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**Research paper**

# Numerical analysis of a train carriage in a subway tunnel under internal explosion

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**Abstract:** The destruction effect of the terrorist explosion attack on the subway tunnel involves large-scale fluid and structure interaction, and the detailed structure has a great impact on the damage form. A fully coupled numerical model of subway carriage, considering the influence of the subway structure on the explosion flow field and the damage pattern of the carriage, was established based on the Lagrangian-Euler coupling algorithm. The propagation characteristics of the explosion shock wave and damage mechanism of the carriage were studied. The influence of the carriage body, the window and charge weight on the response of the subway structure were investigated. Besides, the blast resistance property of the subway tunnel by choosing aluminium foam as the blast protection measure was also analyzed. The results show that the attenuation of the shock wave versus time and space under the combined constraint effect of train and tunnel is much slower than that in tunnel without carriage. The pressure and impulse close to the explosive charge without the window are twice and 2.32 times of the carriage with windows, respectively. The aluminium foam can significantly reduce stress level of the subway tunnel and make the stress distributed evenly, which has a better mitigation effect on the blast wave in the close range.

**Keywords:** train carriage, internal explosion, subway tunnel, terrorist attack, propagation law, aluminium foam

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# 1. Introduction

In recent years, a large number of subway lines have been opened and operated for fast and convenient transportation in many cities. However, with the rapid development of the subway system, the risk of accidental explosions and terrorist attacks on subway carriages continue to increase. With the number of subway system continues to increase, threats of accidental explosions and terrorist attacks may occur during the operation of the system, which cause severe consequences due to its complex structure and concentrated personnel. In the twenty-first century, there have been some notable subway accidental explosions including the London subway tunnel bomb attack in British killed 52 passengers and injured more than 700 people (2005), the Moscow metro tunnel suicide bombings in Russia killed 41 people and injured 120 people (2010) and the Minsk metro tunnel bomb attack in Belarus killed 12 people and injured over 200 people (2011), etc. Hence, blast loads in subway systems considering subway tunnels and carriages have attracted extensive research attention in recent years.

The dynamic behavior of tunnels subjected to explosions is very complicated [1]. A large number of studies were carried out, and some achievements were accomplished by using both experimental methods and numerical simulations. Van den Berg et al. [2] studied the blast effects from the rupture of a 50 $m^3$ LPG pressure vessel in a tunnel system by numerical simulation. Results indicated that the second blast wave in the tunnel section following on an open space could have lethal consequences for fellow tunnel users by car window failure. Silvestrini et al. [3] found that the spatial density of energy was higher than for detonations in free field. The three- dimensional finite element program ABAQUS was used [4] to investigate the dynamic response of cast iron lining of subway structures under internal blast loading. The influence of various factors on the possible damage of subway tunnel, including weight of explosive, ground media, burial depth and characteristics of blast pressure were taken into account in the numerical models. However, the CONWEP algorithm was used to apply a simple explosion load to the lining, and the coupled fluid-solid interaction between the air and the lining structure was not considered. As reported by Benselama et al. [5], the propagation of explosive waves in tunnels presented two patterns. The region close to the explosive charge exhibited a free-field over pressure decay pattern and the region far from the explosion, which underwent much less over pressure decay, exhibited a quasi-one-dimensional pattern. In addition, Feldgun and Karinski [6–9] also carried out systematic theoretical and numerical studies on the complete physical process of the implosion problem of underground tunnels. However, the 2D plane model could hardly reflect the spatial distribution of blast loads. Most recently, Li et al. [10] developed a full-scale fluid structure interaction (FSI) numerical model to investigate the strength and propagation characteristics of a blast shock wave inside a highway tunnel. Kristoffersen et al. [11] conducted experiments on blast loading of tubular concrete structures to assess the blast performance of submerged floating tunnels with circular and rectangular cross-sections. Zhang et al. [12] analyzed the mechanical responding performance of typical mine seals under the impact load by using numerical simulation software ANSYS and put forward suggestions that were conducive to the high safety and economic benefits of the mine seal in underground space.

However, for the structure of subway carriages, it not only has the narrow and confined structure similar to the tunnel but also has special features. First, the length-to-width ratio of subway train carriages is relatively large. Second, the interior components of subway train carriages, including doors, the ceiling, floor, side walls, seats, and interior walls, which are likely to change the propagation characteristics of explosion shock wave inside the carriage. Finally, the relative high speed of the subway train makes the problem quite different from that in tunnels. Therefore, it is necessary to study the characteristic of subway train carriage under internal explosion to provide guidance for the design of train components and materials. Only limited related study can be found in the literature. In the year 2010, Larcher et al. [13] employed fluid-structure interaction modelling to assess the influence of venting areas on high explosives detonation inside single train carriages and inside long trains. Particularly interesting is that Giannopoulos et al. [14] obtained geometric models of metro line station and metro carriage by a laser scanning method, and used the risk analysis module in the finite element code EUROPLEXUS to study the damage range of shock wave after 16.3 kg TNT exploded in the station and 10 kg TNT exploded in the carriage. Later on, Lü et al. [15] proposed a calculation method with discontinuous elements, three-dimensional calculation model to explore the rock breaking and protection of subway station. They also analyzed the antiknock seismic performance of the station management layer of concrete pillar concrete, steel, bandages concrete and foam sandwich steel armor layer concrete under low-energy explosions. According to different protective structure, attenuation of shock wave, energy absorption performance, the optimization of subway station structure and structure protection type have important practical application value. In a recent study, Wang et al. [16] embedded the HJC model into the open source material point method program to study the response law of subway platform and surrounding rock under explosion load. Additionally, Yao et al. [17] studied the propagation law and the characteristics of the explosion shock wave inside the compartment using ANSYS/LS-DYNA. However, it should be noted that the aforementioned achievements mostly focus on the propagation of shock wave and damage evaluation of tunnel under blast loads. Corresponding studies of damage assessment and dynamic behaviors of subway train carriage subjected to blast loads are still scare.

In this study, a comprehensive fully coupled numerical model is proposed to investigate dynamic response of the subway carriage subjected to internal explosion. In the proposed model, the coupled fluid-solid interaction of internal explosion in underground tunnels was considered. Then, finite element analysis results were compared with the test data. The calibrated numerical method was subsequently used to investigate the dynamic response, damage mechanism, and potential mitigation measures of subway train carriage subjected to blast loads. The results would be beneficial to guide blast resistance of a train carriage in a subway tunnel.

# 2. Numerical modelling

## 2.1. Materials

In this study, the air is modelled as an ideal fluid without viscosity, which is described by keyword Mat_Null in LS-DYNA. The state equation of ideal gas is defined by the linear polynomial EOS_LINEAR_POLYNOMIAL [18]. The TNT is modeled as a high energy explosive, which is described via the *MAT_HIGH_EXPLOSIVE_BURN material model with Jones–Wilkins–Lee (JWL) equation of state [19]. The material of aluminum foam is modeled with Crushable_foam model (*MAT_CRUSHABLE_FOAM). The intrinsic relationship of the foam requires the input of a stress-strain curve of the material, which can be obtained through the SHPB test. The mechanical properties of the aluminum foam used in this research are listed in Table 1. The plastic damage model MAT_JOHNSON_HOLMQUIST_CERAMICS is used for the inner and outer glass of the windows, and its material parameters are listed in Table 2. The air material outside the train body and the hollow inert gas layer of the window are described by the MAT_NULL material model and the linear polynomial EOS_LINEAR_POLYNOMIAL state equation.

The wall of the tunnel is mostly a variety of solid rock or concrete. For the calculated shock wave intensity, it can be approximated treated as a rigid wall, and the shock wave energy loss caused by its elastic deformation is not considered.

Table 1. Material properties of aluminum foam

| Density ($kg \cdot m^{-3}$) | Young modulus (GPa) | Poisson ratio | Tensile stress cut-off (MPa) |
|---|---|---|---|
| 1200 | 1.2 | 0.3 | 10 |

Table 2. Material properties of the subway carriage

| Component | Density ($kg \cdot m^{-3}$) | Young modulus (Pa) | Poisson ratio | Yield stress (Pa) | Erosion strain |
|---|---|---|---|---|---|
| Structure | 7800 | 2.1×1011 | 0.28 | 4.0×108 | 0.01 |
| Door | 7800 | 2.1×1011 | 0.28 | 4.0×108 | 0.01 |
| Window | 2500 | 7.35×1010 | 0.25 | 1.38×108 | 0.0005 |
| Floor | 7800 | 2.1×1011 | 0.28 | 4.0×108 | 0.01 |

## 2.2. Model description

A certain type of subway train in China is used as a prototype to establish numerical model. Only one carriage is modelled and not the entire train. A symmetric train carriage (planes of symmetry) is used and only one fourth is modelled (Fig. 1). The train carriage has a length of 19 m, width of 2.8 m, and height of 3.8 m. There are five emergency escape windows on both sides of each carriage. The carriage is built from aluminium alloy material, and the windows are built from tempered glass. The floor of the train is treated as nondeformable. The material parameters for different components of the subway train are shown in Table 2. Since the traveling speed of the subway train is much lower than the propagation speed of the shock wave in the near field of the condensed matter explosion, it is assumed that the structure is stationary at the moment of explosion during the solution process, thus ignoring the influence of the traveling speed of the subway train on the internal explosion process.

The carriage is modelled by the Lagrange algorithm, in which the numerical mesh can distort and move with the physical material. The TNT charge and air are modelled by the Eulerian formulation to avoid the distortion of the finite element grid. The key word

"CONSTRAINED_LAGRANGE_IN_SOLID" is used to couple the pressure transfer and motion coordination between Euler mesh and Lagrangian mesh. The numerical model consists of about 19,008 Lagrange elements and 2,741,872 Euler elements. The fluid-structure coupling algorithm is adopted between the carriage and the air model. In order to make the stress wave propagate freely, the non-reflection boundary is applied to the lateral and bottom surface of the carriage. The fixed boundary condition is applied to the bottom surface.

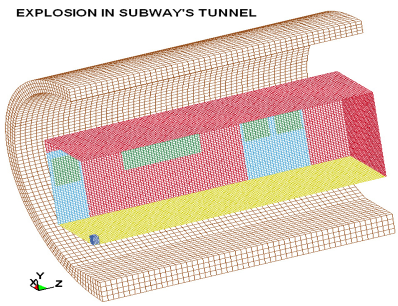



Fig. 1. Finite element model

# 3. Numerical investigation

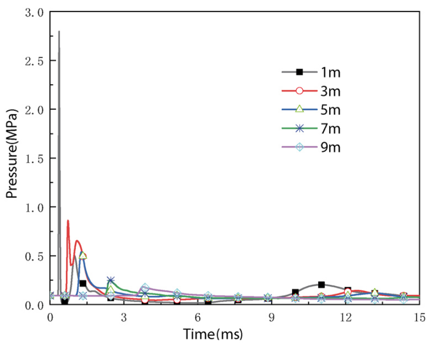
According to the investigation of Federal Emergency Management Agency, the equivalent explosive that terrorists might use in an attack targeting subway structure, such as suicidal bombings or explosions, ranges from 1 to 50 kg TNT. In this chapter, the dynamic behavior of the subway carriage under the explosion of 5 kg TNT charge is discussed.

## 3.1. Influence of carriage

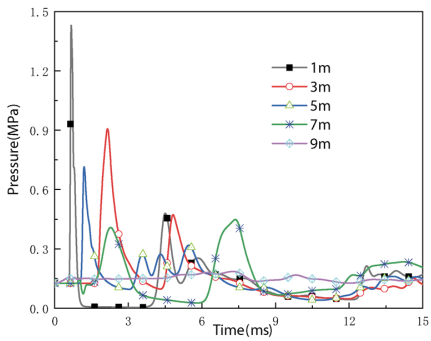
Two numerical models are built. Mode 1 is an explosion process in an open tunnel, that is, a terrorist explosion attack occurs in a subway tunnel when there is no carriage body or other obstacles. The charge is placed at a height of 2.5 m above the ground, close to the center of the tunnel section. Model 2 adopts the fabricated subway train model with consideration of a single, which is shown in Section 3.1. The structure and size of subway tunnel of the two models are exactly the same.

Figure 2 shows the pressure time histories of the two models, measured at five measuring points located at different standoff distances from the center of TNT, which serves as the source of explosion. As shown in Fig. 2(a), it can be seen that the changing trends of pressure at different points in model 1 are very similar. The peak overpressure of shock wave decays approximately exponentially with distance, and the first peak value is significantly greater than the later peak value. According to the classical internal explosion theory (closed explosion theory), the peak pressure of the latter load is half of the previous load, and the duration of the two is equal. As the calculation condition is an opening explosion in an infinite tunnel, the peak value of the latter wave is much smaller than the previous one.

In contrast, the blast loads in Fig. 2(b) consist of shock front followed by a series of pressure pulses. The reason is that, immediately after detonation of the charge, the shock propagation and interface interaction occurred continuously until the energy of the shock wave gradually decays. At the standoff distance of 1.0 m, although the first peak of pressure is the maximum value at the measuring point, there are many smaller peaks at this position after 6 ms, and the peak value tends to increase gradually. At the standoff distance of 7.0 m, there are multiple pressure peaks inside the subway carriage, and the maximum value is not the first peak.




(a)




(b)

Fig. 2. Pressure time history at different standoff distances: (a) Model 1, (b) Model 2

Figure 3 expresses the evolution of the peak pressures with the distance between the two models. According to simulation results, it can be seen that the tunnel without the carriage (model 1) exhibits higher pressure when compared with the train carriage in the tunnel (model 2). This behavior might due to the double constraint effect formed by the train itself and the tunnel, which intensifies the reflection and diffraction of the shock wave and yields the superposition of the shock wave in a certain space. The peak pressure of model 1 near an explosive source is about twice higher than that of model 2. The attenuation of peak pressure with distance in the carriage is no longer in the form of approximate exponential attenuation, and some fluctuation of the curve is observed.

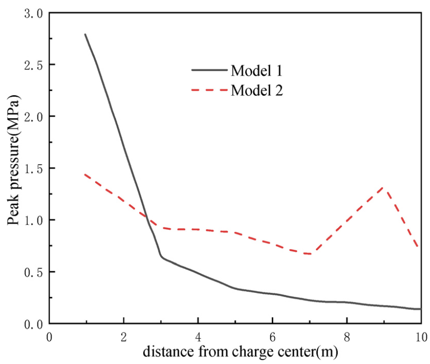



Fig. 3. Comparison of the numerical pressures between model 1 and model 2

### 3.2. Influence of windows in the carriage

The window glass is easy to be broken and injured under the action of strong impact load. According to terrorism researcher Jenkins [20], 70% of the casualties are caused by the high-speed splash debris generated by the damage of the blast wave to the glass. For comparison purpose the corresponding cases with no windows have been run, Figure 4 presents the pressure vs distance from the charge center without windows. Comparing Fig. 2(b) and Fig. 4, it is observed that the propagation law of shock waves between the two cases are very similar. However, due to the presence of pressure relief in windowed carriages, the peak pressure is generally smaller than that in the train without windows. The maximum pressure in the carriage without windows at a standoff distance of 1.0 m (2.88 MPa) is almost twice higher than that with windows (1.43 MPa). What's more, as a large number of shock waves overflow from the windows, the number of overpressure superimposed in the carriage is less, and the number of pressure peaks in the carriage with windows is less than that in the windowless compartment.

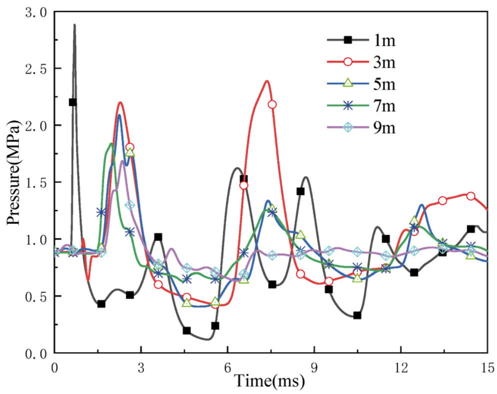
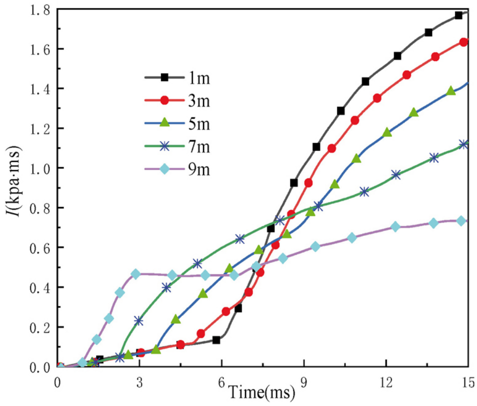
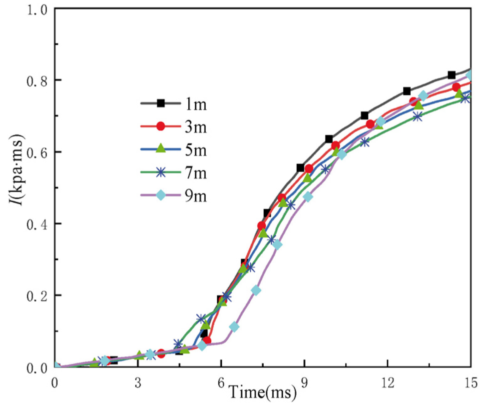



Fig. 4. Pressure time history at different standoff distances of windowless carriage

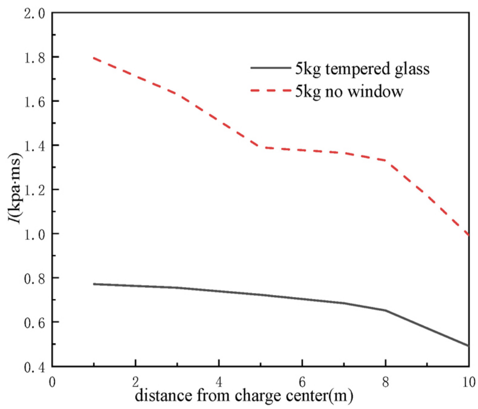
Figure 5 deliberates the distribution of impulse with and without windows under the explosion of 5 kg TNT. The plots presented in Fig. 5(a,b) indicate that the impulse time histories between the two conditions are similar, while the vibration impulse without windows fluctuates more violently (Fig. 5a, b). Unlike with tempered glass, there is a sharp decrease in the impulse of subway carriage as the distance from the blast source increases. What's more, the subway carriage without window exhibits higher impulse when compared with tempered glass. The maximum impulse near an explosive source without windows (1.79 kPa·ms) is 2.32 times higher than that with tempered glass (0.77 kPa·ms), as shown in Fig. 5(c). As the intensity of the blast pressure attenuates rapidly from the blast source, the difference of the window types plays a less significant role in reducing the impulse. In summary, improvement of the blast-resistance performance of the windows can inhibit and delay the explosion development to a certain extent.




(a)




(b)



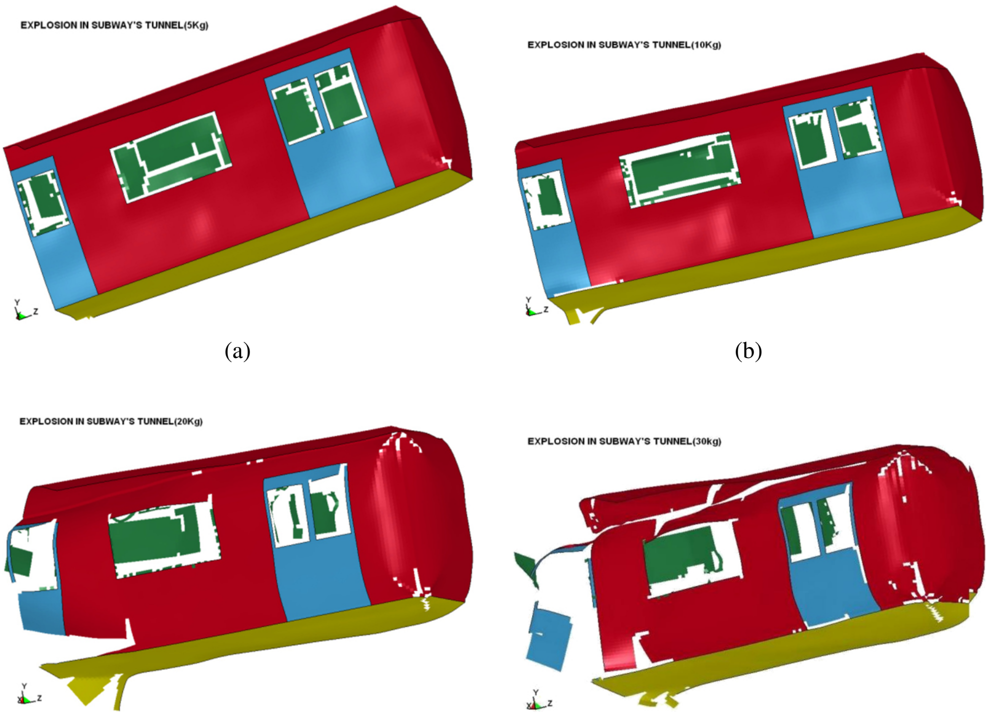

(c)

Fig. 5. Distribution of impulse in carriage: (a) Impulse time history without window, (b) Impulse time history with tempered glass, (c) Comparison of impulse at different standoff distances

### 3.3. Failure patterns of the subway train carriage

In order to assess the performance and damage levels of the subway train carriage, comprehensive numerical simulations of the subway carriage responses to different charge weight are implemented. The simulation of the carriage is performed using 5 kg, 10 kg, 20 kg and 30 kg TNT equivalent, and the charge is placed at the bottom of the carriage, 1.1 m away from the tunnel. Figure 6 manifests the typical damage patterns of the carriage subjected to different internal explosions. The damage level of the carriage increases with the charge weight, and the damage zone diffuses uniformly around the detonation. As shown in Fig. 6(a), for a charge weight of 5 kg TNT, the carriage suffers slight damage, only some of the windows are broken, no penetrating crack occurs on the roof, and the overall deformation is negligible.

If a charge of 10 kg TNT detonates inside the train (Fig. 6b), the carriage suffers moderate damage, the bottom of the carriage is peeled off, and the integrity of the roof is not destroyed. A detonation of 20 kg TNT leads to severe damage of the structure around the explosion (Fig. 6c), the spall damage occurs on both sides of the carriage, multiple damage cracks appears and the integrity of the roof may be destroyed. For a charge of 30 kg TNT, the carriage suffers complete failure (Fig. 6d), there is obvious punching damage and the extremities of the carriage are also destroyed. The spalling on both sides of the carriage will produce high- speed fragments, which may cause casualties inside the carriage and breach the tunnel lining.




(a) (b)

(c) (d)

Fig. 6. Carriage damage with different TNT charge: (a) Slight damage (5 kg), (b) Moderate damage (10 kg), (c) Severe damage (20 kg), (d) Collapse (30 kg)

Figure 7 renders the pressure time history at different standoff distance with various charge weights. As expected, the pressure generally increases with the charge weight, but decreases with the increased standoff distance. The peak pressure at the standoff distance of 1m induced by the explosion of 30 kg TNT is 2.19 MPa. The values due to the explosions of 20, 10, and 5 kg TNT decrease by 49, 62 and 85%, respectively, compared with the explosion of 30 kg TNT. As the standoff distance increases from 1 to 7 m, the peak values of the pressure induced by the explosions of 30 kg TNT are 2.19, 1.43, 0.62 and 0.36 MPa, respectively.

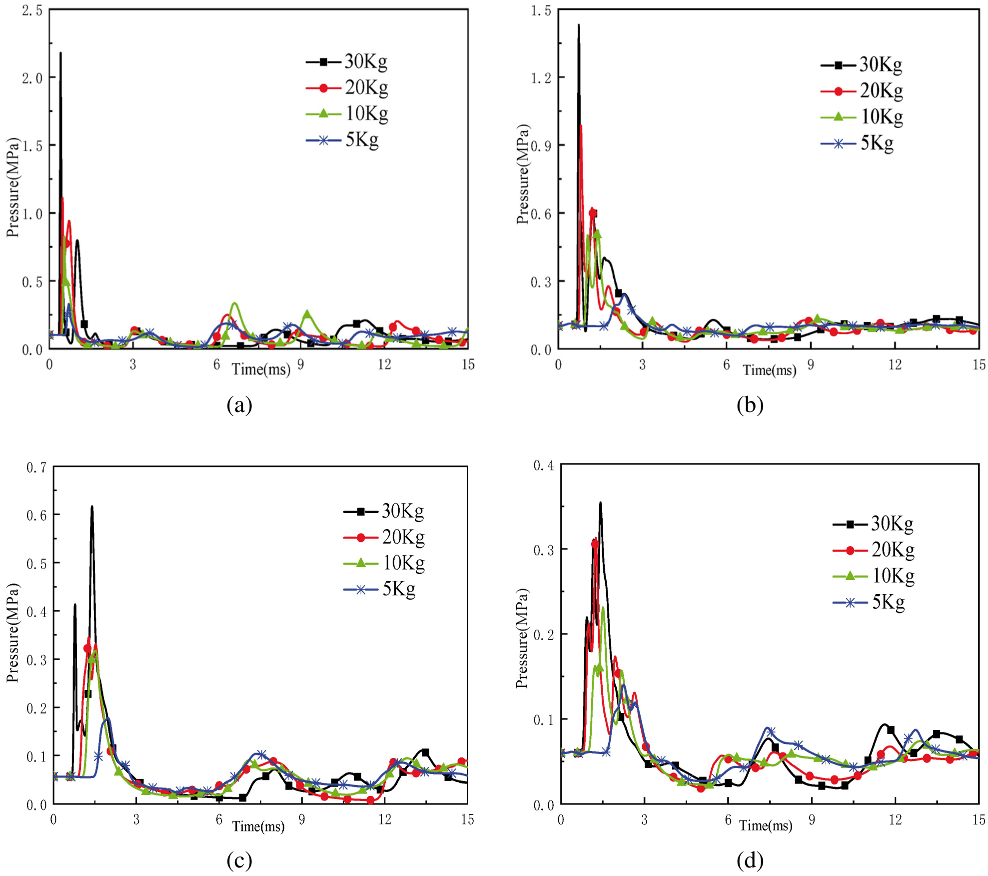



Fig. 7. Pressure time history at different standoff distances for various explosive quantities: (a) 1.0 m, (b) 3.0 m, (c) 5.0 m, (d) 7.0 m

# 4. Mitigation measures

The above numerical results demonstrate that the subway carriage may suffer severe damage under blast loads. Hence, corresponding reinforcement measures are proposed to improve the blast resistance of the subway carriage. Common reinforcement measures include covering a layer of water barrier around or inside the carriage, using high performance materials, installing protective measures, and so on.

Aluminium foam is a porous lightweight construction material with low density, high specific strength, high specific rigidity, and excellent energy absorption ability. Compared with the traditional structure material, it has better blast resistance and inferior quality, and is widely used in the field of disaster preventive and mitigation. The layer thickness of the aluminium foam is 20 cm. Its elastic modulus and density are 1200 MPa and 1200 kg/m$^3$, respectively.

Figure 8 manifests the pressure and strain time history with and without aluminium foam subjected to the explosion of 5 kg TNT with 3.0 m standoff distance. Before application of aluminium foam, multiple reflections occur in the carriage after the incident of explosive wave, and the pressure of the reflected wave is much larger than that of the incident wave, causing the deformation of the carriage to show multiple obvious amplification phenomena. After the application of aluminium foam, the energy of the incident wave transmitted to the carriage and the effect of the reflected wave are significantly reduced, resulting in a significant increase in the pulse width of the shock wave at the monitoring point, showing the characteristics of low amplitude and large pulse width. It can be analysed that when the aluminium foam is used, the reduction rate of the maximum value of the pressure and the strain is 9.26% and 4.52%, respectively.

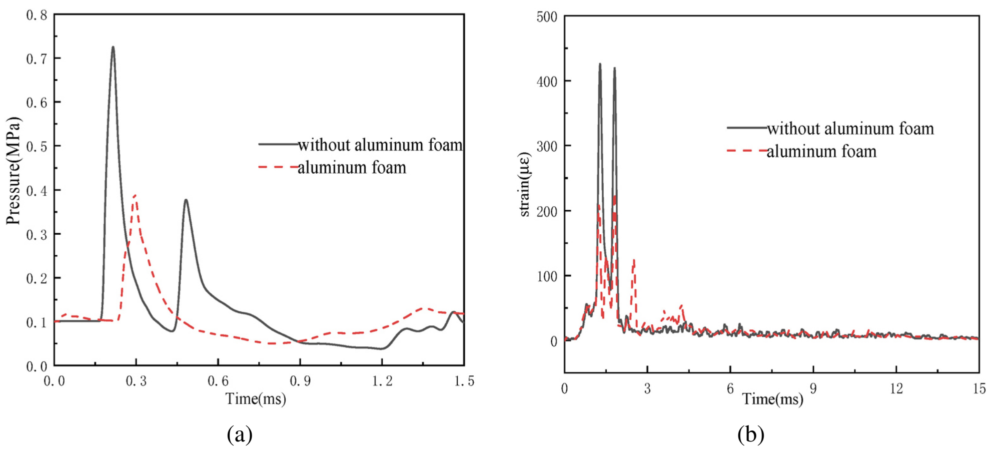



Fig. 8. Comparison of mitigation effects: (a) Pressure time history, (b) Strain time history

A comparison of the peak pressure with and without aluminium foam subjected to the explosion of 30 kg TNT is shown in Fig. 9. Also, the carriage without aluminium foam exhibits higher pressure than that with aluminium foam. At the section close to the explosion source, there is almost 42% reduction in the pressure. As the intensity of the blast pressure attenuates rapidly from the blast source, the change in mitigation measures plays a less significant role in reducing the pressure when the distance from the explosion source exceeds 5 m. This behavior might be due to the circulation convergence effect of the explosion shock wave, the maximum value of the convergence shock wave is higher than that of the corresponding position under the free field condition. It can be concluded that aluminium foam has a better mitigation effect on the explosion wave in the close range, the recommended location is along the tunnel axis within a range of 1.5–2.0 times the tunnel length on both sides of the high-risk area.

The above analysis demonstrates that aluminium foam has a large reflection and attenuation effect on explosion shock wave, which delays the time of explosion load on the lining structure, mitigates the blast effect on the tunnel and improves the anti-explosion safety of the subway carriage.

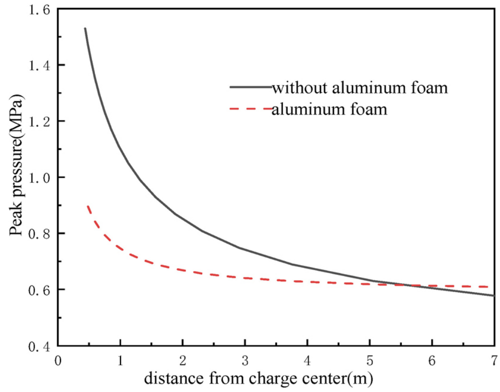



Fig. 9. Comparison of pressure

# 5. Conclusions

In this study, a fully coupled technique has been developed and applied to study the dynamic response of subway train carriage exposed to internal blast loading using explicit dynamic nonlinear finite element software LS- DYNA. The damage characteristic and shock wave propagation of the subway carriage under explosion are discussed in detail. Based on parametric study, the following conclusions can be summarized as follows:

1. The propagation process of shock waves in subway carriage is fundamentally different from that in an empty tunnel. The attenuation of the shock wave versus time and space under the dual action of subway train and tunnel is much slower than that in an empty tunnel, and there are significant fluctuations. The distribution of the overpressure of the shock wave with distance doesn't shown the traditional approximate exponential attenuation.
2. The pressure and impulse of the subway carriage with windows are much smaller than that without windows, indicating that the burst outlet should be appropriately added in the anti-explosion design of the subway carriage.
3. Aluminium foam has excellent energy absorption capacity, and can obviously reduce the pressure and deformation of subway carriage. Away from the point of explosives, the shock wave pressure significantly attenuate, and when the axial distance is greater than 5 m, the blast wave pressure is significantly reduced. The aluminium foam protective layer should be mainly fortified at close distance.

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