Simulation and experimental study on the shock response of vehicle add-on modules subjected to blast loading

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Abstract. Explosion of landmines is recognized as one of the vital threat to armoured vehicles. The detonation of mines may also threaten the survivability of the occupants inside the vehicle by the high intensive blast waves transmitting from vehicle structures. Bottom add-on modules can be very useful to vehicle in blast protecting. The dynamic response of three different add-on structures under bottom explosion was analysed by simulations and experiments. The optimal structure was obtained by computational results and experimental results, and the protection mechanism was summarized based on the research.

1. Introduction
Since World War I, landmines have been regularly deployed in conflict zones [1]. The design of theses landmines changes very little during the preceding years and this kind of landmines have some particularly characteristics: simple mechanism, relatively low cost and easy deployment. Thus, landmines can be easily used by untrained personnel and be a lethal threat to vehicles, especially to the occupants inside the vehicles. Up to now, this kind of threat still exists on the battle-filed where vehicles and personnel carriers are exposed to close-range explosions of landmines or improvised explosive devices [2].

The explosive of landmines or improvised explosive devices will release large impulses that could deform even penetrate the vehicle structure, the shock waves subjected to the blast will transmit from vehicle structures to occupants inside the vehicles, leading to body injuries of the occupants [3,4]. Since then, lots of work has been done to reduce the damage of both vehicles and occupants [5-7].

In the past years, different floor shape designs were invented to improve the vehicle response to blast loading [8]. However, these designs require a quite long distance between the vehicle bottom and the ground, which is a very serious restriction to the ensemble design of tracked vehicles. Since then, the thin add-on modules, which can be assembled under the bottom of vehicles, are also a good choice to help vehicles against landmine blasting and protecting the survivability of human occupants. In this paper, three structures of bottom add-on modules were analyzed by experimental and computational research, and the optimal structure was given due to the results.

2. Add-on modules and experimental set-up

2.1. Add-on modules
The add-on module is fixed on the bottom plane of the vehicle, protecting the vehicle structure from suffering huge deformation or penetration, and to ensure the survivability of occupants inside the vehicle. Three different structures of add-on modules are investigated in this paper.

A1 add-on module is the very typical sandwich panel structure. It contains three parts, the front steel panel, the back steel panel, and the aluminum honeycomb core with hexagonal cells.

A2 add-on module also contains three parts, the front steel panel, the back steel panel, and regular steel-slice structure with square cells.

A3 add-on module contains four parts: the front steel panel, the back steel panel, and the aluminum honeycomb core with hexagonal cells, and regular steel slice structure with square cells.

In order to get the evaluation of protection efficiency conveniently, the geometry restriction is given as bellows. All the add-on modules had length \( L = 1500 \) mm, width \( W = 1500 \) mm, and height \( H = 70 \) mm. In addition, all three add-on modules had nearly the same mass \( M = 533 \) kg. Figure 1(a), Figure 1(b), and Figure 1(c) show the structure of A1\A2\A3 add-on module respectively, Figure 1(d) presents the appearance of the test specimen.

![Figure 1](image-url)

**Figure 1.** Schematic structures of A1\A2\A3 add-on module: (a) A1 module; (b) A2 module; (c) A3 module; (d) test specimen

2.2. **Explosion experimental set-up.**

The explosion experimental set-up is schematically depicted in Figure 2(a) and Figure 2(b). The test facility contains the following key components: four steel kickstands, 1 steel frame supporter, and four 2 t weight steel blocks to simulate the weight of vehicle. The reference steel plate, also called a target plate, was placed upon the add-on module.
A 6 kg TNT blast charge was buried right under the center of the test facility, which was used as landmine or improvised explosive devices.

![Figure 2](image)

**Figure 2.** Explosion experimental set-up: (a) schematic diagram; (b) test facility

2.3. **Experiment results**

According to the different structures of the add-on modules, the experiments were divided into 3 groups, A1 group, A2 group and A3 group. After explosion, the deformation of the target plate (vertical distance from the diagonal intersection point to the center point of the deformed target plate) is given in Table 1, and the photos of the deformed target plate is given in Figure 3.

| Target plate | A2 group | A2 group | A3 group |
|--------------|----------|----------|----------|
| Deformation (mm) | 80 | 74 | 50 |

![Figure 3](image)

**Figure 3.** Photos of target plates in A1, A2, A3 groups after explosion

3. **Finite element model**

Simulation capability can be very useful to estimate the blast loading and structure response. And up till now, advances in commercially available finite element codes have made it suitable and convenient for simulations of coupled blast-structural response [9,10]. The Arbitrary Lagrangian-
Eulerian (ALE) method in the non-linear finite element code LS-DYNA allows a fully coupled approach to solve the landmine-structure interactions in this paper.

3.1. Geometry, modeling, boundary conditions and contact
All numerical simulations were conducted using the explicit FE code LS-DYNA. The add-on structures models were built using a simplified numerical model, where the weight of the 8t ballast and the supporter was replaced by fixed constraints on the edges of the target plate. Since then, the numerical model consisted of the reference still plate, the A1\A2\A3 add-on module, the landmine and air. In the FE model, the thickness of steel welding was neglected.

The geometry of the FE model was exactly the same as which was in experiments. The landmine and air parts had been coupled with the add-on module and the target plate parts using ALE method, which means the detonation and shock wave propagation in the air were modeled using the mesh with the Euler’s formulation, while the response of add-on modules and target plate were modeled using the mesh with the Lagrange’s formulation. The keyword *CONSTRAINED_LAGRANGE_IN_SOLID was applied.

The AUTOMATIC_SURFACE_TO_SURFACE contact algorithm was adopted to account for the connection between the front panel and the internal layer, the internal layer and the back panel as well as the back panel and the target plate.

3.2. Material properties
High-strength steel was used to construct the front panel, the back panel and the target plate, which was also applied as the regular slice structure with square cells in the rib layer. Aluminum honeycomb core with hexagonal cells was also used in A2 and A3 add-on modules. The main parameters used in numerical simulations are given in Table 2.

| Material          | LS-DYNA material type, parameters [11] |
|-------------------|----------------------------------------|
| TNT               | Density 6930 m/s 21.0 Gpa 7.0 Gpa      |
| air               | Initial density 1.293 kg/m³ Initial pressure 1 Bar Ration of specific heats 1.4 |
| High-strength steel | Density 7850 kg/m³ Young’s modulus 206 Gpa Poisson’s rate 0.3 Yield Strength 800 Mpa Tangent Strength 79.4 Gpa |
| Honeycomb         | Density 333 kg/m³ Young’s modulus 69 Gpa Poisson’s rate 0.285 Yield Strength 200 Mpa Relative volume 0.29 |

4. Results and discussion
In order to compare with the experimental data, the displacement curves were deduced from the simulation results in Figure 4, and the schematic deformation contour of a target plate is shown in Figure 5.
As is shown in Figure 4, the maximum plastic deformation of target plate in A1/A2/A3 group is 88mm, 61mm and 39mm respectively. While from the experimental results, the corresponding data is 80mm, 74mm and 50mm. Consider of the specialty of explosion tests and the uncertain factors during the experiments, the results of simulation and experiments are already quite close. Since then, the simulation results were validated.

From Figure 4, the add-on module in A2 group performed better than A1 group in center node displacement. However, that didn’t mean the module in A2 group absorbed more blast energy. In fact, the maximum plastic deformation only provides a reference value to evaluate the blast responding.

Energy data from the simulation results can be very helpful to understand the behavior of the blast phenomenon, and providing an extra explanation to the deformation results. Figure 6 shows the kinetic energy curves of the target plate. From these curves, it is quite clear that target plate in A2 retains more kinetic energy, which means that even the target plate got the smaller deformation, the protected object behind the target plate may still get more injury.

In order to support the analysis above, Figure 7 is shown as a complement proof. The velocity curves of center node in the target plate are presented in Figure 7.

From the experimental results and the computational results, it is obvious that A3 add-on module is the optimal structure, which showed the best ability in deformation and energy control. Blast energy transmitted to the honeycomb layer, honeycomb layer collapsed and part of the blast energy was absorbed. After that, residual energy transmitted to the rib layer, and continued absorbed and dissipated by the deformation of these thin steel slices. Besides, a small part of energy reflected and lost on the interface between the honeycomb layer and rib layer. Thus, most of the blast energy was cleared off during the wave propagating through the mixed core.
5. Conclusions
In this paper, the comparisons for blast response of three add-on modules were presented by experiments and computational simulation. The results showed that A3 add-on modules has a significant improved response to landmine blast loading, which is essential in armoured vehicle defence system designing. The detailed protection mechanism and more structures of add-on modules will be the vital research work in the future.

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