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PRESSURE-IMPULSE DIAGRAM OF MULTI-LAYERED ALUMINUM FOAM PANELS UNDER BLAST PRESSURE

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Abstract

Anti-terror engineering has increasing demand in construction industry, but basis of design (BOD) is normally not clear for designers. Hardening of structures has limitations when design loads are not defined. Sacrificial foam claddings are one of the most efficient methods to protect blast pressure. Aluminum foam can have designed yield strength according to relative density and mitigate the blast pressure below a target transmitted pressure. In this paper, multi-layered aluminum foam panels were proposed to enhance the pressure mitigation by increasing effective range of blast pressure. Through explicit finite element analyses, the performance of blast pressure mitigation by the multi-layered foams was evaluated. Pressure-impulse diagrams for the foam panels were developed from extensive analyses. Combination of low and high strength foams showed better applicability in wider range of blast pressure.

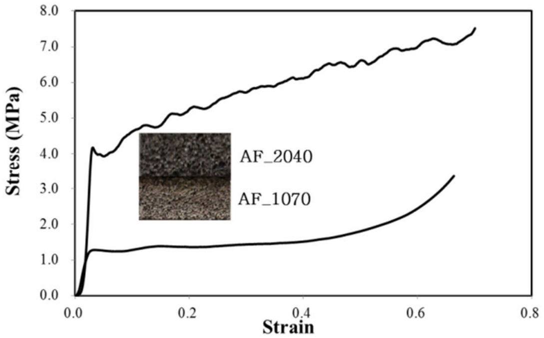
Keywords: Sacrificial foam, Blast pressure, Transmitted pressure, Multi-layered foam, P-I diagram.

1. Introduction

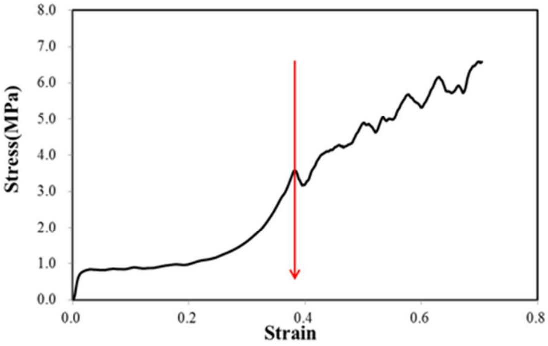
The need and requirements for blast resistance in construction industry have evolved over recent years. The design of blast resistant structures requires knowledge of the blast loading and the behavior of structures under these loadings. The explosion protection system consists of three component: (1) donor system (amount, type and location of explosive), (2) the acceptor system (personnel, equipment, and acceptor explosives), and (3) the protection system (protective structure, structural components or distance). The protection system is to shield against or attenuate the hazardous effects to levels which are tolerable to the acceptor system [1].

The most important feature of blast resistant structure is the ability to absorb blast energy without causing catastrophic failure in the structure or injury to personnel or damage to equipment. Ductile material with longer plastic deformation is adequate for blast protection such as metal foams. Hanssen et al. [2] did blast tests to investigate the blast pressure mitigation by aluminum foam panels considering different scaled distances and relative density. Aluminum foam can be used as a sacrificial cladding to reduce high overpressure by explosion using its large plastic deformation capacity [3-5]. The foam panel on a concrete structure showed excellent pressure mitigation and reduced the transmitted pressure under certain level of its compressive strength [4]. However, the effective range of blast pressure depends on the relative density of the foam.

In this paper, the blast pressure mitigation of multi-layered aluminum foam panels with different density of the foams, as shown in Fig. 1, was investigated through material test and explicit finite element analyses. It is expected to extend the effective range of blast mitigation.



(a) Stress-strain curves of each foam



(b) Effective stress-strain curve of multi-layered foam

Fig. 1. Effect of Multi-Layered Aluminum Foam.

2. Verification of Material Models for Analysis

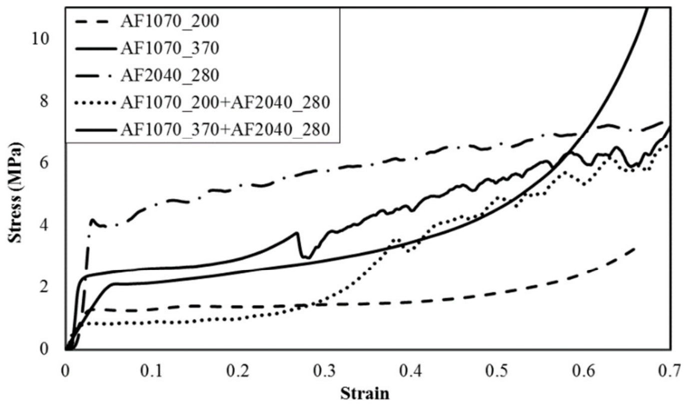
Extensive compression tests were performed to derive typical stress-strain curves of the aluminum foams with 100 mm×100 mm dimensions. Fig. 2(a) shows the stress-strain curves of single and multi-layered aluminum foam panels for AF1070 and AF2040.

For the parametric studies, material models of the aluminum foam need to be verified. The modified honeycomb model in LS-DYNA was chosen [6], and material models for different relative densities using the compression tests were derived by changing the mesh as shown in Fig. 2(b). Mesh dependency in explicit finite element analysis was verified up to 4.7 mm element size. The derived material models of the foams were used to model the multi-layered foam panels. Perfect bond was assumed at the interface of two foams. Figure 2(c) represents the comparisons between the analyses and the compression tests. The explicit analyses gave a good agreement with test results. As found in the research by Deshpande and Fleck [7], test results did not notice any strain rate sensitivity within 0.05 s^{-1} while Shen et al. showed noticeable strain rate effect on both the plateau stress and the densification strain [8, 9]. In this paper, the effect of strain rate was ignored [10].

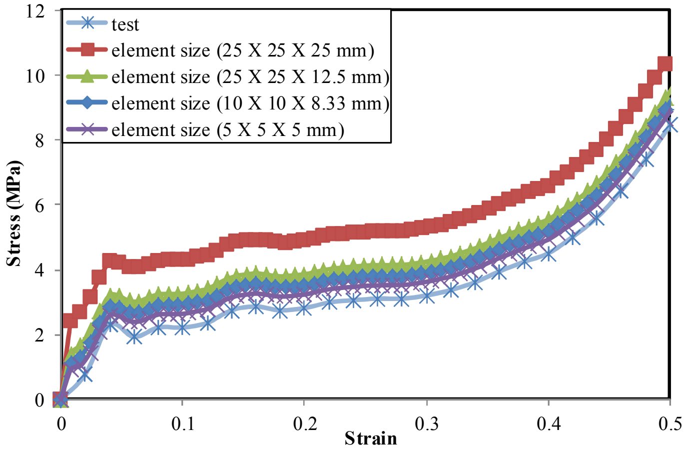
For the design of sacrificial foam claddings, it is important to have data of energy absorption capacity of the foam panel. Table 1 summarises the capacity of the foam panels for different densities and single layered [11] and multi-layered foams. In Table 1, AF1070_200+AF2040_280 means the multi-layered foam with AF 1070_200 material and AF2040_280 material. According to the basis of design (BOD), the appropriate foam panels can be selected considering the energy dissipation capacity.

Table 1. Comparison of Energy Absorption Capacity.

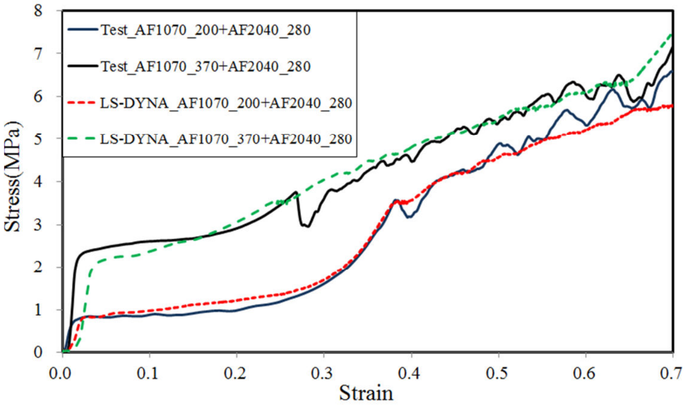
Density	Energy absorption capacity at 20% strain (MJ/m^3)			Energy absorption capacity at 50% strain (MJ/m^3)			Energy absorption capacity at 70% strain (MJ/m^3)		
	Test	Analysis	Test/ Analysis	Test	Analysis	Test/ Analysis	Test	Analysis	Test/ Analysis
AF1070_200	0.20	0.20	1.00	0.61	0.61	1.00	1.06	1.06	1.00
AF1070_370	0.39	0.39	1.00	1.36	1.36	1.00	2.89	2.89	1.00
AF2040_280	0.82	0.82	1.00	2.61	2.61	1.00	4.00	3.98	1.00
AF1070_200+ AF2040_280	0.18	0.19	0.95	0.97	0.99	1.00	2.06	2.03	1.01
AF1070_370+ AF2040_280	0.49	0.43	1.13	1.71	1.73	1.00	2.91	2.96	0.98



(a) Material test results.



(b) Analysis results by different mesh sizes.



(c) Comparison for multi-layered foams.

Fig. 2. Material Models and Verification.

3. Blast Pressure Mitigation

The magnitude of the blast pressure P is roughly proportional to the size of the explosive W and is related as scaled distance ($Z = R/W^{1/3}$). R is the stand-off distance from the center of the charge and W is the charge weight or yield measured in equivalent kg of TNT. According to the scaled distance, blast pressure and its impulse can be estimated. When a target structure has a certain BOD, the high overpressure by explosion should be mitigated using properly designed foam panels.

Using the material models, extensive parametric analyses were performed for various explosive conditions. Air-blast was only considered in the analysis. Figure 3 shows the typical results of the analysis. Po is the reflective pressure on the top surface of the panel. The panel of AF1070_200 under scaled distance of Z=1.25 (TNT 64 kg, 5 m) mitigated the reflective pressure and transmitted 35% of the blast pressure to the structure. However, higher blast pressure of Z=0.75 (TNT 296 kg, 5 m) on the panel with low density showed negligible mitigation. From the analyses of single aluminum foam panels, relative density and thickness of the aluminum foam can be decided to allow the transmitted pressure lower than yield strength of the foam. This design concept is useful for the simple decision of appropriate foam density and thickness according to the design basis of blast condition.

When the basis of design is not clear, it is difficult to design the foam panels. Wider range of blast pressure and impulse needs to be considered in the protective design. Multi-layered foam panels have foam layers with different relative densities. According to the combination of the density, designers can mitigate wider range of blast pressure. As shown in Fig. 3, the induced blast pressure on the panel was reduced and the transmitted pressure had longer duration and smaller magnitude. Combination of AF1070_200 and AF2040_280 reduced the pressure and transmitted 35% of the reflected pressure to the structure for scaled distance of Z = 1.25 (TNT 64 kg, 5 m). For Z = 0.75 (TNT 296 kg, 5 m), the transmitted pressure was 50% of the blast pressure.

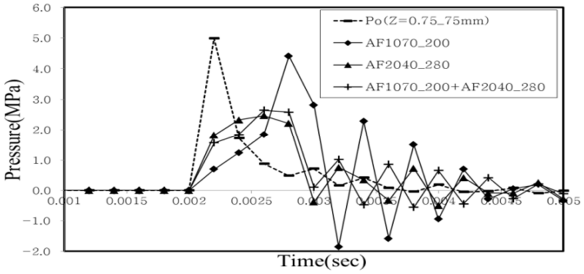
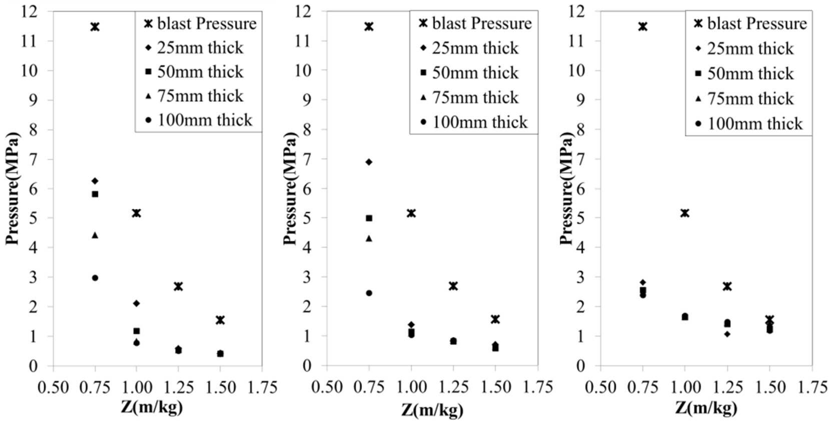


Fig. 3. Blast Pressure History and Transmitted Pressure.

Resistance of structures or members for blast pressure can be calculated using dynamic properties of material. The yield strength of aluminum foam is nearly the same as the level of transmitted pressure when the thickness is properly determined. Therefore, target performance of the sacrificial panel can be decided considering allowable blast pressure on a structure. For example, AF1070_200 has yield strength of 1.0 MPa and the panel using the foam with thickness of 75 mm satisfied the target performance, which is transmitted pressure of 1.0 MPa.

From the analysis results, the transmitted pressure according to scaled distance was estimated as shown in Fig. 4. When the target performance of the foam panel is decided between 1.0 MPa and 3.0 MPa, multi-layered foam panels can satisfy the requirement for high explosive conditions with lighter weight.



(a) AF1070_200 **(b) AF2040_280** **(c) AF1070_200+AF2040_280**

Fig. 4. Transmitted Pressure according to Scaled Distance *Z*.

4. Pressure Impulse Diagrams of Aluminum Foam Panel

Explosion is a sudden release of energy as a result of physical or chemical events. An explosion generates shock pressure in solid materials or blast waves in the surrounding air. The area under the pressure-time curve represents the impulse that is imparted to a structure during blast, as presented in Eq. (1). Since Pressure-Impulse (P-I) diagrams are important tools for preliminary design of protective structures subjected to blast loading. P-I diagrams are isodamage curves based on the predefined damage criteria in the space of pressure and impulse of the blast wave [12, 13]. P-I diagrams for certain structural members are normally developed using single degree of freedom (SDOF) models.

$$\mathrm{I} = \int_0^{t_0} P(t)dt \tag{1}$$

For the effective use of aluminum foam panels, the damage criterion was defined to be full compaction of the foam, which is 70% deformation of its thickness. After full compaction of the aluminum foam, there is no energy dissipation of blast waves. P-I diagrams for the foam with different densities can be utilized to determine initial density and thickness of the sacrificial cladding for a given blast condition.

Different pressure-impulse combinations have been applied to the panel to get the pressure-impulse points for both the near and far-field conditions, as described in Eq. (2)-(4) [14]. Tables 2 and Table 3 summarise the blast load conditions for the analysis. Air blast condition was only considered in this paper.

Impulsive loading region:

$$\mathrm{Z} < 1.19\ \mathrm{m/kg^3} \tag{2}$$

Dynamic loading region:

$$1.19\ \mathrm{m/kg^3} < Z < 3.967\ \ \mathrm{m/kg^3} \tag{3}$$

Quasi-static loading region:

$$\mathrm{Z} > 3.967\ \ \mathrm{m/kg^3} \tag{4}$$

Instead of SDOF models, the explicit finite element models were used to derive P-I diagrams using the verified material models. Appropriate blast conditions to generate different combinations of pressure and impulse were derived from Kingery equation [15]. Table 2 and Table 3 summarise the conditions. Thickness of the foam panels was 25 mm, 50 mm, 75 mm and 100 mm considering practical range of sacrificial claddings.

From the extensive explicit finite element analyses, blast conditions for the predefined full compaction of foam element in the center of the panel were derived by adjusting stand-off distance and charge weight. Figures 5 and 6 show the P-I diagrams for single layered and multi-layered panels, respectively. For multi-layered configurations, it is recommended to use the foam with low density as the front face of a blast wave.

The developed P-I diagrams can be utilized for initial selection of a sacrificial cladding using aluminium foam considering given BOD. Then, the protected structures need to be reassessed by numerical analysis. Without increasing thickness of concrete wall or roof, it is possible to resist more severe blast conditions using the proposed multi-layered foam panels.

5. Conclusions

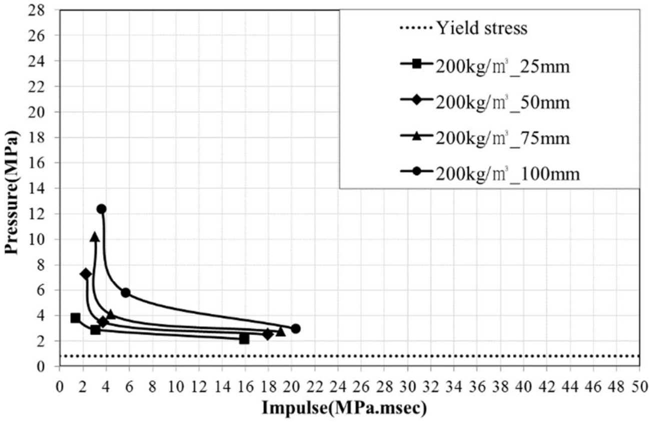
Uncertainty in design of protective structures needs to be overcome by application of innovative material. Metal foam has excellent performance to mitigate blast pressure using its plastic deformation. Light-weight foams can be used as a sacrificial cladding. In order to enhance the performance of the foam panels, multi-layered aluminum foam panels with different density were suggested. The design concept was verified through material tests and explicit finite element analyses. Using the same weight of the foam, the multi-layered foam can satisfy target performance for wider range of blast pressure. A convenient method to decide design parameters of the aluminum foam was derived according to scaled distance. P-I diagram of the foam panels were established for a general design guideline of foam panels. For multi-layered configurations, it is recommended to use the foam with low density as the front face of a blast wave. The proposed concept of multi-layered protection provides resistance of protected structures for more severe blast conditions.

Table 2. Standoff Distance-Charge Weight Combinations of Impulsive Loading Region for Single Layer.

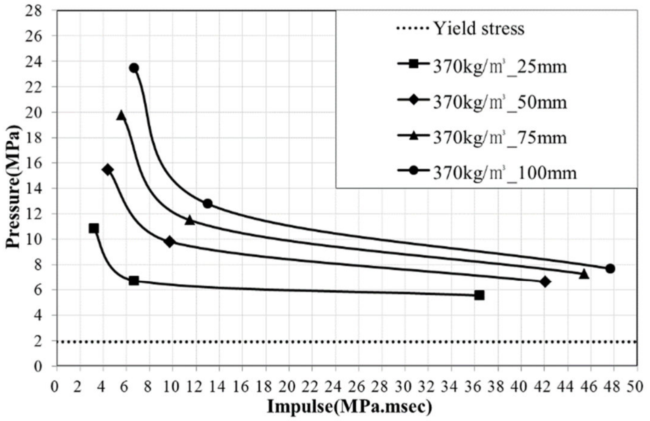
Density (kg/m^3)	Thickness (mm)	Charge weight (kg)	Standoff distance (m)	Z (m/kg^3)	Pressure (KPa)	Impulse (KPa.msec)
200	25	29	3	0.976	3,800	1,358
	50	40	3	0.877	7,271	2,272
	75	58	3	0.775	10,228	3,038
	100	72	3	0.721	12,397	3,603
	25	350	8.5	1.210	2,887	3,094
	50	500	9.0	1.130	3,466	3,771
	75	650	9.0	1.074	4,071	4,416
	100	850	9.0	0.950	5,800	5,663
	25	70,000	55	1.335	2,136	15,924
	50	82,000	55	1.266	2,500	17,939
	75	89,000	55	1.232	2,712	19,084
	100	97,000	55	1.200	2,953	20,369
370	25	62	3	0.758	10,859	3,202
	50	93	3	0.662	15,467	4,415
	75	125	3	0.600	19,788	5,596
	100	155	3	0.558	23,517	6,657
	25	1,100	9.3	0.900	6,746	6,621
	50	2,050	10.0	0.787	9,805	9,764
	75	2,600	10.2	0.742	11,504	11,459
	100	3,200	10.5	0.713	12,795	12,977
	25	240,000	60	0.965	5,539	36,377
	50	290,000	60	0.906	6,630	42,109
	75	320,000	60	0.877	7,272	45,453
	100	340,000	60	0.860	7,694	47,649
280 (Alloy)	25	77	3	0.705	13,148	3,800
	50	103	3	0.640	16,861	4,791
	75	130	3	0.592	20,430	5,776
	100	165	3	0.547	24,703	7,004
	25	1,750	9.9	0.822	8,725	8,743
	50	2,250	10.3	0.786	9,845	10,091
	75	2,500	10.2	0.752	11,110	11,110
	100	3,100	10.5	0.720	12,444	12,655
	25	311,000	60	0.886	7,080	44,457
	50	325,000	60	0.873	7,378	46,005
	75	340,000	60	0.860	7,694	47,649
	100	355,000	60	0.847	8,009	49,280

Table 3. Standoff Distance-Charge Weight Combinations of Impulsive Loading Region for Multi-Layer.

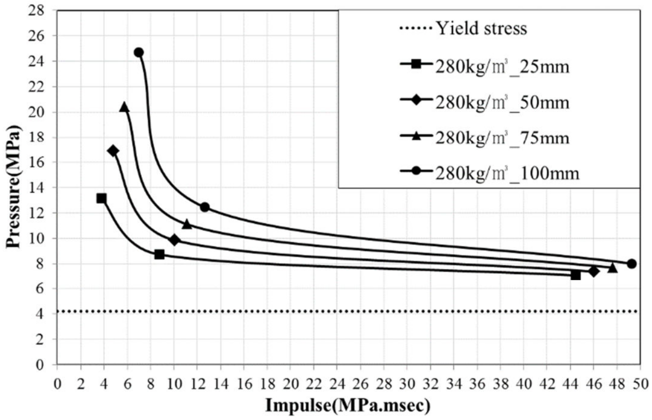
Density (kg/m^{3})	Thickness (mm)	Charge weight (kg)	Standoff distance (m)	Z (m/kg^{3})	Pressure (KPa)	Impulse (KPa.msec)
200+370	25	41	3	0.870	7,441	2,317
	50	61	3	0.762	10,702	3,162
	75	79	3	0.699	13,444	3,878
	100	95	3	0.657	15,750	4,491
	25	690	9.0	1.019	4,746	4,823
	50	1,030	9.4	0.931	6,150	6,204
	75	1,250	9.6	0.891	6,955	7,009
	100	1,800	10.0	0.822	8,709	8,818
	25	140,000	58	1.117	3,624	25,150
	50	155,000	58	1.080	4,003	27,181
	75	170,000	58	1.047	4,381	29,171
	100	182,000	58	1.025	4,680	30,737
200 +280(Alloy)	25	55	3	0.789	9,749	2,914
	50	74	3	0.715	12,699	3,682
	75	95	3	0.657	15,750	4,491
	100	110	3	0.626	17,812	5,050
	25	950	9.2	0.936	6,055	5,995
	50	1,360	9.6	0.867	7,526	7,484
	75	1,680	9.9	0.829	8,522	8,526
	100	1,900	10.0	0.807	9,151	9,199
	25	195,000	60	1.035	4,534	31,009
	50	225,000	60	0.987	5,206	34,612
	75	240,000	60	0.965	5,539	36,377
	100	260,000	60	0.940	5,978	38,696
370 +280(Alloy)	25	75	3	0.711	12,849	3,722
	50	102	3	0.642	16,723	4,754
	75	132	3	0.589	20,684	5,847
	100	170	3	0.542	25,285	7,174
	25	1,450	9.6	0.848	7,988	7,868
	50	2,100	10.0	0.781	10,021	9,950
	75	2,600	10.3	0.749	11,209	11,307
	100	2,830	10.3	0.728	12,083	12,090



(a) P-I Diagram of 200 kg/m^3 Aluminum Foam.

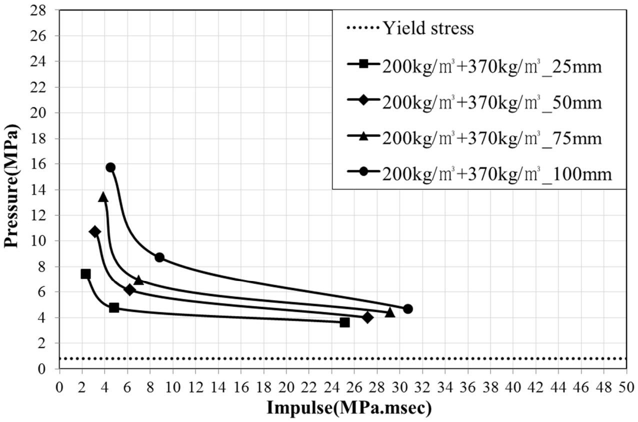


(b) P-I Diagram of 370 kg/m^3 Aluminum Foam.

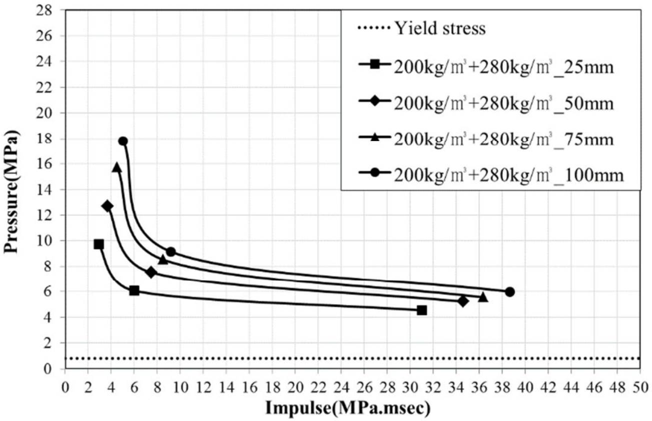


(c) P-I Diagram of 280 kg/m^3 Alloy Aluminum Foam.

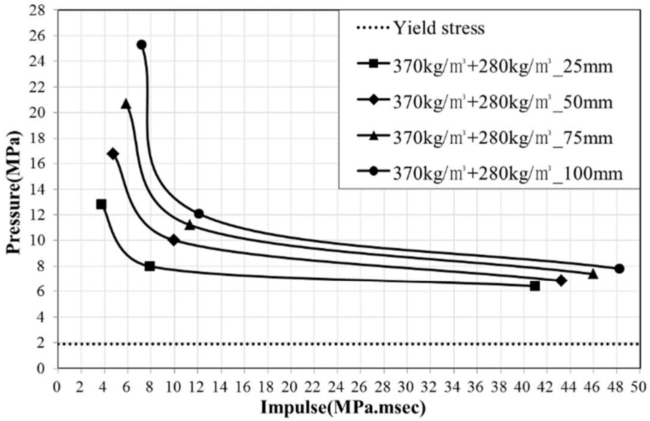
Fig. 5. P-I Diagrams of Single Layered Aluminum Foam.



(a) P-I Diagram of 200 kg/m^3+370 kg/m^3 Aluminum Foam.



(b) P-I Diagram of 200 kg/m^3+280 kg/m^3 Aluminum Foam.



(c) P-I Diagram of 370 kg/m^3+280 kg/m^3 Alloy Aluminum Foam.

Fig. 6. P-I Diagrams of Multi-Layered Aluminum Foam.

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