Research on the effect of UHMWPE cavity protection board on rapid enhancement of wall anti-blast performance

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Abstract: In view of the high cost and self-importance of traditional explosion-proof walls, a fiber composite material cavity protective board made of UHMWPE as a matrix is proposed to protect the walls of general civil buildings to achieve rapid enhancement in response to sudden terrorist attacks. Based on LS-DYNA finite element analysis, the response of the protective board and wall under the impact of the explosion is analyzed. By setting different key parameters such as equivalent weight, burst distance, presence or absence of protective structure, the damage to the wall, the protective effect of the protective board and its own performance characteristics are discussed. The results show that the externally arranged composite material protection board can effectively attenuate and absorb the overpressure and energy generated by the explosion shock wave, and significantly reduce the displacement and deformation of the wall, and it also has excellent performance in its own energy absorption and deformation resistance. But there is a certain safety protection distance under different equivalents.

1. Introduction
Since the 21st century, the development momentum of terrorism around the world has continued unabated, and various explosive shootings have occurred from time to time. Among them, bomb attacks on buildings often produce a chain reaction, causing a large number of indoor and outdoor casualties. Therefore, for relatively fragile civil buildings, wall reinforcement is very important. Traditional explosion-proof walls usually use high-strength concrete or equipped with a large number of steel bars to achieve wall reinforcement. This method is not only troublesome in construction and maintenance, but also has a high cost. It also greatly increases the weight of the structure. More importantly, it cannot be repaired quickly. For this reason, this paper proposes a method of applying a protective barrier on the outside of the wall to resist the impact of the explosion impact on the wall, so as to solve the above problems and realize the rapid enhancement of the general wall.

The lightweight and high-strength sheet composed of UHMWPE (ultra-high molecular weight polyethylene) fiber and polyurethane matrix can not only better resist the penetration of shrapnel, but also has better performance in anti-explosive impact performance. In the field of composite materials, the research on UHMWPE mainly focuses on the anti-shrapnel penetration, and there is little research on its anti-blast performance. Sipei Cai¹,² conducted aerial explosion experiments on composite sandwich panels composed of high-strength polyethylene and foamed aluminum, and explored the difference in anti-explosion performance of composite sandwich panels with different thickness...
combinations, and concluded that the high-strength polyethylene fiber layer adding to porous aluminum foam to make composite laminates can significantly improve impact resistance and penetration resistance. In the field of engineering protection, Ruiqing Zong [3] proposed an anti-explosion protection concept with guardrail-type protective structural columns outside the wall, and tested the attenuation of different protective structural columns by changing the cross-sectional geometry, spacing, and size of the guardrail columns. The ability of the explosion shock wave finally concluded that the protection system with the circular and isosceles right triangle as the guardrail section has a better effect on reducing the overpressure and impulse behind the column. In terms of the anti-blast performance of the wall, Li Tian [4] and others used numerical simulation to explore the displacement ratio of the concrete hollow block-filled wall under the combined action of explosion and fragmentation, the strength of the mortar, and the size of the steel mesh grid. The impact of anti-knock performance. It is concluded that increasing the wall-to-rib ratio of the hollow block and the densification of the steel wire mesh have a significant effect on the enhancement of the anti-blast performance of the wall.

Based on numerical simulation, this paper designs a UHMWPE fiber-reinforced protective panel with a cavity placed in front of the wall, and discusses the effect of the protective panel on the attenuation of the explosion shock wave and the response of the wall behind the panel under different explosion equivalents. The effective protection distance and protection performance characteristics of the protection board under different equivalents are obtained, in order to provide a new design idea for the rapid external enhancement of the building wall.

2. Construction of numerical model

2.1. Calculation model based on LS-DYNA

This paper is mainly based on the LS-DYNA finite element analysis software to carry out a numerical analysis of composite protective panels and walls under near-explosive loads. The model is mainly composed of 4 parts, air, explosives, UHMWPE cavity protection board, and reinforced wall. Considering that there should be a certain distance between the protective plate and the wall to be protected in the actual situation, there should be a buffer zone between the protective plate and the wall to be protected, and in order to better obtain the performance of the protective plate to attenuate the shock wave, so when establishing the model, set the protective plate 10cm distance, in order to accurately extract the pressure change of the air unit. At the same time, in order to save the calculation cost, only a quarter model is established. The specific model is shown in Figure 1 to Figure 3.
Among them, the explosive density is 1.73 g/cm$^3$, the equivalent is controlled by the volume size, the wall concrete strength grade is C30, the plane size is $2m \times 2m \times 20cm$, and it is equipped with double-row longitudinal re-bars with a strength of Q235 and a diameter of 10mm. The UHMWPE protection board is designed as a cavity structure, the plane size is $2m \times 2m$, the cavity thickness is 5mm, and the thickness of the upper and lower boards is used as a variable to discuss the enhancement effect of the protection board's own energy absorption performance.

2.2 Material model

All models of the numerical simulation come from the material library of the post-processing software Ls-Prepost. The air unit uses the *MAT_NULL material model, the explosive uses the *MAT_HIGH_EXPLOSIVE_BURN model, the UHMWPE protection board uses the *MAT_COMPOSITE_DAMAGE model for simulating composite materials, and the concrete adopts the JOHNSON-HOLMQUIST-COOK model, which is widely used in explosive shock loads, the re-bars adopts the *MAT_PLASTIC_KINEMATIC model. In terms of grid properties, Euler grids are used for air and explosives, Lagrange grids are used for the rest of the models, fluid-structure coupling algorithms are used to establish connections, and the coupling method uses penalty function method.

3. Verification of numerical simulation method

In order to verify the accuracy of the simulation, the response of reinforced concrete under explosive load and the material model of UHMWPE under high strain rate were validated.

The explosion impact experiment of reinforced concrete slabs in literature$^{(6)}$ is selected to verify the validity. The experiment takes C30 ordinary reinforced concrete slab and C60 high-strength reinforced
concrete slab as objects. After the measuring points are arranged behind the slab, strain gauges and displacement meters are placed to monitor the strain displacement, and then placed in a closed explosion tank for explosion test. The sample size and explosive environment are shown in Figure 4 and Figure 5. Now select the B2, B4, and B8 working conditions in the experiment to simulate and verify the maximum displacement of the bottom of the plate. For each working condition see Table 1.

![Sample size](image1)

![Explosive environment](image2)

**Figure 4. Sample size.**

**Figure 5. Explosive environment (Support frame).**

| Working conditions | equivalent/g | Explosion distance/mm |
|--------------------|--------------|-----------------------|
| B2                 | 20           | 200                   |
| B4                 | 40           | 200                   |
| B8                 | 30           | 100                   |

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| B4                 | 40           | 200                   |
| B8                 | 30           | 100                   |

In the experiment, in order to prevent the displacement meter from loosening and affecting the test accuracy, the displacement meter is not cleared after each explosion, so the result obtained is the cumulative displacement, so the maximum displacement of the plate center after each explosion is the difference between two adjacent displacements. By establishing the same numerical model as the experiment, the maximum displacement values of the 6 plate bottoms of different plates under three working conditions are calculated and simulated. The displacement time history curves are shown in Figure 6. Among them, the time length settings of the B2 and B4 groups are different to find the peak displacement. By analyzing the simulation results, the maximum displacement of the plate bottom under each working condition can be obtained and compared with the experimental results, as shown in Table 2. The errors are small, so the numerical model and the calculation method used in this paper can be considered stable and reliable.

On the other hand, the material model of the UHMWPE protective board under high strain rate and impact load also needs to be verified for accuracy. Therefore, the experiment of warhead penetration of UHMWPE fiber material in literature[7] is selected for verification. In this experiment, an ultra-high molecular weight polyethylene fiber laminated protective structure (a total of 30 layers) was made and bonded with polyethylene resin, and then a 7.5mm cube flat bullet made of 45 steel was used for the penetration experiment. The destruction of the latitude-free cloth laminate under the penetration of warheads with different initial speeds is shown, and the remaining speed of the warhead is recorded. Among them, the warhead material parameters are shown in Table 3. The first three impacts in the experiments are selected for simulation and comparative analysis, and the corresponding numerical model is established, and the calculated three warhead velocity time history curve is shown in Figure 7.

Among them, the experimental results of the remaining speed are compared with the simulation results in Table 4. It can be seen that the difference between the simulated value and the experimental value of the remaining velocity of the warhead is very small, so it can be considered that in the case of high strain rate, the *MAT_COMPOSITE_DAMAGE model is used to describe the response of the UHMWPE shield with high accuracy.
Table 2. Comparison of experimental and simulated values of displacement behind the plates

|                | B2C30 | B2C60 | B4C30 | B4C60 | B8C30 | B8C60 |
|----------------|-------|-------|-------|-------|-------|-------|
| Experimental results /mm | 2.62  | 1.72  | 3.78  | 1.52  | 3.78  | 2.47  |
| Simulation results /mm   | 2.92  | 1.95  | 2.97  | 2.28  | 5.14  | 1.94  |
| Relative error /%        | 11.5  | 13.4  | 21.4  | 50    | 36    | 21.5  |
| Absolute error /mm       | 0.3   | 0.23  | 0.81  | 0.76  | 1.36  | 0.53  |

Figure 6. Displacement time history curve

Figure 7. Velocity-time history curve of three impacts.

Table 3. Warhead material parameters.

| $\rho$(g/cm$^3$) | E/MPa | $\gamma$ | $\sigma_w$/MPa | Er/MPa | $\varepsilon_f$/% |
|-----------------|-------|---------|----------------|--------|------------------|
| 7.8             | 2000000 | 0.3     | 1900           | 15000  | 2.15             |

Table 4. Experimental and simulation results.

|                | The first time | The second time | The third time |
|----------------|----------------|-----------------|----------------|
| Number of impacts | 30 layers      | 30 layers       | 30 layers      |
| Penetration layer  | 896.27/475.55  | 520.62/334.38   | 485.86/233.13  |
| Velocity change (m/s) | 426.63       | 355.77          | 252.98         |
| Simulation result (m/s) | 10.3         | 6.4             | 8.5            |

4. Parametric analysis of protective boards and walls under shock waves

There are many criteria for judging the protective effect. This article mainly analyzes the response of the wall behind the protective plate to judge the effect of rapid enhancement. Therefore, the main parameters are displacement behind the wall, overpressure on the explosion face of the wall, and the destruction of the front face of the wall\cite{8} etc. Therefore, in this paper, parameters such as explosion equivalent, explosion distance, and presence or absence of protective structures are set as main variables. In addition, in order to analyze the energy absorption and decompression effect of the protective board,
the author set up protective board structures of different thicknesses. The specific working conditions are shown in the following table:

Table 5. Numerical simulation working conditions.

| Working conditions | Equivalent /g | Explosion distance /cm | Protection situation | Thickness of protective board and air field |
|--------------------|---------------|-------------------------|----------------------|--------------------------------------------|
| Ma1                | 664.32        | 20                      | Yes                  | Thickness of upper and lower layers: 5mm   |
| Ma2                | 20            | No                      |                      | The thickness of the air field: 10mm      |
| Ma3                | 30            | Yes                     |                      |                                            |
| Ma4                | 40            | No                      |                      |                                            |
| Ma5                | 664.32        | 20                      | Yes                  |                                            |
| Ma6                | 40            | No                      |                      |                                            |
| Ma7                | 50            | Yes                     |                      |                                            |
| Ma8                | 60            | Yes                     |                      |                                            |
| Mb1                | 20            | No                      |                      |                                            |
| Mb2                | 30            | Yes                     |                      |                                            |
| Mb3                | 50            | No                      |                      |                                            |
| Mb4                | 688.76        | 30                      | Yes                  |                                            |
| Mb5                | 70            | No                      |                      |                                            |
| Mb6                | 80            | Yes                     |                      |                                            |
| Mb7                | 90            | No                      |                      |                                            |
| Mb8                | 100           | Yes                     |                      |                                            |
| Mc1                | 20            | No                      |                      |                                            |
| Mc2                | 30            | Yes                     |                      |                                            |
| Mc3                | 40            | No                      |                      |                                            |
| Mc4                | 50            | Yes                     |                      |                                            |
| Mc5                | 1107.2        | 50                      | Yes                  | Thickness of upper and lower layers: 6mm   |
| Mc6                | 60            | No                      |                      | The thickness of the air field: 10mm      |
| Mc7                | 70            | Yes                     |                      |                                            |
| Mc8                | 80            | No                      |                      |                                            |
| Md1                | 885.76        | 50                      | Yes                  | Thickness of upper and lower layers: 7mm   |
| Md2                | 90            | Yes                     |                      | The thickness of the air field: 10mm      |
| Md3                | 100           | No                      |                      | Thickness of upper and lower layers: 8mm   |
| Md4                | 1107.2        | Yes                     |                      | The thickness of the air field: 10mm      |

Thickness of upper and lower layers: 5mm
The thickness of the air field: 10mm
Thickness of upper and lower layers: 6mm
The thickness of the air field: 10mm
Thickness of upper and lower layers: 7mm
The thickness of the air field: 10mm
Thickness of upper and lower layers: 8mm
The thickness of the air field: 10mm
4.1. Analysis of safety protection distance under different equivalents

After analyzing the damage of the walls under several sets of explosions with different equivalents, it is found that when the explosion distance is small, some walls without a cavity protective board will have surface cracks, and the rebars will be exposed and deformed. This is because the instantaneous overpressure generated by the explosion acts on the surface of the concrete wall, causing the concrete to be crushed. At the same time, the internal rebars are also affected and deformed. Taking Ma2 working condition as an example, the damage of the wall is shown in Figure 8 and Figure 9. But in the case of protection, the reinforced wall has only a small deformation and displacement. Only the protective board is cracked and destroyed from the center by the impact, and the shock caused by the shock wave spreads from the center of the protective board to the surroundings, as shown in Figure 10.

Figure 8. Schematic diagram of wall failure.

Figure 9. Rebar deformation diagram.

Figure 10. Schematic diagram of protective plate damage.

In order to explore the safety protection distance of this protection structure under a certain explosion equivalent, several equivalents of 664.32g, 885.76g, and 1107.2g were set up according to the volume for simulation analysis. The results show that the walls under Ma1, Ma2, and Ma4 have surface crushing and exposed rebars, while the walls of Ma3, Ma5, Ma6, Ma7, and Ma8 are not damaged. Only the protective boards are damaged and teared by impact. This shows that when the equivalent weight is 664.32g and the explosion distance is greater than 30cm, this kind of protective board has a good effect on improving the impact resistance of ordinary steel-concrete walls, it can also be considered that the safety protection distance under this equivalent is 30cm. Similarly, by comparing Mb1-Mc8, it can be found that when the equivalent weight is 885.76g, the protection safety distance is 40cm; when the equivalent weight is 1107.2g, the safety protection distance is also 40cm. It can be found that with the continuous increase of the equivalent, the safety protection distance has not increased significantly. This
shows that UHMWPE fiber composite material has good energy absorption characteristics, and also reflects that the cavity structure has a great effect on energy absorption. The instantaneous overpressure generated by the explosion shock wave is reflected and dissipated in the cavity, and its power is greatly reduced when it acts on the wall.

4.2. Effectiveness and performance analysis of cavity protection board

This section analyzes and compares the numerical simulation results of working conditions Ma1-Mc8, and explores the impact of protective structures on walls under explosive loads. The main analysis indexes are parameters such as pressure attenuation and wall deformation. Because the wall will be crushed and damaged even if there is a protective plate when the explosion distance is relatively close, the overpressure change at a safe distance is studied. When the equivalents are 664.32g, 885.76g, and 1107.2g respectively, taking the explosion distance of 40cm as an example, the overpressure curve changes of the air unit on the explosion face of the wall are shown in Figure 11. It can be seen that the peak overpressure of the wall with protection has been greatly reduced compared with that without protection. The specific attenuation rate under each working condition is shown in Table.

![Figure 11. Pressure time history curve.](image)

![Figure 12. Displacement time history curve.](image)

| Working condition | Ma3 | Ma5 | Ma7 | Mb5 | Mb7 | Mc3 | Mc5 | Mc7 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Attenuation rate %| 63.2| 90.7| 90.5| 91.1| 94.9| 87.0| 94.9| 92.4|

This shows that the UHMWPE protective board can not only greatly reduce the peak overpressure on the front face of the wall, but also has a certain effect on delaying the arrival of the peak overpressure.
The greater the explosion distance, the greater the attenuation amplitude, because in the actual situation, air is a natural energy-absorbing material, most of the energy has been consumed in the process of the explosion shock wave freely spreading in the air. After being blocked by the protective board, the peak overpressure will be greatly reduced. In addition, the displacement of the protected wall has also been significantly reduced. Similarly, taking the explosion distance of 40cm as an example, the time history curve of the displacement of the center point behind the wall under different equivalent conditions is shown in Figure 12. It can be seen that the peak displacement of a wall with a protective structure is significantly reduced. Compared with a wall without a protective structure, the development speed of the displacement has also been significantly reduced.

In addition, through the analysis of the numerical simulation results of the working conditions Md1-Md4, the influence of the change in the thickness of the protective board on the attenuation of the explosion energy can be obtained. Without considering the thermal energy, the energy absorption effect of the protective board can be reflected by analyzing the change in internal energy of the wall. The analysis shows that in 2000μs, compared with Md1, the internal energy of Md2-Md4 is reduced by 19.1%, 29.6%, 46.1%, as shown in Figure 13. It shows that the energy absorption capacity of UHMWPE protective boards has grown significantly with the increasement of the thickness. And from the results, with the small increase in the thickness of the protective board, the ability of the protective plate to resist deformation after being impacted has also been significantly enhanced. Outside the damage radius of the board, the displacements at different distances from the center of symmetry are shown in Figure 14. Looking at the four working conditions individually, the displacement is greater at the place closer to the center of symmetry, while the displacement near the edge of the protective board is small. On the whole, the maximum displacement of Md4 is reduced by 28% compared to Md1, and the minimum displacement is reduced by 50%. It also shows that the protective board exhibits strong toughness when resisting explosive shock waves. UHMWPE fiber matrix can withstand large deformation without damage, so it can be used as a high-quality external protective material.

5. conclusion
This article puts forward an idea for rapid enhancement of anti-blast performance of general civil building walls. Through numerical simulation, the UHMWPE composite cavity board is used to protect the wall outside, and the response of the protection board and the wall under the impact of the explosion is obtained. The main conclusions are as follows:

(1) The safety protection distance of the UHMWPE composite cavity board is inversely related to the explosion equivalent. When the explosion distance is greater than the safety protection distance, the displacement and deformation of the wall are minimal and will not cause damage. This inverse correlation is worthy of further study.
(2) UHMWPE protective board can significantly reduce the peak overpressure on the wall surface. Under the working conditions in this paper, the minimum attenuation rate and the maximum attenuation rate reached 63.2% and 94.9%, respectively. And under the action of the protective board, the maximum displacement of the wall and the displacement development speed have been significantly reduced. As far as the protective board itself is concerned, an appropriate increase in thickness can significantly improve its energy absorption performance. For every 1mm increase in thickness, the energy inside the wall is reduced by 19.1%, 29.6%, and 46.1%, respectively.

(3) This concept of rapid external reinforcement of walls can be extended to more buildings and structures, but due to the poor fire resistance of fiber composite materials, other refractory materials can be considered to make protective boards with better performance.

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