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PERIDYNAMICS ANALYSIS OF GLASS FRACTURE UNDER EXPLOSION LOAD

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ABSTRACT

To model and predict dynamic fracture of glass accurately, several computational methods in LS-DYNA software were reviewed. Bond-Based Peridynamics (PD) computational model were adopted due to its advantages to deal with damage and fracture behavior of glass without failure criterion. Based on this method, the fracture process of the glass under the explosion load of different amount of explosive was simulated. Simulation results show that damage arises in the border of glass panel and propagate to the center quickly. The more explosive mass, the less size of glass fragments.

Keywords: explosion load, soda-line glass, peridynamics, numerical simulation.

INTRODUCTION

In recent years, many bombing terrorist attack and accidental explosion occur from time to time around the world. Under explosion load, the building glass would fracture and produce a lot of flying debris very easily, which would cause a large number of loss of life and personal injury, and property loss. Therefore, it is significant to study the fragmentation of the glass under explosion load for the design of glass doors and windows.

There are many methods in LS-DYNA software which can simulate the generation of crack and the fracture process of the glass: (1) Delete the failure elements method. It can be achieved as follows: using the material model with failure criterion, such as *MAT_STRAIN_RATE_DEPENDENT_PLASTICITY, or adding failure criterion such as principal stress, principal strain or tensile stress with keywords *MAT_ADD_EROSION; (2) Nodes separation method. The nodes which are at the same location are fixed by *CONSTRAINED_TIED_NODES_FAILURE (Shi, 2015). When the plastic strain reaches a certain level, the nodes disconnect with each other and the crack forms; (3) Using constitutive model containing damage model, i.e., *MAT_JOHNSON_HOLMQUIST_CERAMICS (Wang, 2016), which also contain element failure criterion. The crack can be expressed with damage; (4) Insert cohesive elements between adjacent elements; (5) XFEM method; (6) EFG, SPH and DEM method. These methods have certain shortcoming in respect of crack propagation. For the first four kinds of methods, we need know the form, the size and the starting position of the crack in advance. The mesh should be obtained pointedly. The fracture failure or damage model is also needed, and the simulation result has a strong dependence on the grid. For the last two kinds of methods, there is no direct connection between the strain softening of the material and the critical energy release rate. XFEM method allows the crack extends along the surface of the elements, and this method usually is combined with cohesive

elements method to deal with the crack propagation problem of brittle material. The disadvantage of XFEM method is as follows: the gird should remesh repeatedly, and the calculation process take a lot of time; the crack branching aren't allowed, and it is unsuited for the crack propagation and the interaction between several crack; it can be used for shell element only, and it can't be used for the simulation of three-dimension crack propagation. EFG, SPH and DEM are meshless method, and they are unstable when deal with several crack.

To overcome the difficulty of traditional numerical simulation method on discontinuity problem, and predict the initiation and propagation of the crack, Silling *et al*. (Silling, 2000) proposed Peridynamics (PD). Based on this method, many researchers (Hu, 2013) simulated the fragmentation problem of glass under striking. This method was insert into LS-DYNA software in 2015. The PD method doesn't model based on the continuity hypothesis, and there is no need for the external failure criterion. The crack can initiate and propagate naturally. The dependence on the computational grid was eliminated completely. There are two kinds of PD methods: Bond-Based Peridynamics and State-Based Peridynamics) (Silling, 2007), which is used for the simulation of crack of brittle material and ductile material separately. The soda-line glass is a kind of brittle material. In this paper, Bond-Based Peridynamics would be used to investigate the dynamic fracture problem of glass under explosion load.

BOND-BASED PERIDYNAMICS METHOD

The traditional numerical simulation methods, such as finite element model theoretical, are based on continuum mechanics. The governing equations of these methods contain the derivation of space. As a result, there is singularity when dealing with the discontinuity region, such as crack, while PD method is a meshless method which is based on the non-local scope theory. The object is discretized into material point at a series of spatial domain. The state of any material point is influenced by the material points which are within a finite radius. The motion of the material point is described by integral equation. This theory is broken through the solving bottleneck of continuum assumption and the discontinuity problem of space differential equation.

The Bond-Based Peridynamics can be seen as the molecular dynamics from the macroscopic point of view. The equation of motion of arbitrary point (X) at the time of "t" can be described as follows,

$$\rho \ddot{u} = \int_{H_X} f(u(X^{'},t) - u(X,t), X^{'} - X)\ dV_{X^{'}} + b(X,t)$$

Where H_X is the neighbourhood in a radius of δ; $H_X = \left\{ X^{'} \| X^{'} - X \| \leq \delta \right\}$; "f" is the force function between the connection point X and $X^{'}$; b is the density function of external force.

Introduce two variables, relative location ξ and relative displacement η,

Where

$$\xi = X^{'} - X, \qquad \eta = u(X^{'},t) - u(X,t)$$

The force takes effect in certain neighbouring regions,

When $|\xi| > \delta$, $f(\eta,\xi) = 0$.

The newton's third law is also applicable,

$$f(-\eta,-\xi) = -f(\eta,\xi).$$

In Bond-Based Peridynamics method, the material is seen as micro-elasticity. So, the force can be obtained as follows,

$$f(\eta,\xi) = \partial w(\eta,\xi) / \partial \eta.$$

Where $w(\eta,\xi)$ is the potential-energy function, which is the elastic energy existing in the bond.

The total potential energy of the bond in point X is,

$$W = \frac{1}{2} \int_{H_X} w(\eta,\xi) dV_{X'}.$$

In the micro-elasticity material,

$$w(|\eta|,|\xi|) = \frac{1}{2} c s^2 |\xi|.$$

Where c is the micro-modulus, and it is a constant, which can be obtained with bulk modulus k,

$$c = \frac{18k}{\pi \delta^4}$$

s is the elongation of the bond,

$$s = \frac{|\xi + \eta - |\xi||}{|\xi|}.$$

Under small deformation condition, the force function is,

$$f(\eta,\xi) = \frac{cs\xi}{|\xi|}.$$

When the elongation of the bond between two points exceed the critical value s_c, the bond disconnect. s_c is related with the breaking energy G_c of classical fracture mechanics. Under three-dimensional condition,

$$G_c = \frac{\pi c s_c^2 \delta^5}{10}.$$

THE SIMULATION MODEL OF GLASS BROKEN

In the simulation, soda-line glass was used, whose length, width and thickness was 1m, 1m and 8mm. The glass was fixed constraint by window frame. The geometric model was shown in Figure 1. In the simulation model, the grid size in the direction of the length, breadth, thickness of the glass pane was 5mm, 5mm and 4mm. In PD method, each glass element was separately with the element adjacent, and they didn't have same nodes.
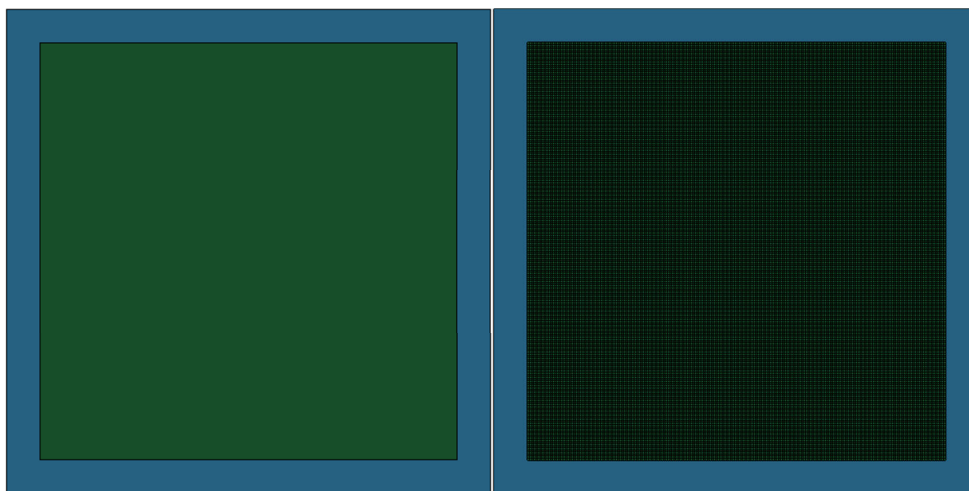
Fig. 1 - The geometric model

The window frame used *MAT_RIGID material model. *MAT_ELASTIC_PERI model was used for the glass, where the parameter was chosen as follows: density $\rho = 2440 \text{kg/m}^3$, elasticity modulus $E = 72 \text{GPa}$, fracture energy $G_c = 8 \text{J/m}^2$. In PD method, the poisson ratio is chosen as 0.25.

The contact form between the window frame and the glass is *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The mass of the explosive is 0.6kg, 0.8kg, 1.2kg and 1.6kg, respectively. The centre of the explosive ball and the centre of the glass are at the same height, and their distance is 5m.

The explosion load was applied to the surface of the glass by the keywords *LOAD_BLAST. This keywords adopt ConWep explosion load model (Glenn, 1997). ConWep model was based on the summary and analysis of a large number of test data for explosion, and it is accurate and reliable. The load calculation for elements at different location can be described as

$$P_l = P_r \cos^2 \theta + P_i (1 + \cos^2 \theta - 2\cos\theta)$$

Where P_r is normal reflected pressure, P_i is incident pressure and θ is the included angle between the element normal and the connecting line between element centre and explosion centre.

The explosive blast has positive pressure section and negative pressure section. After the explosion of 0.6kg explosive, Figure 2 shows the incident pressure curve and reflected pressure curve 5m away from the explosion centre with ConWep model. It can be seen from this figure that ConWep model only considers the positive pressure section.

RESULTS

Figure 3 shows the fracture process of glass under the explosion load of 0.6 kg explosive. Assuming zero time was the explosion time of the explosive. At 9.7 ms, the shock wave arrived in the middle of the glass. At 10.5 ms, the first annular crack initiated at the inner edge of the window frame. At 11ms, the second annular crack initiated at 0.12m away from the inner edge of the window frame. Then it cut-through with the first annular crack along the catercorner.
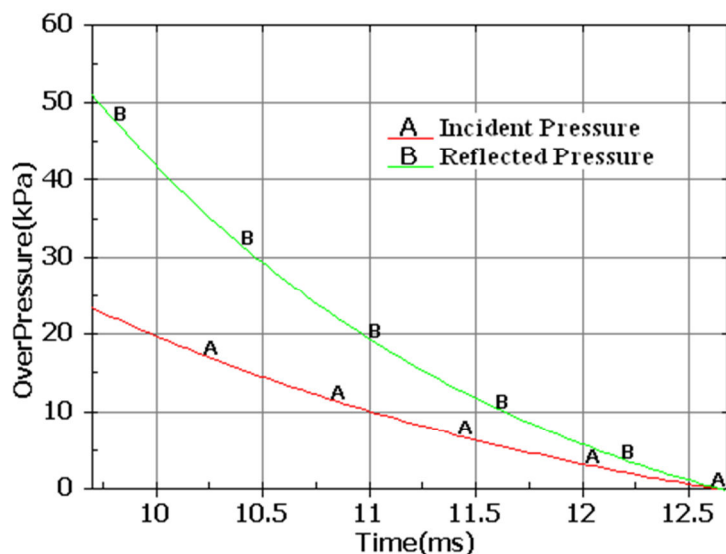
Fig. 2 - After the explosion of 0.6kg explosive, the incident pressure curve and reflected
pressure curve 5m away from the explosion center

The fragmentation region gradually got bigger and bigger at the corner of the glass, which
was caused by the reflection and the superposition at the corner. At 11.5 ms, the third
annular crack initiated at 0.17m away from the inner edge of the window frame. Then it cut-
through with the second annular crack along the diagonal. At 13ms, the breadth of the crack
increased. The second and the third annular crack connected with each other at many spaces.
At the same time, many radial pattern crack initiated at the centre of the glass, and these
pattern crack connected with the annular crack. Then big fragment formed. At 24 ms, the
broken square block at the centre of the glass completely separated with the noumenon, and it
flied off in the loading direction, while the surround glass flied off in the opposite direction.
Ge *et al*. (Ge, 2014) found the phenomenon of opposite direction flied off in the building
glass explosion experiments. He thinks this phenomenon is caused by the negative pressure
section of the shock wave. ConWep loading model doesn't include the negative pressure
section of the shock wave, but the simulation result of this paper indicate that the positive
pressure of the shock wave can cause the opposite direction splash of the glass fragment. It
may be caused by the fluctuation effects of glass pane under the explosive load.

Compared Figure 3b with Figure 3c, and compared Figure 3g with Figure 3h, it can be found
that the destruction of the backside (back to the explosion) of the glass is bigger than that of
the front side of the glass (faces the explosion) at the same moment. It is caused by the tensile
wave at the backside of the glass.

Figure 4 shows the side image of glass broken under the explosion load of 0.6kg explosive
(Time=24ms).

Figure 5 show the fragmentation image of the glass under the explosion load of various
amount of explosive (the time is 26us). The velocity curve for the central point of the glass
under various amount of explosive is shown in Figure 6. It can be seen that more explosive
would cause stronger and higher velocity shock wave, glass fragment with smaller size, and
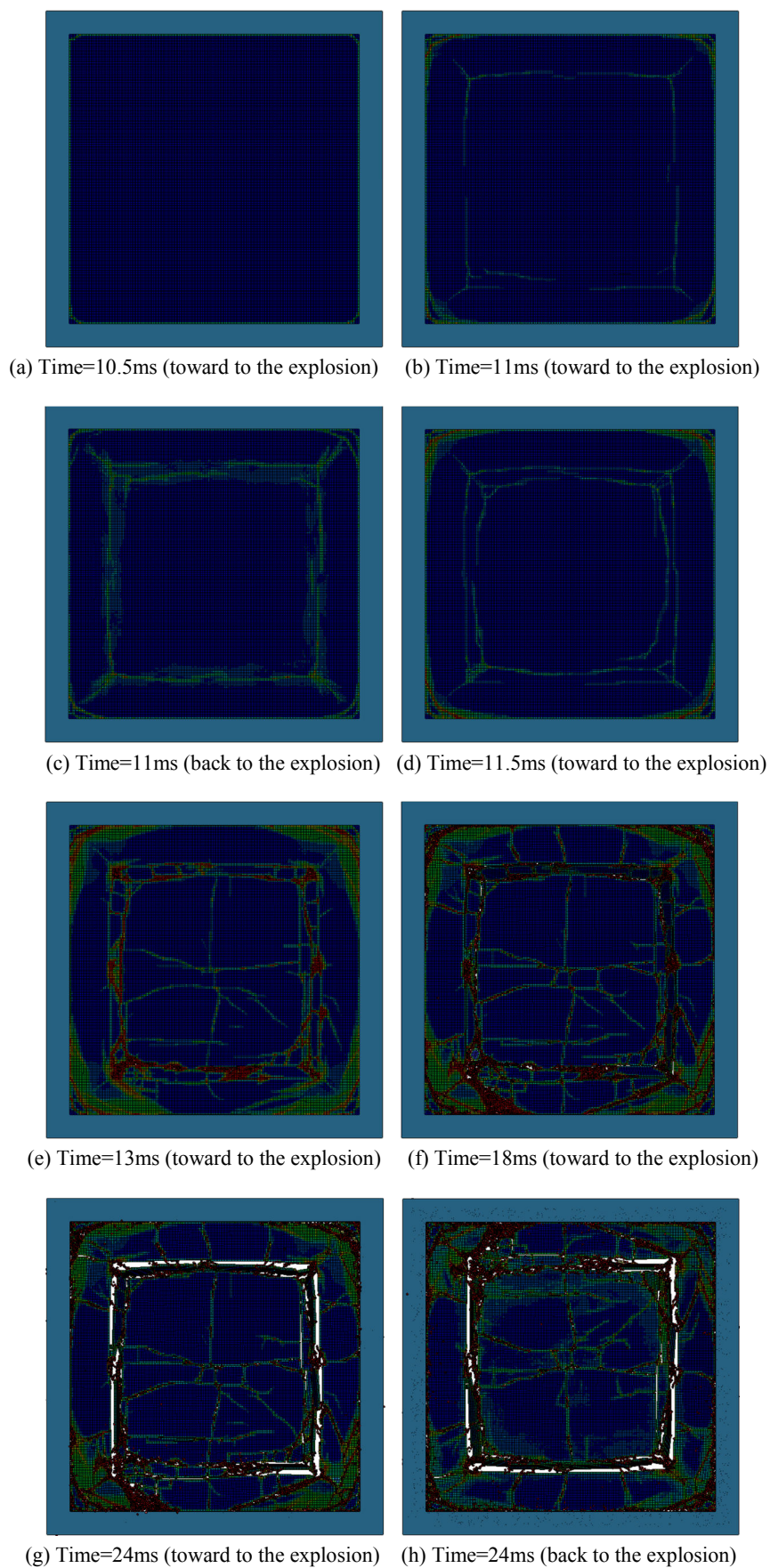central point of the glass with higher velocity.

(a) Time=10.5ms (toward to the explosion)   (b) Time=11ms (toward to the explosion)

(c) Time=11ms (back to the explosion) (d) Time=11.5ms (toward to the explosion)

(e) Time=13ms (toward to the explosion)   (f) Time=18ms (toward to the explosion)

(g) Time=24ms (toward to the explosion)   (h) Time=24ms (back to the explosion)

Fig. 3 - The fragmentation process of the glass under the explosion load of 0.6 kg explosive
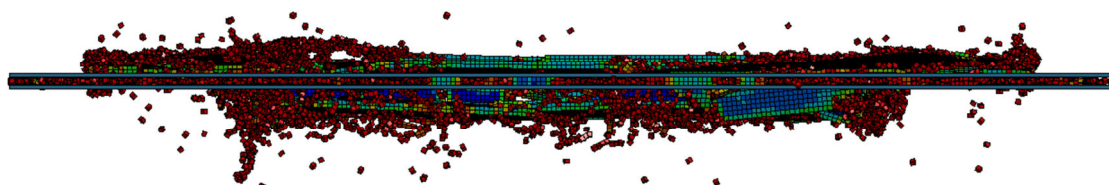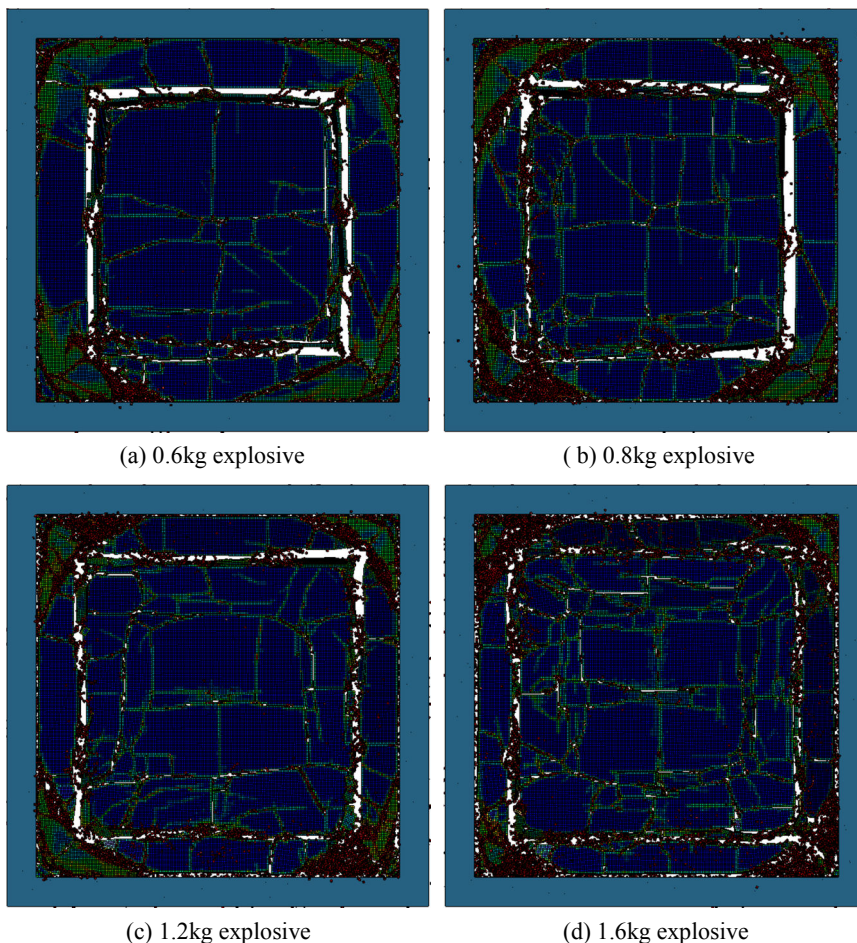
Fig. 4 - The side image of glass broken under the explosion load of 0.6kg explosive (Time=24ms)

(a) 0.6kg explosive

(b) 0.8kg explosive

(c) 1.2kg explosive

(d) 1.6kg explosive

Fig. 5 - The fragmentation image of glass under the explosion load of different amount of explosive (Time=26ms)
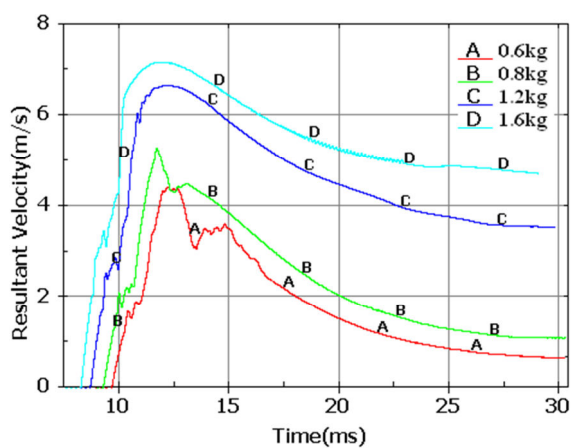

Fig. 6 - The velocity curve for the central point of the glass under various amount of explosive

CONCLUSION

This study shows that Bond-Based Peridynamics method is well suited for the simulation of the initiation and the propagation of cracks in the fragile material. In this paper, the fracture process of the glass under the explosion load of different amount of explosive was investigated with this method. It can be conclude that:

1) Although the shock wave arrive in the centre of the glass pane first, the crack start at the edge of the glass first. Then it propagates to the glass centre, and the glass centre separates with the noumenon first.

2) The central area of the glass fly off in the direction of the loading, while the surrounding glass fly off in the opposite direction. The reverse fly off isn't caused by the negative pressure of the shock wave.

3) The more explosive mass, the less size of glass fragments.

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