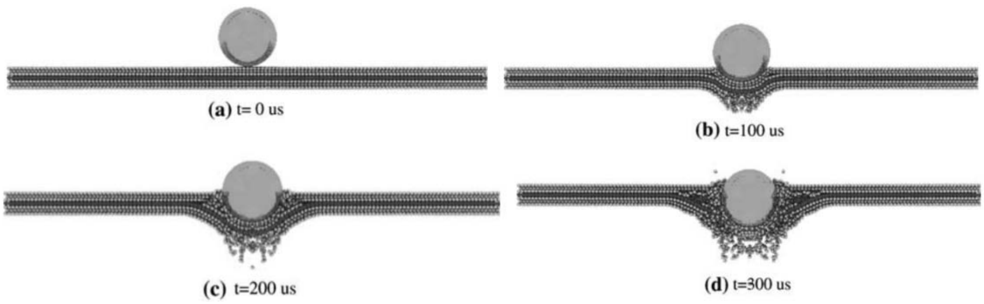
Up to now, various numerical simulations have been carried out to investigate the impact fracture behaviors of laminated glass. The most common technique is the element deletion method [1-3], which is available in the commercial FE solvers, such as LS-DYNA. A series of works in Zang's research group [4-9] have been devoted to developing the DEM and the DEM-FEM for the impact fracture analysis of laminated glass. Xu et al. [10] numerically investigated the impact cracking behaviors of laminated glass by using the extended finite element method (XFEM). Recently, another notable work in Zang's research group is to adopt the CZM in the framework of the finite element method for the application of interest here [11].

In this work, we review the three kinds of numerical algorithms developed in our group, namely the DEM, the DEM-FEM and the CZM, for the impact fracture simulations of laminated glass.

2 Numerical algorithms

2.1 DEM

The DEM was originally proposed by Cundall et al. to describe non-continuum based interactions [12]. Later, Oda and Zang [13] extended its application (in two dimensions) to fracture simulations of laminated glass, where the transition processes of materials from continuum to non-continuum occur. Furthermore, Zang et al. [4] simulated the impact fracture and fragmentation phenomenon of laminated glass by using a three-dimensional (3D) DEM, and the simulation results can be seen in Figure 1.



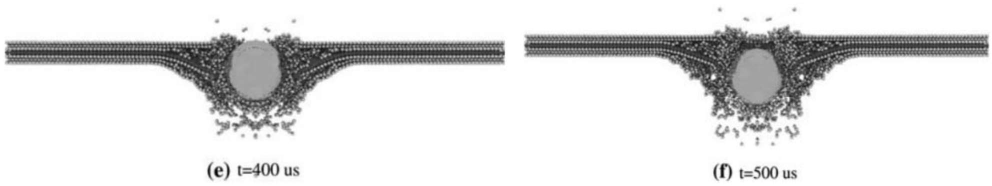


Figure 1.Impact fracture process of laminated glass by using a 3D DEM [4].

2.2DEM-FEM

Though the DEM is capable of capturing the impact fracture phenomenon, it suffers from two main drawbacks: the computational process is rather time-consuming; it is unable to describe large deformation behaviors in PVB. Considering the merit of mature ability of the FEM to solve continuum problems, we have been devoted to combining the DEM and the FEM to overcome these shortcomings. Three coupling algorithms have been proposed, namely the layered coupling algorithm [5, 9], the in-plane coupling algorithm [6] and the adaptive coupling algorithm [7, 8].

2.2.1 Layered coupling algorithm

In this coupling algorithm, the computational domain is decomposed into two parts, the DEM domain and the FEM domain. Each domain is solved independently, and the interface between them is connected by using a penalty function. As for the laminated glass, the glass is discretized into a series of spherical DEs, while the PVB film a series of FEs because it is prone to large deformation. Besides, Gao et al. [9] introduced a cohesive zone model into this coupling algorithm to describe the progressive brittle failure in laminated glass under impact. In [9], the impact fracture process of a laminated glass beam was simulated (see Figure 2), and the crack location and sequence were found to be in good agreement with those of the experiment.

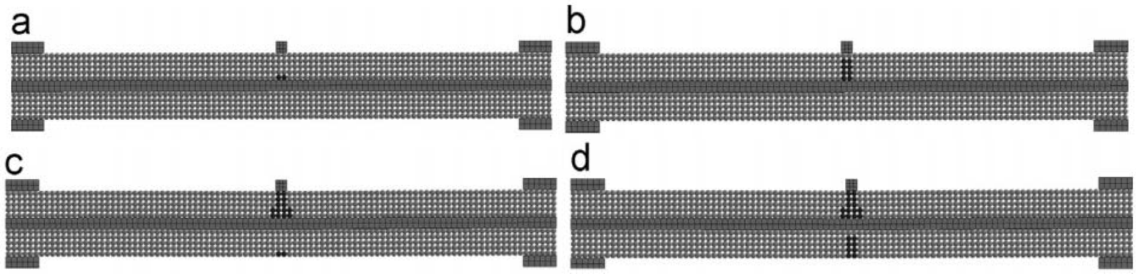


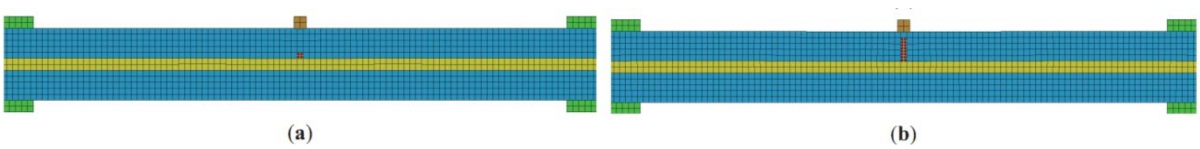
Figure 2. Impact fracture process of a laminated glass beam by using a layered coupling algorithm [9] .

2.2.2 In-plane coupling algorithm

On basis of the layered coupling algorithm, aiming to reduce the computational cost, the region that is to discretize into DEs in glass is restricted to be minimal in this coupling algorithm. That is to say, only the region in glass where cracks are possible to occur will be discretized into DEs, while the other region a series of FEs. Moreover, Xu et al. [6] proposed a four-point coupling algorithm in order to avoid the possible zero energy mode in [5]. Also, the impact fracture behaviors of a laminated glass beam were simulated to validate the proposed coupling algorithm.

2.2.3Adaptive coupling algorithm

In order to further improve the computational efficiency, the so-called adaptive coupling algorithm was proposed [7, 8], where the glass is initially discretized into FEs, then the FEs will be replaced by clusters of DEs when a defined criterion is met during calculations. To verify the efficiency and accuracy, the impact fracture simulations of a laminated glass beam was carried out (see Figure 3), and it was found that the computational efficiency of the adaptive coupling algorithm was almost ten times higher than that of the DEM [8].



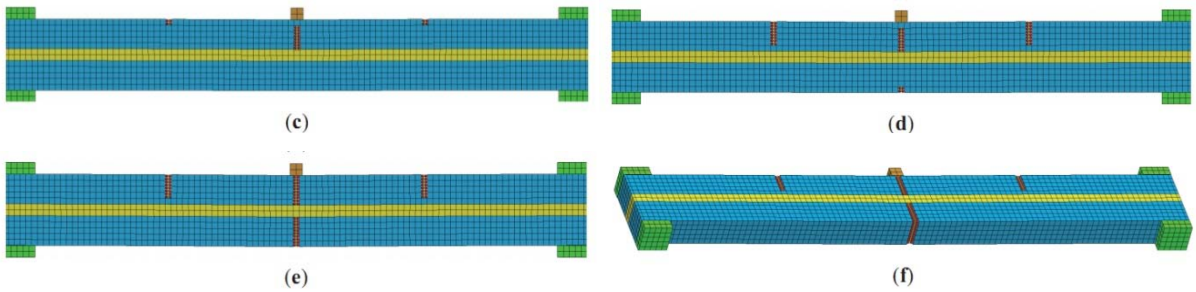


Figure 3.Impact fracture process of a laminated glass beam by using a 3D adaptive coupling algorithm [8].

2.2.4 DEM-FEM Contact algorithm

To tackle the contact interactions between discrete elements and finite elements, a 3D DEM/FEM was proposed based on a Node-to-Surface contact algorithm [14]. In this algorithm, discrete elements are treated as the slave nodes. Several other DEM/FEM contact algorithms can be found in [15-16].

2.3CZM

Considering the advantages of high computational efficiency and accuracy of the FEM, we advocated the well-known CZM in the framework of the FEM for the application of interest here. We adopted an extrinsic cohesive model to model the glass-ply fracture. In this model, cohesive elements are adaptively inserted into the boundaries between finite elements when a defined stress-based fracture criterion is satisfied. As shown in Figure 4, a cohesive element contains two faces, i.e. the upper face 1-2-3-4 and the lower face 5-6-7-8, and a middle face Sm is defined for the cohesive force calculation. Also, topological information of the finite element model needs to be updated along with the insertions of cohesive elements, as shown in Figure 5.

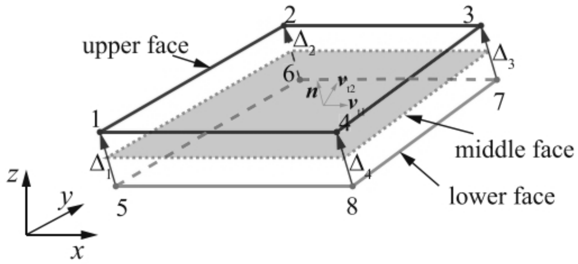


Figure 4.Schematic diagram of the cohesive element [11].

Another important aspect is the contact algorithm. We have developed an efficient global contact search algorithm and an accurate local contact search algorithm [11]. The global search algorithm includes a regular search process and an adaptive search process. The local search algorithm involves node-face and edge-edge contacts. Moreover, the judgments of node-face and edge-edge contacts can be performed by using a unified inside-outside algorithm, as shown in Figures 6 and 7.

We simulated the impact fracture behaviors of a laminated glass plate under drop-weight impact loading by using the proposed method. The geometric model used in the impact simulation is shown in Figure 8. The impact processes of the laminated glass plate can be found in Figure 9. The comparisons between simulation results and experimental outcomes in terms of fracture patterns and the impact force are presented in Figures 10 and 11, which also validates the capacity of the proposed algorithm in the impact fracture simulations of laminated glass.

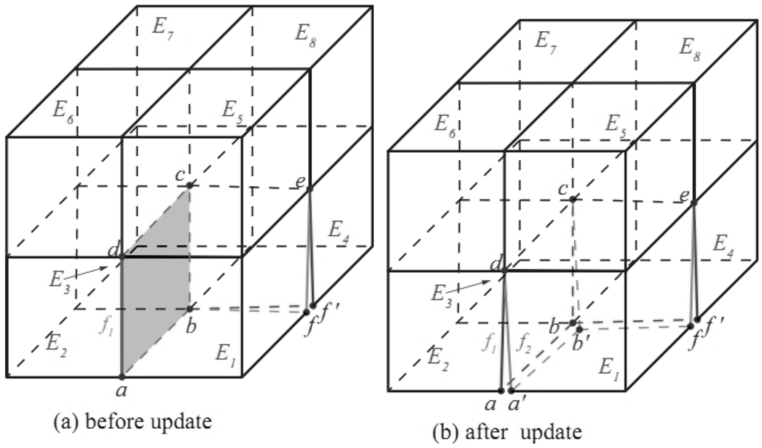


Figure 5. Topological information changes due to the insertions of cohesive elements [11].

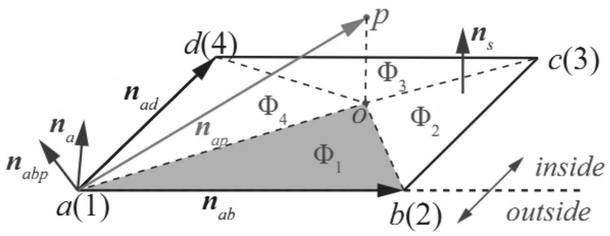


Figure 6. The contact judgment of the node-face contact [11].

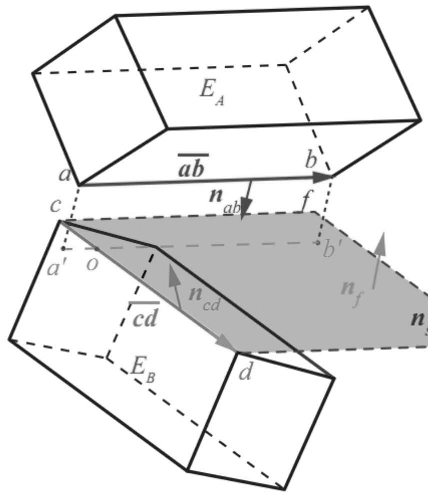


Figure 7. The contact judgment of the edge-edge contact [11].

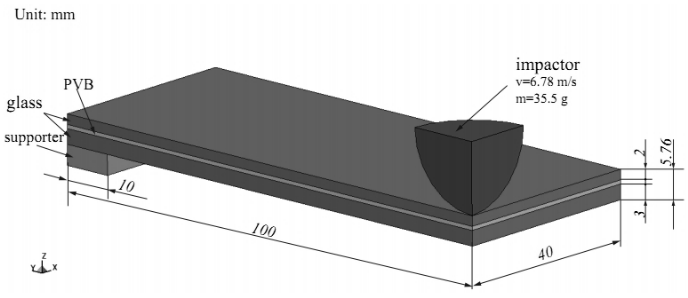


Figure 8 The geometrical model used in the impact simulation [11].

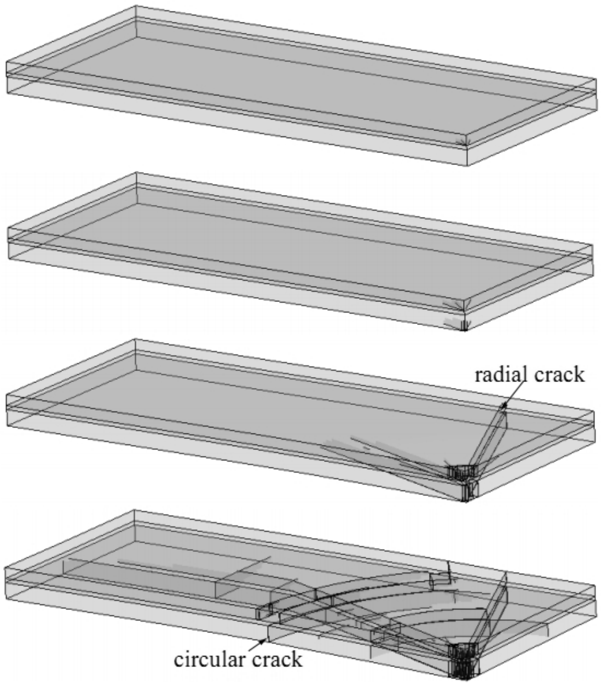


Figure 9. Impact fracture processes of a laminated glass plate by using the CZM. [11].

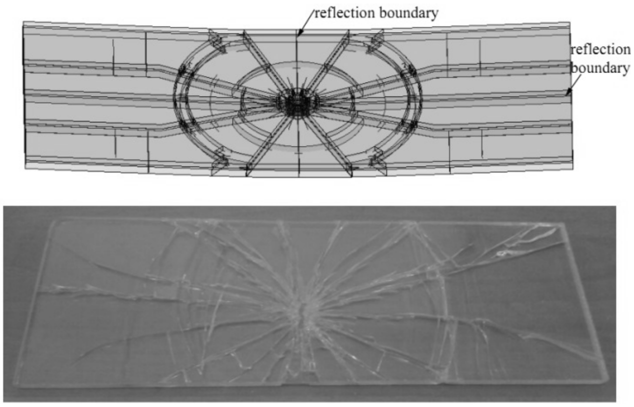


Fig. 10 The fracture patterns of the laminated glass plate. The top one is the simulation result and the bottom one is the experimental outcome. [11].

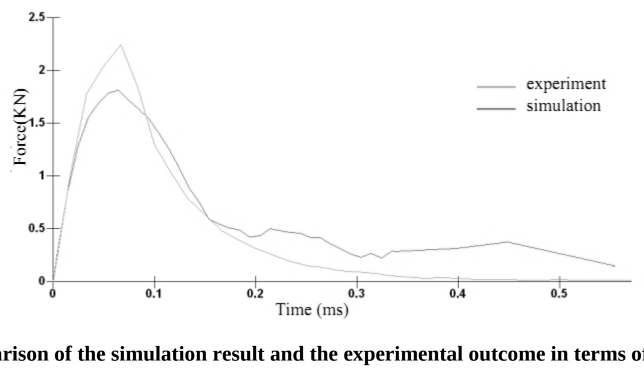


Figure 11. The comparison of the simulation result and the experimental outcome in terms of the impact force [11].

3 Discussions and future works

As stated above, the adaptive DEM/FEM coupling algorithm is certainly the most accurate and computational efficient among the proposed DEM and coupling DEM/FEMs. However, this algorithm is still limited to simulate simple fracture pattern, and its ability to capture the propagation and the branching of multi-fracture needs to be proved. In this regard, CZM appears to be a good alternative. However, contact situations are much more complicated in this algorithm, since the crack interactions in DEM/FEM are simplified as the interactions between spherical discrete elements.

Future works in our group involve: the development of the adaptive DEM/FEM to simulate multi-fracture phenomenon; the development of robust and accurate contact algorithms for the CZM-based simulations; and GPU parallel computing of the two algorithms above.

Acknowledgement

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