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# Numerical Study on the Performance of RC Slab with Protective Aluminum Foam Cladding under Near-field Explosion

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**Abstract:** Aluminium foam material has excellent properties and a wide application prospect in the field of protective engineering. Present study is to study the protecting effect of aluminium foam plate on RC slab. First, quasi-static compression test and SHPB test were conducted to verify the material parameters of aluminium foam with different porosity (87% and 77%). Then, the dynamic response and the failure modes of RC slabs were calculated and analysed using LS-DYNA software. The results show that the increase in the thickness of aluminium foam plate changes the failure mode of RC slabs, from the overall bending failure mode to the local spall failure mode. Reasons were discussed and some useful suggestions for design were given at last.

## 1. Introduction

Aluminum foam could absorb large energy through compressive deformation and attract many researchers' attention in the field of anti-explosion<sup>0</sup>. In recent years, many studies were carried out on the dynamic response of RC plates with foam aluminum claddings under near-field explosion. Yuan et al.<sup>[2]</sup> used the numerical simulation method to analyze the protective effect of aluminum foam under blast load. The analysis results show that the aluminum foam protective layer has a good attenuation effect on the explosion shock wave and effectively improves the blast-resistance of RC slab. Wu et al.<sup>[3]</sup> carried out an explosion experiment on several foamed aluminum protective layer RC plates, and proposed a theoretical dynamic response calculation method. Xia et al.<sup>[4]</sup> proposed an optimized design method for the foam cladding based on the load-cladding-structure (LCS) model. Although many very meaningful works were done on the protective performance of RC slabs with cladding aluminum foams, the above studies did not analyze the failure modes of RC slabs.

In this paper, the static and dynamic experiments of foamed aluminum were carried out. Material parameters were calibrated based on the experimental results. Then, numerical simulation studies on the dynamic response and failure modes of RC plates with aluminum foam cladding under near-explosion were carried out. The spall damage of the RC slabs was analyzed. Some useful suggestions for the design were given at last.

## 2. Experiments of foamed aluminum and calibration of material parameters

Closed-cell foamed aluminum was manufactured in the material laboratory of Southeast University. The base material is aluminum copper alloy. The test specimen has a pore size of 2 to 4 mm. In order



to avoid the edge effect, the length of test specimen should be greater than or equal to 7 times the length of the cell diameter<sup>[5]</sup>. Therefore, the cylindrical test specimen used in the test is 30 mm in length and 30 mm in diameter. The quasi-static test was carried out in Nanjing University of Science and Technology. Figure 1 shows the test piece and the loading device. The nominal strain rate is  $0.001 \text{ s}^{-1}$  and the loading speed is  $1.8 \text{ mm/min}$ . The SHPB test was also completed in the laboratory of Nanjing University of Science and Technology. The bullet size is  $0.6 \text{ m}$ , the incident rod size is  $2 \text{ m}$ , the projection rod size is  $2 \text{ m}$ , and the rod diameter is  $37.5 \text{ mm}$ . The SHPB rod is made of LC4 aluminum alloy. Two kinds of porosity aluminum foam were tested and the porosities were 87% and 77%.



Figure 1. Test specimen and the loading device

In present study, aluminum foam was simulated by \*MAT\_CRUSHABLE\_FOAM in LS-DYNA. Parameters of the material model were determined according to the test results, as shown in Table 1. Quasi-static test was simulated, as shown in Figure 2. A typical simulated compression process is shown in Figure 3. It can be seen that the simulation results are roughly consistent with the experimental data, which means the numerical models could simulate the response of aluminum foam well.

Table 1. Parameters of \*MAT\_CRUSHABLE\_FOAM

Porosity	$R_0/(\text{kg/m}^3)$	$E/(\text{MPa})$	$P_R$	$TSC/(\text{MPa})$	DAMP
87%	365	676	0.01	1	0.1
77%	646.3	790	0.01	1	0.1

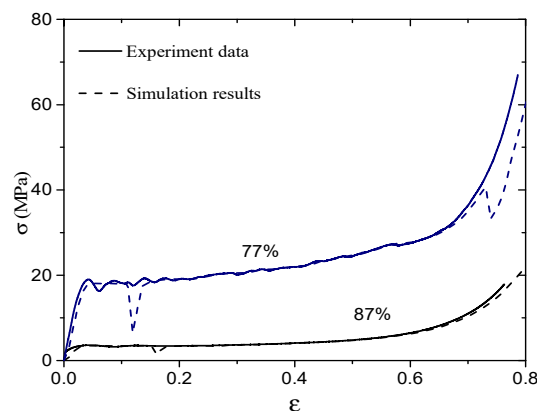


Figure 2. Stress vs strain relations of foamed aluminum (quasi-static compression)

Figure 2 and Figure 3 show that the compression stress-strain curve of aluminum foam is obviously divided into three stages. The first stage is the elastic deformation stage. When the compressive strain is relatively small, the material is linear elastic. The second stage is the plastic platform stage. As the deformation of the foamed aluminum increases, the strain continues to increase and the stress remains unchanged. The stress value at this time is called the platform stress. The third stage is the compaction stage. When the deformation continues to increase, the total pore volume decreases rapidly. Meanwhile, the stress increases rapidly. The properties of the test specimen gradually approach the properties of matrix material.

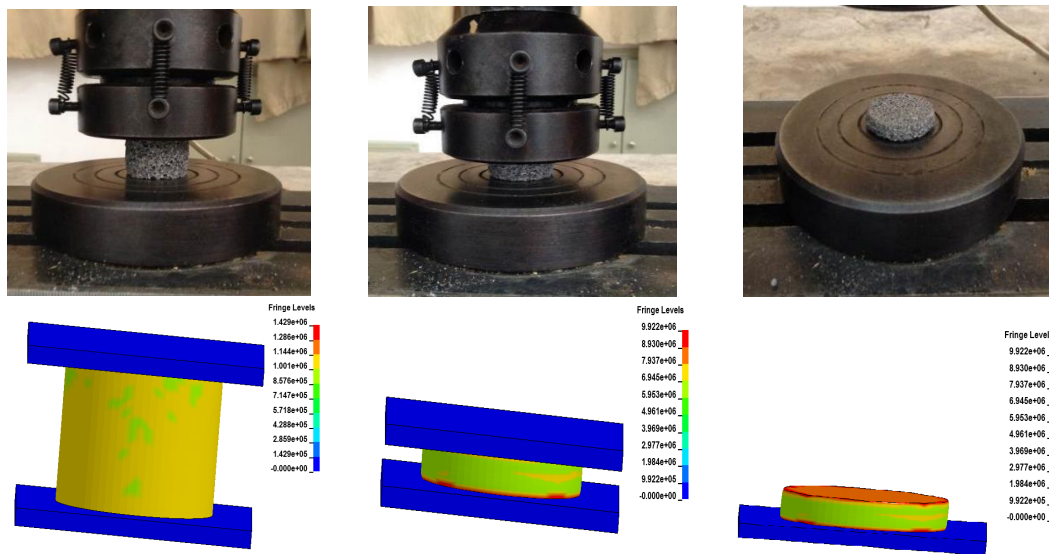


Figure 3. Simulated compression process and the test results (87% porosity)

SHPB test was also simulated. \*MAT\_ELASTIC model is used for the bullet and the rod. The calculation results are shown in Figure 4. It is shown that the experimental data and the numerical simulation results are in good agreement, which means that the numerical model could be used to simulate the response of the aluminum foam cladding.

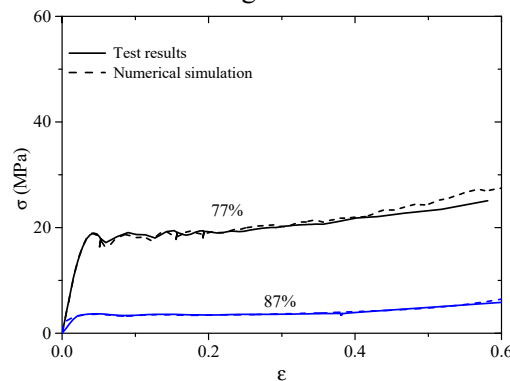


Figure 4. Stress vs strain relations of foamed aluminum (SHPB)

### 3. Protective effect of foam aluminum cladding under near-field explosion

A schematic diagram is shown in Figure 5. The RC plate is a one-way plate with long-edge fixed support. The dimensions is  $1.0\text{ m} \times 2.0\text{ m} \times 0.1\text{ m}$ . The steel bar diameter is 6 mm with a spacing of 100 mm. Those bars are double-layer bidirectional arranged. The protective layer thickness is 20 mm. A spherical explosive of 7.0 kg TNT is placed at a height of 1.0 m from the center of the RC plate surface.

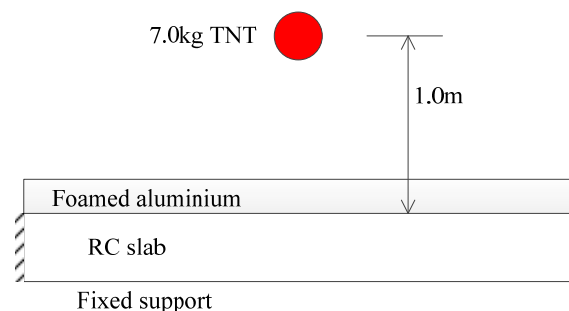


Figure 5. Sketch diagram of RC slab with aluminum foam protective layer

The blast load was simulated by \*LOAD\_BLAST, and the aluminum foam was simulated by \*MAT\_CRUSHABLE\_FOAM. The steel bars were simulated by the \*MAT\_PLASTIC\_KINEMATIC, and the concrete was simulated by \*MAT\_CONCRETE\_DAMAGE\_REL3. Material parameters of concrete and steel are shown in Table 2.

Table 2. Material parameters.

Steel	$E/(\text{GPa})$	$\gamma$	$\sigma/(\text{MPa})$	$E_p/(\text{MPa})$	$\rho/(\text{kg/m}^3)$	$\beta$	$C/(\text{s}^{-1})$	$p$
	200	0.3	300	2000	7800	1	40.4	5
Concrete	$E_c/(\text{MPa})$	$\gamma_c$	$f_c/(\text{MPa})$	$\rho_c/(\text{kg/m}^3)$	Failure strain			
	$3.15 \times 10^4$	0.19	22.9	$2.25 \times 10^3$	0.08			

### 3.1 87% porosity

The mid-span response of the reinforced concrete slab is shown in Figure 6. Figure 6 shows that the protective effect of 87% foam aluminum cladding is obvious, and will be more obvious with the increase of thickness. This is because thicker aluminum foam claddings absorb more energy for 87% porosity. The plastic strain diagram of the RC plate is shown in Figure 7. It shows that RC slab suffer from bending failure mode. With the thickening of the foamed aluminum cladding, the damage degree in the middle of the RC plate is smaller.

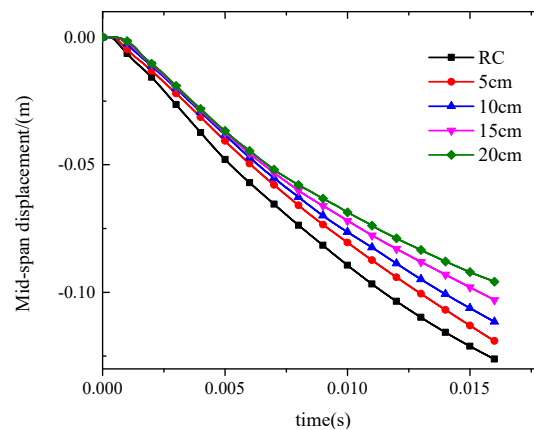


Figure 6. Mid-span displacement of RC slab (87% porosity)

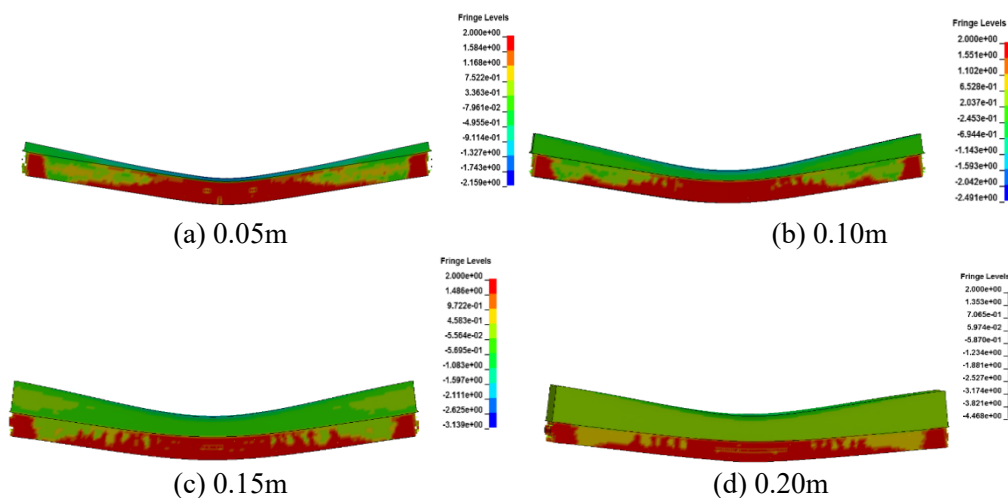


Figure 7. Failure patterns of RC slab with different foamed aluminum thickness (87% porosity).

### 3.2 77% porosity

The mid-span displacement of the RC slab is shown in Figure 8. As shown in Figure 8, the deflection

is significantly reduced as the thickness of the aluminum foam cladding increases. It can also be seen from the curves that the rebound time of the reinforced concrete slab is also advanced as the thickness of the protective layer increases, because the aluminum foam cladding increases the rigidity of the overall structure.

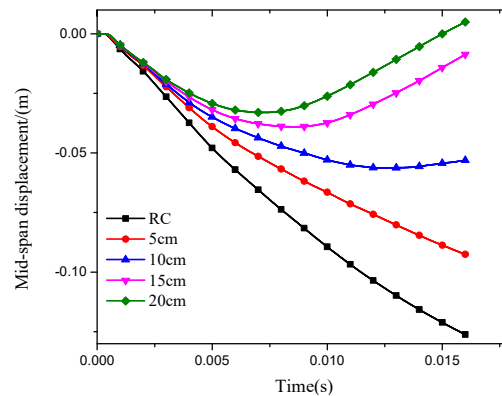


Figure 8. Mid-span displacements of RC slab (77% foamed aluminum).

As shown in Figure 9, it is found that the failure mode of the reinforced concrete slab is changed from the overall bending failure to the local spall failure. This indicates that increasing the thickness of the protective layer in this case significantly changes the failure mode of the RC plate.

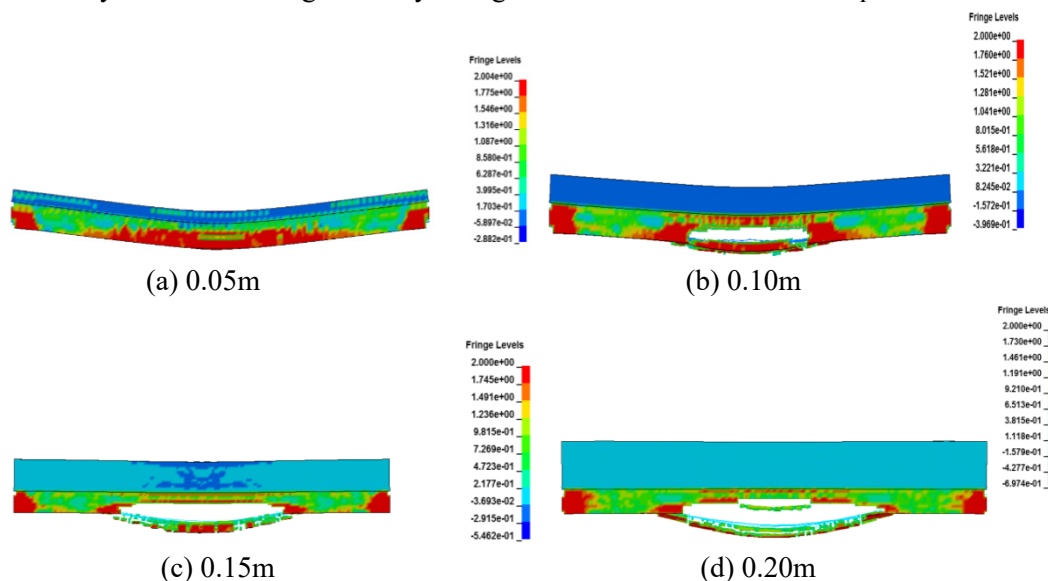


Figure 9. Failure patterns of RC slab with different foamed aluminum thickness (77% porosity)

#### 4. Discussion

The central compressive stress-time history curves on the top surface of the RC slabs are shown in Figure 10. Compressive ratios of foamed aluminum claddings are shown in Figure 11. The foam aluminum cladding of 87% porosity have a platform stress stage, which means that foam aluminum claddings are compressed to the platform stress stage. Meanwhile, the compression ratios reach 50.5% ~ 73.4%, shown in Figure 11. This is because the foam aluminum cladding of 87% porosity have a smaller platform stress and easier to be compressed. Therefore, those claddings absorb a large amount of energy. The compressive stress wave is reduced obviously, which causes a smaller reflective tensile wave. Thus, there is no local spall damage. As for the 5cm cladding, the compressive stress reaches 35 MPa after sufficient compaction, but the bending plastic hinges is formed at the platform stress stage. Therefore, the local spall damage has no chance to be formed.

The foam aluminum cladding of 77% porosity also has a platform stress stage, but the stress value

is larger, reaching to 19 MPa, which is consistent with the platform stress of 77% foam aluminum. Figure 11 shows that 77% foam aluminum compressed aluminum reached 9% to 14%. When the aluminum foam is thin, the overall rigidity of the structure is small. Therefore, the overall response of the RC slab is obvious. The plastic hinge in the span is formed earlier, which causes the RC plate to exhibit a bending failure mode quickly. As the cladding thickening, the overall rigidity of the structure increases. Hence, the bending plastic hinge of the RC plate is more different to be formed. The reflective tensile stress wave causes the collapse damage earlier before the plastic hinge was formed.

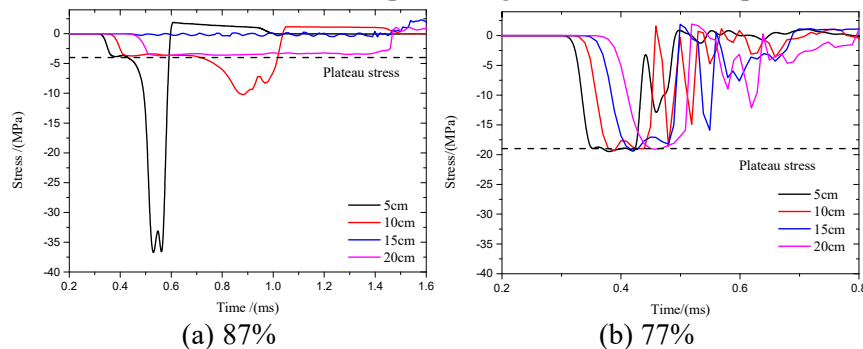


Figure 10. Relations between compressive stress and time at the center of the upper surface

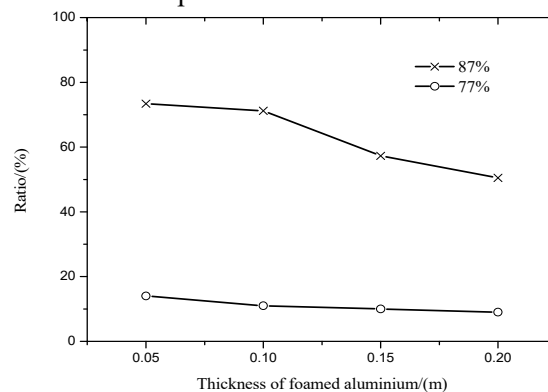


Figure 11. Compressive ratios of foamed aluminum

## 5. Conclusion

In this paper, the finite element method is used to study the dynamic response and failure modes of RC plates with different thickness and different porosity aluminum foam claddings under near-field blast load. The results show that:

- (1) The thickness and the porosity of the aluminum foam claddings are all important factors affecting the protective effect;
- (2) The foam aluminum cladding reduces the mid-span displacement of the RC plate, and increases the rigidity of the overall structure at the same time, thereby affecting the overall response of the structure;
- (3) The change in the thickness of the aluminum foam claddings affects the failure modes of the RC plate. In present study, the increase in thickness causes the change of failure mode from overall bending damage to local spall damage.

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