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Abstract

Owing to its advantages of high strength and low density, composite explosion containment vessel (CECV) can limit the scope of internal explosion shock wave, thereby reducing the damage to the surrounding environment and protecting human life and property. However, due to the complexity of the explosion process and related structure, the mechanism by which shock wave is induced on the inner lining of the explosion containment vessel (ECV) and the influence of the structural parameters of ECV on the reflection overpressure of the inner wall are not understood clearly. In this study, the characteristic of the internal explosion pressure load of a single-layer ECV is examined through experimental tests and simulations, and a three-dimensional mesoscopic model is established and verified. Furthermore, to solve the problem of the restricted explosion resistance of the single-layer ECV, a new steel plate-aluminum honeycomb-fiber cloth sandwich structure with sliding lining is proposed to design a multi-layer CECV. For the arrangement of fiber filaments, uniform distribution, random distribution, and honeycomb distribution algorithms are established

22 based on Python language. Finally, a finite element model of the CECV is established, and a series
23 of explosion simulations are conducted. The results indicate that the laying angle of the fibre cloth
24 has no effect on the peak overpressure inside the ECV, and the ECV exhibits the best protective
25 property when the laying angle of the fibre cloth is $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$. It is also observed that the
26 steel plate-aluminium honeycomb-fibre cloth sandwich structure prolongs the action time of the
27 explosion shock wave and greatly reduces the peak pressure in the CECV. Remarkably, for the
28 weakest position of the tank, the strain for the multi-layer CECV under 3000 g TNT is even less
29 than that for the single-layer ECV under 150 g TNT.

30 **Keywords:** Composite explosion containment vessel; Overpressure; Three-dimensional mesoscopic
31 model; Steel plate; Aluminum honeycomb; Fiber cloth

32 **1 Introduction**

33 The safe handling of discarded weapons and ammunition and reduce its destructive effect is a
34 topic of current research [1]. Explosion containment vessels (ECVs) have been widely used in
35 military, civil and industrial fields to limit the scope of internal explosion shock wave, protect
36 personnel and equipment [2,3]. Notably, several drawbacks, such as bulkiness, single structure and
37 limited blast-resistance performance against high charge explosives, gradually appear in commonly
38 used single-layer ECVs. Therefore, some improved ECVs with new materials and structures have
39 been designed to contain the impact of explosion. Particularly, composite ECVs (CECVs) has been
40 widely used because of its high strength, low density and better performance than steel ECVs [4].

41 Over the recent years, the propagation and attenuation of shock waves in ECVs have been
42 extensively examined through experiments. Ren et al. [5] studied the attenuation characteristics of

43 stress wave in aluminum foam sandwich cylindrical explosion tank through experiments. It was
44 found that aluminum foam greatly reduced the strength of stress waves, and the "hard-soft-hard"
45 composite structure was proved to a reasonable explosion-proof structure. Wang [6] studied the load
46 distribution and dynamic response of a CECV with filament wound metal lining and found that the
47 beat phenomenon appeared on the cylinder of the vessel. Such a vessel is lightweight and has good
48 anti-explosion ability. Cui et al. [7] examined the dynamic response of a multi-layer ECV under the
49 action of internal explosion. It was suggested that the transmission of stress waves in the multi-layer
50 medium caused the outer wall to be first subjected to impact compression from the inside. Dong et
51 al. [8] experimentally analyzed the dynamic response of carbon fiber cylindrical shells. The results
52 indicated that the carbon fiber cylindrical shells demonstrated better explosion-resistant
53 performance than the glass fiber cylindrical shells for the specific types of tests and shell
54 configurations considered. Liu et al. [9] designed a single-layer cylindrical ECV and a new
55 multi-layer cylindrical ECV composed of single-layer ECV and aluminum foam sacrificial inner
56 lining, and the results showed that the energy-absorbing inner lining has a certain protective effect
57 on the CECV, shortens the vibration time of the CECV and changes the strain growth mechanism of
58 the vessel shell.

59 However, experimental investigations are usually difficult selection of the test site, high cost,
60 heavy workload, and time-consuming, and it cannot provide insights on the explosion-resistant
61 mechanism and dynamic response of ECV. Further, the existing theoretical studies on ECV mostly
62 focus on its elastic response. Baker [10] investigated the elastic-plastic response of a thin spherical
63 shell under spherically symmetric internal transient pressure loading. Analytic solutions are

64 obtained to the linear, small-deflection equations of motion for shell materials which exhibit various
65 degrees of strain-hardening. Duffey and Mitcheli [11] presented an experimental and theoretical
66 investigation of the high explosive containment ability of ECV. Based on the rigid-plastic material
67 relation for the ECV, the functional expression of the final circumferential strain or radial
68 displacement and the length of the cylinder length is derived.

69 Zhu et al. [12] conducted the formation and development of dynamic strain growth and the
70 factors which affect it of ECV under internal blast loading, and theoretical treatment of the strain
71 growth and strain growth factor is given for the first time. It is pointed out that the superposition
72 and interaction of different modes of response with similar frequencies is regarded as the
73 mechanism of strain growth. Wang et al. [13] developed an elastodynamic method to determine the
74 dynamic stresses in a multi-layered ECV subjected to dynamic pressure, and the dynamic stresses in
75 a two-layer cylinder and a sandwich cylinder subjected to sudden interior pressure were calculated.
76 Zheng et al. [14] studied the dynamic elastic response of a discrete multi-layered cylindrical shell
77 (DMC) under uniformly distributed pressure pulse, and the effects of parameters, such as thickness
78 ratio of the inner shell to that of the complete shell, material parameters, and winding-angle, were
79 discussed. Chen et al. [15] established a cylindrical ECV model and the dynamic burst pressure
80 equation of the ECV under the explosive load was obtained, finally the accuracy of this equation
81 was verified by comparison with the results of finite element (FE) method.

82 In general, the mesoscopic model can effectively reveal the mechanism by which the ECV
83 contains the internal explosion shock wave, and the protective structure of each layer of the ECV
84 can be modeled separately from the air, so that the gas-solid interaction can be easily captured, and

the protective effect of each layer of the multi-layer ECV can be analyzed separately. Karpp et al. [16] investigated the response of steel containment vessels to the blast loading by both finite-difference (FD) and FE computer codes. The two-dimensional motion, which occurred after significant wave interactions had taken place in the test vessels, was simulated by FE method. Dong et al. summarized the previous studies [17-19] and systematically analyzed the strain growth mechanism of cylindrical shells to propose a design method for ECVs based on an equivalent single-degree-of-freedom (SDOF) design method and three-dimensional (3D) FE analysis [20]. Due to the complexity of the explosion process and relevant structure, the propagation process and influence law of the shock wave in the sandwich layer of the ECV as well as the influence of the structural parameters of the ECV on the reflection overpressure on the inner wall have not been clarified yet. Furthermore, in the earlier studies, the explosion load was usually simplified to a uniform pressure, which is an impractical assumption. Therefore, in this paper, a 3D mesoscopic model of single-layer ECV is established, and its explosion-resistant performance is examined both experimentally and numerically. Then, a new type of multi-layer CECV is established, and it is proved that the multi-layer CECV is superior to the single-layer ECV in terms of both anti-explosion ability and energy absorption effect. Furthermore, the effects of lining form and material on the anti-explosion ability are analyzed. The failure and deformation of the sandwich layer and the dynamic response of the shell are also investigated.

2 Experiments setup

Four tests with different charge weight (27 g, 64 g, 120 g and 150 g) were conducted, TNT explosive charges were used to generate the shock wave, and the experimental data such as internal

106 pressure and strain of the single-layer ECV are recorded and discussed in detail.

107 **2.1 Single-layer cylindrical explosion container vessels**

108 The internal explosion experiment was performed in the single-layer ECV designed by our
109 group [9], whose dimensions are listed in Table 1. The single-layer ECV shell, bottom head, flange
110 and head cover, as shown in Fig. 1. The bottom head was welded on the shell, and the head cover
111 was coupled with the shell by bolts. The upper end cap was tightly connected to the container body
112 through a flange and bolt structure. The ellipsoidal end cap was connected to a cylindrical flange.
113 Eight test holes were reserved on symmetrical sides of the cylinder, and a pressure relief valve was
114 installed on the pressure relief pipe. The inner diameter and the thickness of the shell are 150 mm
115 and 18.5 mm, respectively.

116 **Table 1.** Dimensions of the ECV

Inner diameter	Cylinder height	Length/diameter ratio	Thickness	Dynamic load coefficient	Equivalent static load
800 mm	1170 mm	2:1	22 mm	0.56	6.79 MPa

117 **2.2 Experiment vessels and test system**

118 In the experiment, a total of five measurement points (P1-P5) were set on the side wall of the
119 cylinder to test the reflection overpressure and strain of the wall surface. The locations of these
120 points are shown in Fig. 1. The points P2, P3, and P4 are 150, 300, and 450 mm away from P1, and
121 P5 is located at the pole point of the oval-shaped lower end cap.

Fig. 1 Layout of the measurement points (left) and a snapshot of the ECV (right)

2.3 Experiments on Shell Response

Fig. 2 compares the typical pressure-time curves of the measurement points when 120 g charge explodes at different positions in the container. The pressure-time curve is consistent with the basic waveform of the explosion shock wave reflection, i.e., there is a very steep rising edge. After the shock wave pressure reaches its peak, it decreases almost exponentially, and multiple superimposed waveforms are generated. For different locations under the same charge, the reflection overpressure and the specific impulse at the P1-P4 position gradually decreases with the increase in the distance from the explosion center, and the time to reach each measuring point is obviously prolonged. There is obvious reflection overpressure at the points P1, P2 and P3 in a short time, and there is no reflection overpressure at the P4 measuring point at the same time. The P5 measurement point is located at the bottom of the end cap. The peak value of overpressure increases significantly after superposition, and the superposition effect is obvious. Table 2 shows the peak pressure of each measurement point under different charges. The empirical value is obtained by the simulation

equation of explosion load in an enclosed ECV, as proposed by Deng et al. [21] and Lin et al. [22].

Fig. 2 Peak overpressure-time curves for each measurement point under the action of 120 g TNT equivalent

Table 2. Experimental and simulated values of the peak overpressure at each measurement point

No.	Charge quantity (g)	Peak pressure (MPa)					
		P1			P2		
		Experimental	Empirical	Error	Experimental	Empirical	Error
		value	value		value	value	
1	27	1.69	1.78	0.05	1.56	1.8	0.13
2	64	2.52	2.53	0.00	2.63	2.26	0.16
3	120	4.54	3.88	0.17	3.81	3.48	0.09
4	150	6.75	5.4	0.25	5.27	4.83	0.09

No.	Charge quantity (g)	Peak pressure (MPa)					
		P3			P4		
		Experimental	Empirical	Error	Experimental	Empirical	Error
		value	value		value	value	
1	27	0.98	1.18	0.17	0.59	0.73	0.19
2	64	1.7	1.69	0.01	1.13	1.57	0.22
3	120	2.9	2.6	0.12	1.6	1.17	0.37
4	150	4.39	3.62	0.21	2.7	2.5	0.08

No.	Charge	Peak pressure (MPa)					
-----	--------	---------------------	--	--	--	--	--

quantity		P5		
(g)		Experimental	Empirical	Error
		value	value	
1	27	4.52	0.57	6.90
2	64	9.18	0.73	18.59
3	120	9.74	1.88	4.19
4	150	13.6	1.55	7.9

142 It is clear that there is a large deviation between the experimental and calculated values for the
143 measurement at point P5, indicating that the Lin's equation [22] is not suitable for the simulation of
144 peak overpressure at the end cap pole points of an ellipsoid. For the measurement at points P1, P2,
145 P3 and P4 on the cylindrical shell, the errors between the experimental and calculated values are
146 within 0-37%, and only two measurement points have errors of more than 20%. This suggests that
147 there is some deviation between the experimental and empirically calculated values. Therefore, to
148 improve the simulation accuracy of the peak overpressure under an internal explosion load, Lin's
149 equation is modified based on the peak overpressure of measurement at points P1, P2, P3 and P4.

150 The peak overpressure and the proportional explosion distance of the measurement at the
151 P1-P4 position in Table 2 are fitted using MATLAB, and the corresponding results are shown in Fig.
152 3. The regression equation is as follows:

$$153 \quad f(x) = a * \exp(-b * x) \quad (1)$$

Fig. 3 Fitting curves of the peak overpressure and proportional explosion distance at each measurement point under different charge quantities

In the regression model, the correlation coefficient is 0.98 in the 95% confidence interval, and the specific values of constants are determined as $a = 28.99$, $b = 2.267$, respectively. The determination coefficient R^2 is 0.9561. Because the determination coefficient is close to 1, it can be inferred that the regression equation is reasonable with high fitting accuracy. Therefore, the revised equation of the peak reflection overpressure of shock wave is expressed as,

$$f(x) = 28.99 \times \exp(-2.267 \times R / \sqrt[3]{W}) \quad (1)$$

where R denotes the linear distance between the explosive and the measurement point on the shell, and W denotes the mass of the explosive. It can be seen from the figure that the peak overpressures of the measurement at the P1-P4 position under the different charge quantities decrease with the increase in the distance from the explosion center.

3 Numerical modeling and parameter selection

To analyze the formation mechanisms of characteristics of the blast loading in the ECV, a 3D

169 mesoscopic FE model of single-layer ECV is established based on the dimensions of the explosion
170 test system in which the influence of actual explosives is considered. The anti-explosion ability and
171 energy absorption effect of ECV are numerically simulated using LS-DYNA.

172 3.1 Model parameters of the materials

173 The 3D mesoscopic FE model of the field test model is composed of TNT explosive, air, and
174 ECV, and a fluid-solid coupling algorithm is used, as shown in Fig. 4. The shell is modeled by
175 Lagrange sub-grid with a hexahedral mesh size of $5.5 \times 5.5 \times 5.5 \text{ mm}^3$, the number of elements is
176 281823. However, the air and TNT charge are modeled by Euler sub-grid with a hexahedral mesh
177 size of $10 \times 10 \times 10 \text{ mm}^3$, and the number of elements is 1583282. The Eulerian (fluid) domain grid
178 is slightly larger than the Lagrangian (solid) domain grid to ensure the effective fluid-solid
179 interaction considered in the coupling algorithm available in LS-DYNA. The charge weight of the
180 explosive are 27 g, 64 g, 120 g, and 150 g, respectively.

181
182 **Fig. 4** 3D model of ECV

183 To accurately describe the mechanical properties of the ECV in the explosion, especially the
184 deformation under the action of explosion load, the Johnson-Cook (JC) material model is used to
185 simulate the mechanical behavior of the ECV. The vessel body is made of Q345 steel. The

parameters of JC material model are shown in Table 3.

Table 3. Simulation parameters of the JC material model for the vessel body

D_1	D_2	D_3	D_4	D_5	G (GPa)	C	S_1	γ_0
0.05	3.44	-2.12	0.002	1.61	82.82	0.4569	1.49	2.17
n	C_p (J/kg·K)	m	T_r	μ	A	B	ρ (kg/m ³)	
0.18	460	1.0	293	0.3	345	477	7870	

The TNT explosive is simulated by the filling method in LS-DYNA. The detonation of the explosive is modeled with Jones-Wilkins-Lee (JWL) equation of state [23]. The parameters are shown in Table 4.

Table 4. Parameters of the JWL equation of state

ρ (kg/m ³)	A (GPa)	B (GPa)	R_1	R_2	PCJ (GPa)	E (J/m ³)	D (m/s)	v	ω
1500	347.6	3.39	4.15	0.95	17.92	6.34×10^9	6957.2	1.0	0.28

An arbitrary Lagrangian-Eulerian (ALE) grid is used for air modeling. The parameters of the air model are shown in Table 5.

Table 5. Simulation parameters of the air [24]

C_0 (MPa)	C_1	C_2	C_3	C_4	C_5	C_6	ρ (kg/m ³)
-0.1	0	0	0	0.4	0.4	0	1.225

The nuts and bolts were made of 35CrMoA steel. To ensure an effective balance between the simulation accuracy and efficiency, a simplified JC model is used for the nuts and bolts. The simulation parameters of this model are shown in Table 6.

Table 6. Simulation parameters of the JC material model for the nuts and bolts

Parameter	E (GPa)	C	μ	A	n	B	m	ρ (kg/m ³)	T_r
Value	82.82	0.014	0.2804223	835	0.26	510	1.0	7850	293

3.2 Numerical results and discussion

The simulation results of the typical pressure at each measurement point when 27, 64, 120, and 150 g charges are exploded at different positions within the single ECV are shown in Fig. 5. The peak reflection overpressure at each measurement point on the explosion center torus increases with the increase in the charge quantity. It is observed that the peak reflection overpressure of 64 g TNT equivalent explosion shock wave at points P1-P4 increases by 2.08-2.56 times. When the explosive mass is 120 g, the peak reflection overpressure at P1-P4 is 1.83-3.71 times higher than that when the explosive mass is 27 g. At 150 g TNT equivalent, the peak reflection overpressure at P1-P4 is 3.07-5.35 times higher than that at 27 g. For different charge quantities at the same position, the reflection overpressure and the specific impulse gradually increase with the increase in the charge quantity, which is consistent with the results of Langdon et al. [25, 26] and Jacob et al. [27]. For different positions with the same charge quantity, the reflection overpressure, and the specific impulse at P1-P4 decrease with the increase in the distance from the explosion center.

Fig. 5 Numerical simulation results of the peak overpressure at each measurement point under different charge quantities.

Fig. 6 shows the numerical and experimental results as well as the fitting curves of the peak pressure imposed by explosion shock waves using 27, 64, 120, and 150 g charges at the measurement points P1-P4. To quantitatively describe the difference between the experimental and simulation results, the numerically simulated peak pressure imposed by the explosion shock waves is taken as the X-axis and the experimental results are taken as the Y-axis in Fig. 6a. Here, the straight line with a slope of 1 indicates that the simulation results are identical to the experimental results. When the test point is below (above) this straight line, it indicates that the numerical value is higher (lower) than the experimental value. It is clear from Fig. 6a that the test points fall between the solid line with a slope of 1 and the dashed line with a slope of 0.8, indicating that the error is generally within 20%.

Fig. 6 Comparison between the numerical and experimental results of the peak overpressure. (a) Comparison between the experimental and simulated values; (b) fitting curve of the experimental and simulated values.

As shown in Fig. 6b, the numerical simulation results under different charge quantities are in good agreement with the experimental results. The peak reflection overpressure of the measurement points P1-P4 gradually decrease with the increase in the proportional explosion distance. The fitting

231 curves of the experimental and simulation results are approximately coincident, indicating a good
 232 simulation accuracy. It can be noted from Fig. 6b that the experimental values are slightly higher
 233 than the simulated values.

234 A comparison between the results based on the experiment and improved Lin's equation is
 235 presented in Table 7. It is evident that the error between the experimental value at P1-P2 and the
 236 calculated value using improved Lin's equation is within 0-14%, which indicates the improvement
 237 in the simulation accuracy of the peak overpressure of the explosion load in the enclosed ECV.

238 **Table 7.** Simulation results of the peak overpressure at each measurement point.

No.	Charge quantity (g)	Peak pressure (MPa)					
		P1			P2		
		Experimental	Empirical	Error	Experimental	Empirical	Error
		value	value		value	value	
1	27	1.69	1.53	0.10	1.56	1.45	0.07
2	64	2.52	2.65	-0.05	2.63	2.35	-0.04
3	120	4.54	4.99	-0.10	3.81	4.34	-0.14
4	150	6.75	6.69	0.01	5.27	5.68	-0.08

No.	Charge quantity (g)	Peak pressure (MPa)					
		P3			P4		
		Experimental	Empirical	Error	Experimental	Empirical	Error
		value	value		value	value	
1	27	0.98	1.04	-0.06	0.59	0.58	0.02
2	64	1.7	1.77	-0.04	1.13	1.20	-0.06
3	120	2.9	3.06	-0.06	1.6	1.56	0.02
4	150	4.39	4.06	0.08	2.7	2.58	0.04

No.	Charge	Peak Pressure (MPa)					
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quantity (g)		P5		
		Experimental	Empirical	Error
		value	value	
1	27	4.52	0.90	0.80
2	64	9.18	1.20	0.87
3	120	9.74	1.88	0.81
4	150	13.6	2.28	0.83

239

240 3.3 Shock wave propagation

241 Fig. 7 shows the change of air pressure in the internal with time (0 to 10 ms) in the ECV under
242 the TNT charge weight of 150 g. For each measurement point, the time at which the first pulse
243 reaches the measurement point Pl after the charge explodes at the center of the vessel is taken as the
244 reference time. In the model experiment, the initiation and the propagation process of the explosion
245 wave is clearly seen. The numerically simulated pressure-time curve is consistent with the basic
246 waveform of the explosion shock wave reflection, i.e., there is a very steep rising edge. After the
247 shock wave pressure reaches its peak, it decreases almost exponentially, as shown in Fig. 7b. At 0
248 ms, the charge explodes. The shock wave reaches the vessel wall around 0.16 ms. The shock waves
249 are reflected due to the barrier of the vessel wall, and they move along the inner wall of the vessel
250 to the end. At 0.34 ms, the intersection of the Mach reflection and the three waves is evident. At
251 0.58 ms, the first shock wave that is generated by the shock wave converging at the vessel center
252 reaches the end cap. The first pressure peak appears at the pole point, and the shock wave
253 propagates faster in the denser air medium. However, due to the barrier of the vessel wall, the
254 convergence wave reaches the end cap pole point at 0.66 ms and forms the second peak before the

255 Mach wave. At 0.7 ms, the Mach reflection wave converges at the end cap pole point, forming the
 256 third peak, as shown in Fig. 7a.

257 **Fig. 7** ECV pressure analysis. (a) ECV pressure contour; (b) peak overpressure-time curve at the
 258 end cap.

259 **3.4 Specific impulse comparison**

260 The experimental groups with 27 g and 150 g TNT equivalents were selected, and the specific
 261 impulse was obtained by integrating the pressure during the action time of positive pressure. A
 262 comparison between the numerically simulated and experimentally obtained values of specific
 263 impulse is shown in Fig. 8. Here, the simulation and experimental results are taken as the X-axis
 264 and Y-axis, respectively. The straight line with a slope of 1 indicates that the simulation results are
 265 exactly identical to the experimental results. When the test point is below (below) the straight line,
 266 it indicates that the simulated value is higher (lower) than the experimental value. It can be seen
 267 from the figure that the test points mostly fall between the solid line with a slope of 1 and the
 268 dashed line with a slope of 0.8, demonstrating that the experimental value of the specific impulse is
 269 smaller, and the error is generally within 20%. There were two main reasons for this error. Firstly, in

the experimental test, the explosion process has a certain discreteness. Therefore, small differences exist in the results of multiple tests even if the mass and density of the charge are the same. Secondly, in the numerical simulation, the ideal gas state equation is used to describe the high temperature and high-pressure air, which induces errors. Furthermore, the presence of the grid causes truncation and discretization errors.

Fig. 8 Comparison between the experimental and numerically simulated specific impulse.

4 Design of composite multi-layer tank

Shock wave is a kind of intermittent strong compression wave with high amplitude, short duration and strong destructive force [28], and the damage effect mainly depends on the peak overpressure and positive pressure action time. For the CECVs, several possible criteria can be used to evaluate its explosion resistance, one criterion is the deflection of outer face sheet (DF). The DF under the internal explosion should be reduced to ensure the safety of the CECVs. Second, the attenuation effect of the protective material under the shock wave can be evaluated according to the pressure reaching the vessel.

Based on the experimental and simulation results of single-layer tank, it is concluded that the weakest position of the ECV is the end cover, so a sliding steel plate-aluminum honeycomb-fiber

287 cloth structure is used to design the composite multi-layer explosion canister and increase the
288 thickness of the aluminum honeycomb core at the weakest end cover. Under the explosion load, the
289 sliding lining can compress the protective layer to the maximum extent, so that it can fully absorb
290 the energy released by the explosion and reduce the explosion load directly acting on the outer wall
291 of the explosion tank. The new multilayer CECV has an excellent application prospect in improving
292 the anti-explosion ability [29-31]. In this section, the 3D model of aluminum honeycomb core and
293 fiber cloth is established. The 3D solid meso-model at 1:1 is established by LS-DYNA software,
294 and the explosion resistance of the new CECV is examined by numerical simulation.

295 **4.1 Finite element model**

296 The algorithm for the generation of aluminum honeycomb core consists of three steps. Firstly,
297 the honeycomb geometry is generated through an array (as shown in Fig. 9). Secondly, the
298 structural FE model is established to set the cell wall thickness for the extracted honeycomb
299 geometry. Finally, the mesh mapping is carried out in the structural FE model, the coarse aggregate
300 is deleted, the aluminum honeycomb core mesh is extracted, and the 3D FE model of aluminum
301 honeycomb core is obtained. The 3D model of ECV lining and end cover lining is shown in Fig.10.

302
303 **Fig. 9 Honeycomb model.**

(a) Explosion containment tank lining

(b) End cover lining

Fig. 10 3D honeycomb model.

The generation algorithm of the carbon fiber cloth consists of four steps. In the first step, the representative volume unit of the unidirectional (UD) mesoscopic model of carbon fiber epoxy resin and glass fiber-reinforced plastic (FRP) epoxy resin is analyzed. A Python program is used to generate the UD microscopic model of fiber, as shown in Fig. 11(b), where the fiber content is 50% and the fiber radius is 3 μm . The fiber filament and epoxy resin are connected by a common node, and the epoxy resin is used as the matrix, which ensures the continuous deformation at the interface between the fiber and epoxy resin and the complete transmission of node and unit information, as shown in Fig. 11(c).

(a) Carbon fiber filament (b) UD geometric model (c) Finite element model

Fig. 11 UD microscopic model of fiber.

The parameters of the composite materials are calculated by the quasi-static stretching method, as shown in Fig. 12. One end of the fiber is stretched with a fixed constraint, and the other end is stretched with a constant displacement. The average tensile speed is 2 mm/min, and the other directions are set by periodic boundary, as shown in Fig. 12.

Fig. 12 Quasi-static stretching diagram.

To explore the influence of the arrangement of fiber filaments on the properties of fiber cloth, a microscopic model of fiber cloth with different fiber filling coefficients is established, as shown in Fig. 13. The fiber filaments are arranged in the following ways: honeycomb arrangement, uniform arrangement, and random arrangement. The filament diameter of each arrangement is 50 μm . It is clear from the figure that compared to the honeycomb arrangement, the uniform arrangement can hold less filaments, and the random arrangement can contain the maximum filaments among the three cases.

333 **Fig. 13** Yarn diagram of filaments arranged in different ways.

334 The representative microscopic model of fiber cloth is loaded with uniaxial tensile load, and

335 the stress-strain analysis is carried out. The elastic modulus is calculated according to the average

336 stress and strain values of the representative elements under each fiber arrangement, as shown in

337 Table 8. It can be found that the law of elastic modulus is similar to that of stress, and the higher the

338 randomness, the smaller the stress and elastic modulus. Consequently, it can be concluded that

339 when the fiber content remains constant, the honeycomb fiber composites can improve the bonding

340 interface between resin and fiber, the elastic modulus and friction properties of the materials, and

341 the load-bearing capacity. Therefore, in the second step, the representative volume unit of the

342 mesoscopic model of carbon fiber reinforced polymer (CFRP) and epoxy resin reinforced braided

343 fiber cloth is modeled by using the honeycomb arrangement method. The macroscopic material
 344 parameters of CFRP and epoxy resin reinforced braided fiber cloth are calculated by using the same
 345 mechanical calculation method to transfer them from mesoscopic scale to macroscopic scale. In the
 346 third step, the macroscopic plane is modeled through the software SpaceClaim. In the fourth step,
 347 ANSYS ACP software is used to build the lay-up model for the macroscopic plane model. The
 348 material parameters extracted from the macroscopic model are used as the lay-up material
 349 parameters, and the lay-up effects from different angles are considered. Finally, the models are
 350 combined.

351 **Table 8.** Representative unit indicators of different arrangements

Arrangement mode	Average strain	Mean Mises stress (GPa)	Elastic modulus (MPa)
Honeycomb	0.693	19.25	0.432
Well pattern	0.711	18.21	0.315
Random	0.719	15.22	0.249

352 The FE model of the CECV is illustrated in Fig. 14. The honeycomb, fiber cloth, steel plate,
 353 foamed aluminum, and tank are modeled by Lagrange sub-grid with a hexahedral mesh of average
 354 size, while the air and TNT charge are modeled by Euler sub-grid with a hexahedral mesh of
 355 average size.

356

Fig. 14 FE model of the CECV.

The specific parameters of each part of the CECV are shown in Table 9.

Table 9. Specific parameters of CECV

Fiber cloth thickness (mm)	Honeycomb core thickness (mm)	Thickness of lined steel plate (mm)	Thickness of honeycomb core of end cover (mm)
10	60	10	189.95

4.2 Material model and contact algorithm of particles

The fiber cloth is composed of epoxy resin reinforced braided carbon fibers and glass FRP epoxy resin UD model, which are defined as Fabric 2 and Fabric 1, respectively. The laying order is 1-2-1-2-1. Five working conditions under fiber laying angles of $0^\circ/0^\circ/0^\circ/0^\circ/0^\circ$, $0^\circ/30^\circ/60^\circ/30^\circ/0^\circ$, and $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$ and explosive masses of 1.4, 1.6, 1.8, and 3 kg are set. The material parameters of carbon fiber epoxy resin UD model and FRP epoxy resin UD model obtained by quasi-static tensile test are shown in Table 10 and 11.

Table 10. Material parameters of carbon fiber epoxy resin UD model

Name	ρ (g/cm ³)	X- Young's modulus (GPa)	Y/Z- Young's modulus (GPa)	XY/XZ- Poisson's ratio	YZ- Poisson's ratio	XY/XZ- Shear modulus (MPa)	YZ- Shear modulus (MPa)
UD model	1.67	200.77	14.5	0.22	0.42	0.23	0.42

Table 11. Material parameters of FRP epoxy resin UD model

Name	ρ (g/cm ³)	X- Young's modulus (GPa)	Y/Z- Young's modulus (GPa)	XY/XZ- Poisson's ratio	YZ- Poisson's ratio	XY/XZ- Shear modulus (MPa)	YZ- Shear modulus (MPa)
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UD model	2.0	45	10	0.3	0.4	5.0	3.846
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369 The material parameters of carbon fiber epoxy resin braided fiber cloth are obtained by
370 numerically simulating the quasi-static tensile test of the representative volume unit of its
371 meso-model, as shown in Table 12.

372 **Table 12.** Material parameters of carbon fiber epoxy resin braided fiber cloth.

Name	ρ (g/cm ³)	Elastic modulus (GPa)	Shear modulus (GPa)	Poisson's ratio
Weaving model	1319.6	42.881	1.775	0.47595

373 To accurately analyze the nonlinear behavior of aluminum honeycomb core under strong
374 dynamic load, the PLASTIC KINEMATIC material model in LS-DYNA is used to describe its
375 material properties. The matrix material of aluminum honeycomb core is aluminum alloy, and its
376 composition is Al-Si (7-9%)-Mg (0.5-1%). The specific parameters are shown in Table 13.

377 **Table 13.** Material parameters of aluminum honeycomb core

ρ (g/cm ³)	E (GPa)	ν	$SIGY$ (MPa)	$ETAN$ (GPa)
2.73	70	0.34	185	4.62

378 According to the varying shape of aluminum honeycomb core, its erosion strain is determined
379 as 0.37 [32]. It may be noted that friction exists between the matrix material and fiber material in
380 actual fiber composite components, and the measurement of friction coefficient is very difficult.
381 Therefore, to simplify the model and reduce the amount of calculation, in the macroscopic model of
382 fiber composite materials, the contact between matrix epoxy resin and fiber materials is set to
383 common node contact. The FE model of carbon fiber braided fabric and the UD model of FRP

384 epoxy resin are divided by a hexahedron, and the mesh quality is high.

385 4.3 Numerical results and discussion

386 Fig. 15 shows the pressure-time history curve of multi-layer CECV and single-layer ECV at
387 the measurement point P1 under 150 g TNT equivalent. Through comparison, it is clear that the
388 steel plate-aluminum honeycomb-fiber cloth protective structure can prolong the action time of
389 explosion shock wave and reduce the peak pressure in the explosion tank. Thus, the anti-explosion
390 performance of CECV is significantly enhanced.

391

392 **Fig. 15** Peak overpressure-time curves of multi-layer CECV and single-layer ECV at the end cap.

393 Fig. 16 shows the pressure-time history curve of each measurement point of the CECV under
394 1.2 kg and 1.6 kg explosives for different fiber laying angles. The peak reflection overpressure of
395 each measurement point decreases with the increase in the proportional blasting distance, and the
396 peak pressure is the highest at the measurement point P5, and the load at the end cover is the largest,
397 which is still the weakest position of the explosion tank. The pressure-time history curves of each
398 measurement point under different laying angles of fiber cloth are basically similar, which indicates

399 that the laying angle of fiber cloth has no effect on the peak overpressure in the explosion tank.
 400 Furthermore, it is clear from Figs. 16(a) and (b) that as the weight of explosive increases, the
 401 pressure of each measurement point in the explosion tank increases.

402 **Fig. 16** Pressure-time curves inside the explosion tank.

403 Figs. 17 and 18 show the stress-time curves and peak stress values, respectively, of the CECV
 404 at each measurement point under different fiber laying angles for the explosive mass of 1.2, 1.4, 1.6,
 405 1.8, and 3 kg. When the explosive mass is 3 kg and the fiber laying angle is $0^\circ/0^\circ/0^\circ/0^\circ/0^\circ$, the
 406 composite tank is destroyed, so the corresponding stress value is not shown. It can be seen from the
 407 figure that the peak stress of each measurement point gradually decreases with the increase in the
 408 proportional blasting distance under the three laying angles. The peak stress under 1.2 kg explosive
 409 shows a linearly decreasing trend, and the maximum stress is obtained at the end cover. Further,
 410 under the three fiber laying angles, the stress of the composite tank increases with the increase in
 411 the amount of explosive. The peak stress value of each measurement point under different explosive
 412 quantities and fiber laying angles is summarized in Fig. 18. It can be found that under different

explosive quantities, for the fiber composite plate with single-direction laying angle, the increase of laying angle has no obvious effect on the vibration isolation performance of the CECV. The peak stress value of the CECV for fiber laying angle of $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$ is less than that for the other two fiber laying angles. This indicates that the best protective effect of CECV is obtained when the laying angle of the fiber cloth is $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$.

Fig. 17 Stress-time curves.

Fig. 18 Peak stress of CECV.

Table 14. Summary of peak stress of CECV

Explosive quantity (kg)	Laying angle	Measurement point				
		P1	P2	P3	P4	P5
1.2	$0^\circ/0^\circ/0^\circ/0^\circ/0^\circ$	332.00	244.88	218.52	201.37	488.89
	$0^\circ/30^\circ/60^\circ/30^\circ/0^\circ$	323.76	243.00	203.00	194.00	471.00
	$0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$	310.41	241.23	197.71	188.67	470.55
1.4	$0^\circ/0^\circ/0^\circ/0^\circ/0^\circ$	357.28	269.79	261.66	223.86	525.00
	$0^\circ/30^\circ/60^\circ/30^\circ/0^\circ$	355.00	264.00	260.00	216.00	519.37
	$0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$	344.65	263.59	256.54	203.06	517.82

1.6	0°/0°/0°/0°/0°	362.29	324.59	316.97	258.04	525.20
	0°/30°/60°/30°/0°	358.00	317.00	306.00	255.00	519.00
	0°/45°/90°/45°/0°	332.23	304.14	282.35	253.04	505.57
1.8	0°/0°/0°/0°/0°	383.24	327.84	367.17	273.97	541.29
	0°/30°/60°/30°/0°	381.00	316.00	345.00	252.00	533.00
	0°/45°/90°/45°/0°	366.98	311.37	339.03	245.04	515.62
3	0°/30°/60°/30°/0°	522.79	486.92	496.95	331.46	623.56
	0°/45°/90°/45°/0°	514.03	479.20	491.69	348.33	610.52

419 Now, the stress state of steel plate and aluminum honeycomb core is analyzed. Figs. 19 and 20
420 show the peak stress of steel plate and aluminum honeycomb core at different fiber laying angles
421 under 1.2, 1.4, 1.6, 1.8, and 3 kg explosives. It is clear that the peak stress of each measurement
422 point of the composite tank gradually decreases with the increase in the proportional blasting
423 distance under the three laying angles, and the five measurement points (P1-P5) exhibit the
424 maximum stress, i.e., the stress of the steel plate and aluminum honeycomb core is highest at the
425 end cover. Further, under the three fiber laying angles, the stress of steel plate and aluminum
426 honeycomb core increases with the increase in explosive amount, but the increase of aluminum
427 honeycomb core is larger than that of steel plate. According to Figs. 19 and 20, it can be inferred
428 that under different explosive quantities, for the fiber composite plate with laying angle of 0°/ 0°/
429 0°/ 0°/ 0°, the increase of laying angle (0°/ 30°/ 60°/ 30°/ 0°) has no obvious effect on the explosion
430 resistance of protective materials (steel plate and aluminum honeycomb core) of composite tank.
431 The peak stress value of the steel plate and aluminum honeycomb core for the fiber laying angle of

432 $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$ is less than that for the other two fiber laying angles. This verifies that the
 433 protective effect of the explosion tank is the best when the laying angle of the fiber cloth is $0^\circ/45^\circ/$
 434 $90^\circ/45^\circ/0^\circ$.

435
 436 **Fig. 19** Peak stress of steel plate

437
 438 **Fig. 20** Peak stress of aluminum honeycomb core

439 Finally, we analyze the strain at each measurement point of the CECV. Fig. 21 shows the
 440 strain- time history curve of the P1 measurement point of the multi-layer CECV and the single-layer

ECV. It is clear that the protective layer of the composite tank can greatly reduce the circumferential strain of the explosion tank. After adding the protective structure of steel plate-aluminum honeycomb-fiber cloth, the strain is reduced and the beat effect of the explosion tank is avoided, while the strain of the shell of the single-layer explosion tank shows a consistent periodic fluctuation characteristic due to the beat effect, which continuously oscillates in the time duration of 5 ms. It shows that the inner lining design can significantly improve the anti-explosion and wave-absorption ability of the ECV.

(a) $0^\circ/0^\circ/0^\circ/0^\circ/0^\circ$

(b) $0^\circ/30^\circ/60^\circ/30^\circ/0^\circ$

(c) $0^\circ/45^\circ/90^\circ/45^\circ/0^\circ$

Fig. 21 Strain-time history curves of the measurement point P1

453 **5 Conclusion**

454 In this paper, the internal explosion pressure load of a single-layer ECV was examined through
455 experiments and numerical simulations. Then, the load characteristics were analyzed, and the
456 weakest position of the ECV was determined, based on which a multi-layer CECV was designed.
457 The random distribution and uniform distribution characteristics of fiber filaments in the yarn were
458 studied at the micro scale, and uniform distribution, random distribution, and honeycomb
459 distribution algorithms were proposed for the fiber well pattern based on Python language.
460 Furthermore, a 3D meso-model of the multi-layer CECV was established, and the internal load
461 distribution of the explosion tank and the stress of the protective structure were analyzed. The main
462 results of the study are summarized as follows:

463 (1) When the fiber content remained constant, compared with the uniform arrangement and
464 random arrangement of fiber filaments, the fiber composites with honeycomb arrangement of fiber
465 filaments improved the bonding interface between resin and fibers as well as the elastic modulus
466 and friction properties of the materials and exhibited higher load-bearing capacity.

467 (2) The simulation results of the single-layer ECV were in good agreement with the
468 experimental results, which verified the accuracy of the 3D numerical model. The 3D model could
469 predict the propagation of the shock waves in the single-layer ECV, and the end cover was
470 determined as the weakest position.

471 (3) A sliding steel plate-aluminum honeycomb-fiber cloth protective structure was used to
472 design the multi-layer CECV, and the corresponding meso-model was established. Under the action
473 of explosion, the protective structure of steel plate-aluminum honeycomb-fiber cloth prolonged the

474 action time of explosion shock wave and reduced the peak pressure in the explosion tank, and the
475 laying angle of fiber cloth did not affect the peak overpressure inside the explosion tank. The best
476 protective effect was obtained when the laying angle of fiber cloth was 0°/ 45°/ 90°/ 45°/ 0°.

477 (4) The protective structure of steel plate-aluminum honeycomb-fiber cloth enhanced the
478 anti-explosion ability of the CECV. Consequently, the strain value of P1 measurement point of
479 composite tank under 3 kg TNT was less than that of single-layer tank under 150 g TNT.

480 **Conflicts of Interest**

481 The authors declare no conflict of interest.

482 **Acknowledgement**

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486 **Data availability statements**

487 The data used to support the findings of this study have been deposited in the “figshare”
488 repository (Yuan Qi, Chen Heng, Gu Wenbin, Wang Zhen, Hao Likai (2021): data.zip. figshare.
489 Dataset. <https://doi.org/10.6084/m9.figshare.16419627.v1>), and the data used to support the
490 findings of this study are included within the article.

491

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