View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Defence Science Journal

Defence Science Journal, Vol. 59, No. 5, September 2009, pp. 499-504
© 2009, DESIDOC

Propagation Characteristics of Explosive Waves in Layered Media Numerical Analysis

Xia Changjing*,**, Dong Yongxiang**, Chen Liping*, Xue Dongjie* and Wang Shunhong**

*State Key Laboratory of Coal Resource and Mine Safety, China University of Mining & Technology, Beijing-100083, China
**State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing-100081, China

ABSTRACT

The layered media under one-dimensional strain with different wave-impedance materials have been studied. The three typical prototypes have been analysized, including steel plate, aluminum foam, and concrete as the middle layer, and the upper and lower layers are concrete material. The attenuation of the amplitude of stress at different positions, the peak stress and the duration at the dissimilar material interface, and the absorbing energy distribution in different layers for different models have been obtained by numerical simulation. The material of the middle layer with lower impedance can effectively reduce the amplitude of stress, increase the duration of explosive wave, and change the distribution of energy in different layers. But the influence of the middle layer with higher impedance material on layered media is contrary. The middle layer with soft material is the better matching of wave impedance to explosive wave propagation. The analytical conclusions are of great significance for the design of protective structures against the explosion-induced hazards and mine safety protection from outburst and explosion.

Keywords: Explosive wave, layered media, wave impedance, numerical simulation, explosive wave propagation

1. INTRODUCTION

Protection against mine explosion is a key and unsolved problem related to the safety of people and property. How to design the protective structure to minimise the damage from outburst and explosion, is always a concerned problem. As it is known, the layered media with different wave impedance have a significant effect on the attenuation characteristics of explosive wave for military protection and civil engineering [1,2]. So, it is an effective way to adopt layered structures. However the matching of material impedance is the key problem to be solved during the design of the multilayered protective structures.

Tedesco, *et al.*[3] pointed out that layered structures can effectively protect targets against attack and the proper combination of different materials can weaken explosion waves. Protective abilities of three kinds of layered structures were compared such as concrete-air-concrete, concrete-polystyrene-concrete, and concrete-soil-concrete using numerical simulation. The results showed that each structure can reduce or eliminate the scabbing of the inner wall of structure. The protective role of the laminated structure against the conventional weapons has been investigated further by Tedesco, *et al.*[4]. Study on wave reflection and transmission of the layered interface, indicated that the mis-matching of material wave impedance has an important effect on the attenuation of stress wave. Franz, *et al.*[5] conducted the study on the dynamic behaviour of glass-fibre laminated medium under blast loading by experiments. The result showed that the media with low impedance and high energy absorption should be used as the protective materials to bear explosion loading in the vicinity of explosive charge. And the material with high strength and high bending resistance should be chosen around the protected objects. Those conclusions provided guidance for the design of multilayered protective structures.

This paper presents a reasonable analysis for the influence of material impedance on the dynamic response of a layered structure subjected to blast loading. The main discussion focuses on study of explosion wave propagation characteristics in different impedance media using numerical simulation. The analytical conclusions are of great significance for protection against mines from outburst and explosion.

2. NUMERICAL SIMULATION MODEL

In this section, the calculation was performed in 2-D axisymmetric configuration with the LS-DYNA commercial code. The propagation of explosion wave in a three-layered structure has been studied. As shown in Fig.1, the high explosive TNT is put on the surface of the sandwich plate whose top surface was ignited at the same time $t = 0$. The different layers, layer-I, layer-II, and layer-III from top to bottom have a different thickness of δ_1, δ_2, and δ_3 shown in Table 1. δ_e and R represent the thickness of the explosive and the radii of different layers in the simulation model, respectively.

Received 28 September 2008, Revised 12 May 2009

Table 1. Structure sizes of simulation model

δ_e(cm)	δ_1(cm)	δ_2(cm)	δ_3(cm)	R(cm)
0.5	8	3	14	50

The diameter of sandwich panel is 100 cm, just four times as large as the thickness of the sandwich panel. So centre elements near the axis can be considered as one-dimensional strain since the side-discharging effect can be neglected. Meanwhile, boundaries of radial direction of different layers are regarded as non-reflection (*Nr*) boundaries which are the transmitting boundaries, and the bottom surface of the lowest layer is free surface (*Sf*). B_1 and B_2 are contact interfaces with middle layer. The coordinate system is established, as shown in Fig.1.

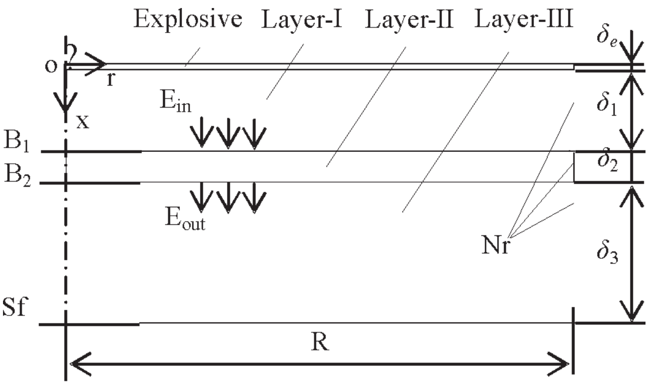


Figure 1. Schematic of simulation model.

The typical three layered media composed of different wave impedance materials are listed as follows to compare their influence on explosion wave propagation.

(a) Concrete-Concrete-Concrete (3C)
(b) Concrete-Steel-Concrete (C-St-C)
(c) Concrete- Aluminum foam-Concrete (C-FAl-C).

The dissimilar materials have different wave impedance in three models. The inequation of wave impedance with the different material is $(\rho C)_{St} > (\rho C)_C > (\rho C)_{FAl}$, where the subscripts *St, C* and *FAl* denote the material of steel, concrete, and aluminum foam, respectively.

In the present simulation, Johnson-Holmquist constitutive model (JHC) was used for concrete [6-9]. In this model, the normalised equivalent stress is defined as $\sigma^* = \sigma / f_c^{'}$ and expressed as

$$\sigma^* = [A^{'}(1-D) + B^{'}P^{*N}][1 + C\ln(\dot{\varepsilon}^*)]$$

where D is the damage, $P^* = P / f_c^{'}$, P is the actual pressure, $f_c^{'}$ is the quasi-static uniaxial compressive strength, and $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$, $\dot{\varepsilon}$ is the actual strain rate and $\dot{\varepsilon}_0 = 1.0 s^{-1}$ is the reference strain rate.

The damage expression is

$$D = \sum \frac{\Delta\varepsilon_P + \Delta\mu_P}{D_1 (P^* + T^*)^{D_2}} \quad T^* = T / f_c^{'}$$

where $\Delta\varepsilon_P$ and $\Delta\mu_P$ are the equivalent plastic strain and plastic volumetric strain, respectively. *A′, B′, N* and *C* are material constants determined by experiments. D_1 and D_2 are damage constants. *T* is maximum tensile hydrostatic pressure.

The crushable-foam model[10] was applied for the aluminum foam. The JWL equation of state was adopted to describe the behaviour of the explosion product. The main material parameters[11-15] has been listed in Tables 2-4. Here, ρ and *E* are the density and elastic modulus, D_H the detonation velocity, P_{CJ} the *C-J* pressure, E_0 the internal energy per unit volume, μ Poisson ratio, and *A, B, C,* R_1, R_2 ω are material constants of JWL equation. In Table 3, $P_c = f_c^{'} / 3$ and $\mu_l = \rho_{grain} / \rho_0 - 1$, where ρ_{grain} is the grain density. μ_c is the crushing volumetric strain corresponding to the pressure Pc, μ_l is the crushing volumetric strain corresponding to the pressure Pl. ε_{fmin} is the amount of plastic strain before fracture; K_1, K_2 and K_3 are pressure constants, *G* is the shear modulus. In Table 4, σ_c is the uniaxial compressive strength, damp, the damping coefficient of materials.

3. NUMERICAL RESULTS AND DISCUSSIONS

3.1 Stress Wave in Different Models

The evolution of the explosive wave with time and space in the upper concrete layer has been discussed as follows. Figures 2 and 3 give the stress σ_x versus the position along the *x* axis and time *t* curves respectively in 3C model. Though the multilayered media consists of

Table 2. Main parameters of the TNT explosive

ρ/ (g/cm^3)	D_H / (m/s)	P_{CJ} / GPa	A / GPa	B / GPa	R_1	R_2	ω	E_0 / GPa
1.63	6930	20.60	373.8	3.75	4.15	0.9	0.35	6.0

Table 3. Material constants used in calculation for concrete using JHC model

ρ/(g/cm^3)	A'	B'	N	C	f'_c /GPa	S_{max}	G /GPa	D_1	D_2
2.46	0.75	1.45	0.61	0.007	0.03	7.0	18.0	0.06	1.0
ε_{fmin}	P_C /GPa	μ_C	K_1 /GPa	K_2 /GPa	K_3 /GPa	P_l /GPa	μ_l	T/GPa	
0.01	0.016	0.001	85	-171	208	0.80	0.10	0.004	

Table 4. Main parameters of the foam material

Material properties	Aluminum foam	Volumetric strain	Yield stress / MPa
P / (g/cm^3)	0.80	0.0	0.0
E / MPa	5.0e+02	0.07	20.0
μ	0.21	0.45	30.0
σ_c / MPa	15.0	0.55	46.0
Damp	0.2	0.60	70.0

different middle materials, the stress-space curves of the upper layer are similar. The curves show the rapid decrease with time and space and it is in agreement that the explosive wave attenuates quickly, especially in the solid medium. It can be seen that the stress peak value nearby the explosive charge is over 10 GPa, but at the position of several millimeters and over ten ms, it is a tenth part of the original value. It also shows that high frequency explosion wave at the initial time of detonation is oscillatory in Fig. 2.

Figures 4-6 show stress σ_x versus the x axis at different time in different models which are 3C, C-St-C and C-FAl-C. The models are all of the same thickness to the corresponding layers and the same boundary conditions except the middle layers with different materials. The stress σ_x at the different positions along the x axis and time t is different in each model, and the tendencies of stress σ_x at the position of middle layer are different in three models. Especially at the position of B_1 and B_2, and the contact interfaces with middle layer, the change laws of stress σ_x are different. For 3C model, the stress peak value attenuates with the distance stably. But for C-St-C model, the stress peak value increases rapidly at the position B_1 and fall sharply at the position of B_2. So there is an obvious change when the explosive wave propagates in the middle steel layer. For C-FAl-C models, there is a rapid drop in the stress peak value at the position of B_1 and the stress peak value still keeps a smaller value at the position of B_2. Thus, the sequence of decreasing gradient of the stress σ_x through the middle layer is C-FAl-C model, C-St-C model, and 3C model. It shows that the propagation of explosion wave in different models is obviously affected by the different wave impedance materials from the corresponding stress waveforms in different models. The conclusion can be drawn that the trend of the curves in the first part changed with the middle material and the contact interface with middle layer from Figs 4-6. In Fig. 4, there exist the slight ascend which deviates from the straight line at the position of B_1, it may be related to the contact problem and the reflection and transmission on contact interface.

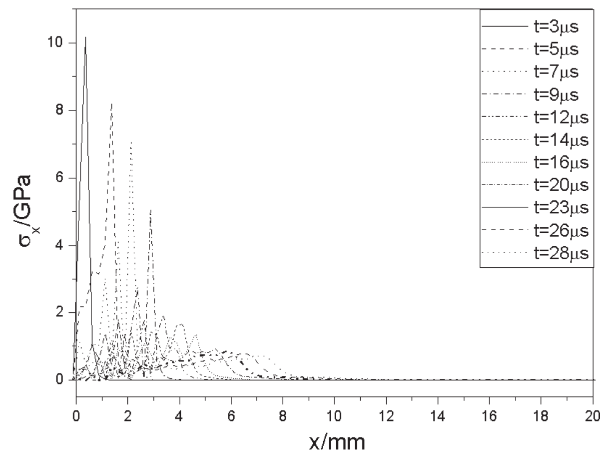


Figure 2. Stress σ_x versus position x at different time.

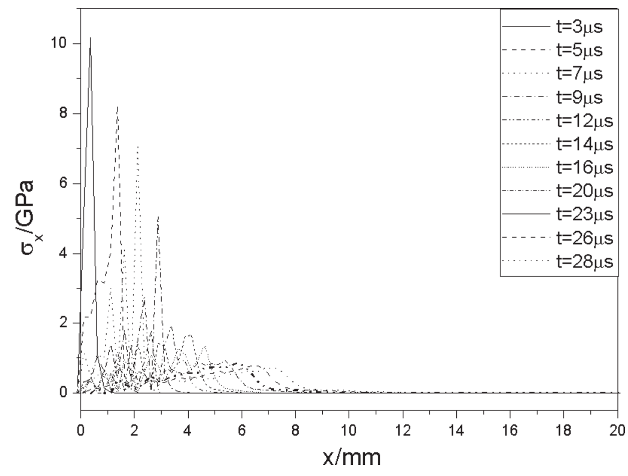


Figure 3. Stress σ_x versus time t at different positions.

3.2 Interface Stress in Dissimilar Materials

Figures 7-9 present the stress σ_x at positions of B_1 and B_2 with time for 3C, C-St-C, and C-FAl-C models, respectively. The decreasing sequence of the peak stress value of explosive

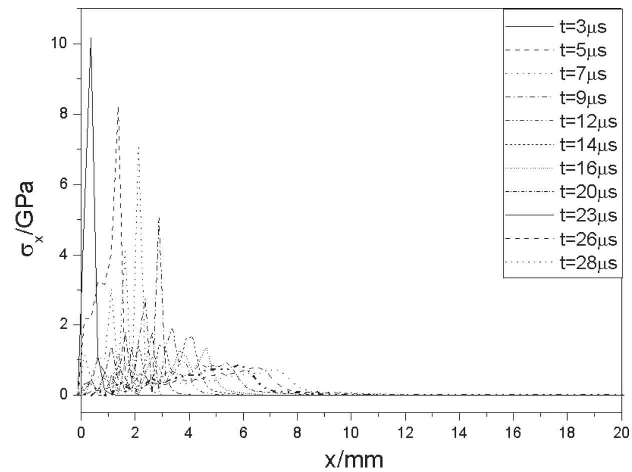


Figure 4. Stress σ_x versus x at different time in a 3C model.

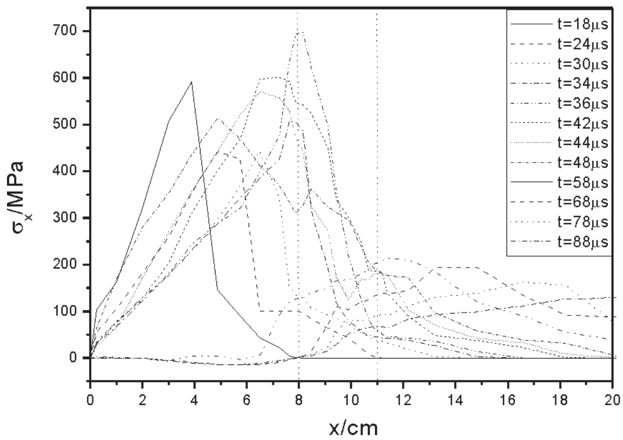


Figure 5. Stress σ_x versus x at different time in C-St-C model.

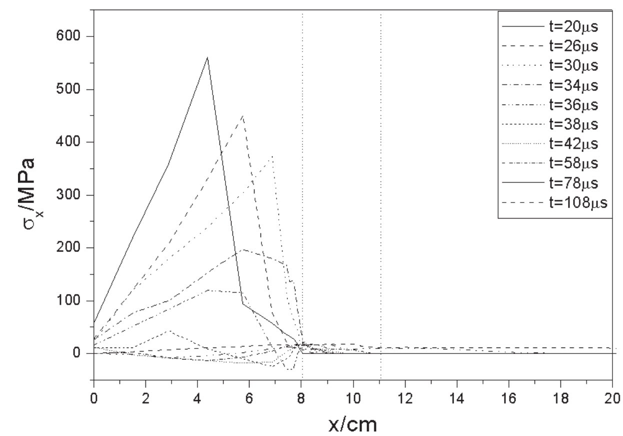


Figure 6. Stress σ_x versus x at different time in C-FAl-C model.

wave at the position of B_1 is C-St-C, 3C and C-FAl-C models, and that of B_2 is 3C, C-St-C and C-FAl-C models in sequence. Furthermore, the peak stress σ_x of C-St-C model is about 2 times as large as that of 3C model, and the peak stress σ_x of C-St-C model is about an order magnitude of that of C-FAl-C model. The duration of C-FAl-C model is about four times as percentage as that of 3C and C-St-C models. Thus the multilayered media with soft middle layer can not only reduce the stress peak value effectively but also change the duration of explosion wave[7,16]. The layered media with the hard middle layer can lead to the high stress value in the incident interface at B_1 and the lower stress at B_2. Different middle materials obviously change the loading distribution in the multilayered media. Figure 9 shows that the curve of stress with time experiences a light periodic oscillation because of the reflection and transmission of stress wave to get the stress balance in the soft layer.

3.3 Energy Distribution in Different Layers for Different Models

To gain more information about characteristics of explosive wave propagation in models with different wave impedance materials, energy distribution in different layers for different modes have been studied.

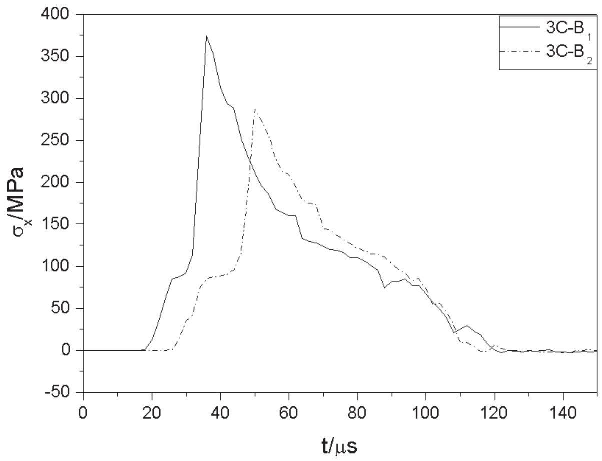


Figure 7. Stress σ_x versus time t at the interfaces in 3C model.

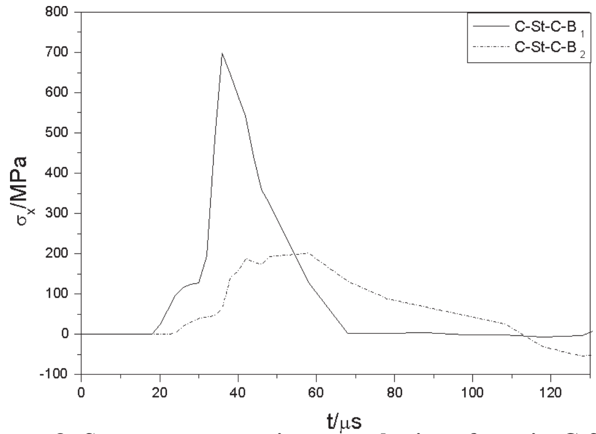


Figure 8. Stress σ_x versus time t at the interfaces in C-St-C model.

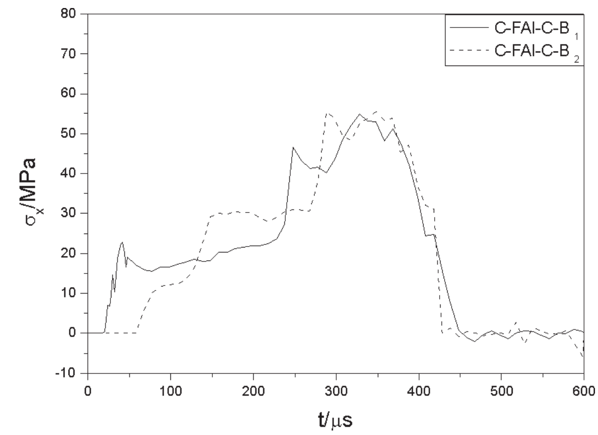


Figure 9. Stress σ_x versus time t at the interfaces in C-FAl-C model.

Figures 10-11 show the energy density in Layer-I, Layer-II, and Layer-III of three models of 3C, C-St-C and C-FAl-C. Here the energy density E_{ab} is the absorbing energy per unit area. Figure 10 indicates that the absorbing energy of Layer-I in different models is similar. Comparing with Fig.11, the absorbing energy is over an order magnitude of that of Layer-II and Layer-III. It can be seen that the increasing sequence of energy in Layer-II is C-St-C, 3C

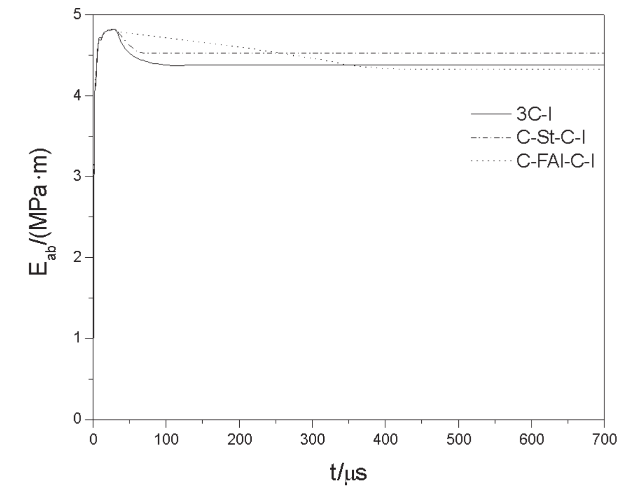


Figure 10. Curves of the absorbing energy density E_{ab} of layer-I versus time t in different models.

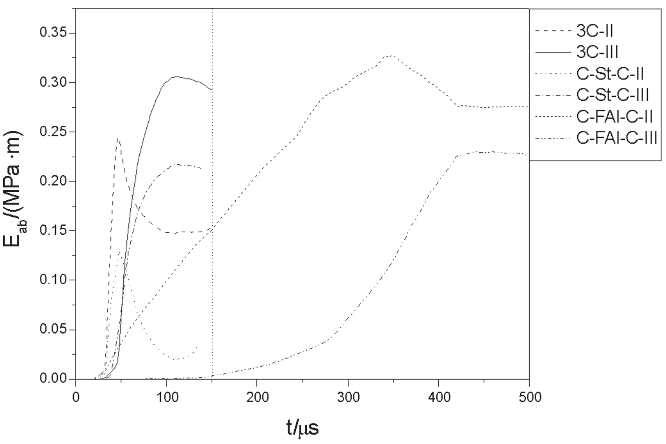


Figure 11. Curves of the absorbing energy density E_{ab} of layer-II and layer-III versus time t in different models.

and C-FAl-C models from Fig.11, but that of Layer-III is C-St-C, C-FAl-C and 3C models in sequence. It indicates that the middle aluminum foam layer in the C-FAl-C model has the higher absorbing energy density than the steel layer in C-St-C module. However, the steel layer in the C-St-C model has the lower absorbing energy density and the higher energy in Layer-III. Therefore, synthesising the stress amplitude and energy, the C-FAl-C model is the best protective structure.

4. CONCLUSIONS

This paper presents a simple analysis and computational results on the explosion wave propagation in layered media with different wave impedance. The main conclusions from the study have been drawn as follows:

The better matching of wave impedance for layered media can change the stress peak value, duration and energy distribution based on the consideration of wave attenuation and energy dissipation. As a coupling of explosion loading and media, wave impedance match and energy absorption by the media should be taken into account in design. To reduce the strong impact effect due to outburst and explosion, the alternative way is to add a soft material sandwiched in between hard materials.

ACKNOWLEDGEMENTS

This work was sponsored by Open Foundation of State Key Laboratory of Coal Resource and Mine Safety, China University of Mining & Technology (Beijing) (Grant No. 2008-04), State Key Laboratory of Explosion Science and Technology of Beijing Institute of Technology.

REFERENCES

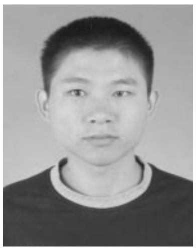
1. Carruthers, J.J.; Kettle, A.P & *et al*. Energy absorption capability and crashworthiness of composite material structures: A review. *Appl. Mech. Rev.,* 1989, **51**(10), 635-49.
2. Dong, Y.X. Study on the explosive wave propagation with its attenuation behaviour in a multilayered media. Institute of Mechanics, Chinese Academy of Sciences, Beijing, 2004, PhD Thesis. (in Chinese).
3. Tedesco, J.W.; Hayes, J.R & *et al.* Dynamic response of layered structures subject to blast effects of non-nuclear weaponry. *Comput. Struct.*, 1987, **26**, 79-86.
4. Tedesco, J.W. & Landis, D.W. Wave propagation through layered systems. *Comput. Struct*. 1989, **28**, 625-38.
5. Franz, T.; Nurick, G.N. & *et al*. Experimental investigation into the response of chopped strand mat glass fibre laminates to blast loading. *Int. J. of Impact Eng.*, 2002, **27**, 639-67.
6. Holmquist, T.J.; Johnson, G.R. & Cook, W.H. A computational constitutive model for concrete subjected to large strains, high strain rates, and high pressures. *In* 14th International Symposium on Ballistics. Quebec, American Defense Preparedness Association, 1993. pp. 591-600.
7. Dong, Y.X.; Feng, S.S. & Xia, C.J. Dynamic behaviour of concrete sandwich panel under blast loading. *Def. Sci. J.*, 2009, **59**(1), 22-29.
8. Dong, Y.X.; Feng, S. S. & Xia, C.J. Numerical analysis on protecting performance of layered arch structures subjected to blast loading. *Def. Sci. J.*, 2009, **59**(2), 31-6.
9. Song, S.C. & *et al*. SPH algorithm for projectile penetrating into concrete. *Explo. Shock Waves*, 2003, **23**(1), 56-60. (Chinese)
10. Hallquist J.O. LS-DYNA Theoretical manual. Livermore Software Technology Corporation, 1998.
11. Taylor, E.A.; Tsembelis, K. & *et al*. Hydrocode modeling of hypervelocity impact on brittle materials: Depth of penetration and conchoidal diameter. *Int. J. Impact Eng.*, 1999, **23**, 895-904.
12. Grote D.L.; Park S.W. & *et al*. Dynamic behaviour of concrete at high strain rates and pressures: Pt I. Experiment characterisation. *Int. J. Impact Eng.*, 2001, **25**, 869-86.
13. Xu, Z.X. Influence of the duration of the severe ground movement on the collapse of the structure. *J. Tongji Univ.*, 1982, **2** (Chinese).

14. Cliffton, R.J. *Appl. Mech. Rev.,* 198, **38**, 1276-278.
15. Santosa, S.P.; Wierzbicki, T…*et al*. Experimental and numerical studies of foam-filled sections. *Int. J. Impact Eng.*, 2000, **24**, 509-34.
16. Dong, Y.X.; Huang, C.G. & Duan, Z.P. Influence of multilayered media on stress wave propagation. *Chi. J. High Pressure Phy.*, 2005, **19**(1), 59-65. (Chinese)

Contributors

Mr Xia Changjing obtained his PhD from the University of Science and Technology of China in 2003. He joined School of Mechanics and Civil Engineering, China University of Mining and Technology in 2005. At present, he is working as an associate professor and his research interest is in rock mechanics and explosion dynamics.

Dr Dong Yongxiang obtained her PhD from Institute of Mechanics, Chinese Academy of Sciences in 2004. She joined the State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology in 2004. At present, she is working as an associate researcher and her research interests are in explosion dynamics, impact dynamics and explosion protection.



Mr Chen Liping graduated from China University of Mining and Technology in 2008. He is a graduate student for master's degree in the School of Mechanics and Civil Engineering, China University of Mining and Technology. His research interest includes rock mechanics.

Mr Xue Dongjie graduated from Shandong University of Science and Technology in 2007. He is a graduate student for master's degree in the School of Mechanics and Civil Engineering, China University of Mining and Technology. His research interest include rock mechanics.

Mr Wang Shunhong graduated from North University of China in 2008. He is a graduate student for master's degree in State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology. His research interest includes explosion dynamics and impact dynamics.