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Research Article

Analysis of Transmission and Diffraction Effects of Air Shock Wave upon Flexible Anti-blast Wall

Zhang Yao[1,2], Nian Xinzhe[1], Yan Dongjin[1]
[1]PLA University of Science and Technology, Nanjing 210007, China
[2]PLA University of International Studies，Nanjing 210039, China

***Corresponding author**
Zhang Yao
Email: 15996264008@163.com

Abstract: In order to study the transmission and diffraction phenomena of air shock wave impacting upon a flexible wall, FE models were set up to conduct numerical simulations of air blast pressure flow field by LS-DYNA software. The weights of TNT charge used in simulation were 5kg, 10kg, 15kg and 20kg respectively. The transmission and diffraction phenomena of air shock wave behind the flexible wall were analyzed and variations of pressure time history were compared. Finally, the air blast pressure distributions of transmission and diffraction wave behind the wall were presented. The results show that there are two major peak pressures behind the flexible wall. One is the transmission pressure and the other is the diffraction pressure. Transmitted pressure is caused by the motion of the deformed wall and depends on the wall's deformation rate. Diffraction pressure is caused by the diffraction of air shock wave propagated over the wall. The distributions and variations of transmission pressure and diffraction pressure are different, and the analyses about them should be treated differently.
Keywords: Blast; Air shock wave; Anti-blast wall; Transmission pressure; Diffraction pressure

INTRODUCTION

Anti-blast wall is an important facility to protect against blast air shock wave. RC anti-blast wall is characterized by high resistance and good effects of protection, but it is fixed in position and requires relatively long construction cycle. RC anti-blast wall which meets the requirements of resistance, has little deformation under the impact of blast shock wave, therefore, it can be regarded as rigid wall in the flow field analysis. The anti-blast wall which made of high-strength polyethylene fiber has the features of low density, good elasticity, easy movement and convenient deployment and can resist against the shockwave of blast of small shot explosives. This kind of flexible fiber anti-blast wall can also be called flexible anti-blast wall or flexible wall. Currently, there have been a lot of researches into the reflection and diffraction rules of rigid wall[1,2], but there is little public report on the research into the interactions between shock wave and flexible wall and the influences on the flow field behind the wall. This article aims at the numerical analysis of the transmission and diffraction effects of air shock wave upon the flexible anti-blast wall.

NUMERICAL ANALYSIS MODEL AND VERIFICATION

LS-DYNA, as a famous finite element dynamic analysis program, can realize FSI simulation and is fit for the analysis of interaction between air shockwave and structure[3,4]. The highly effective ALE technology in the program is adopted in this thesis, and the FSI algorithm is used to conduct the analysis of interaction between air shockwave and anti-blast wall[5,6].

The body of the flexible anti-blast wall uses high-strength polyethylene fiber cloth. Adopting section steel, the vertical beam, horizontal joining beam, and inclined strut form a multi-span steel framework to support the body of flexible wall. Each span is 2m wide and 2.5m tall. To reduce the calculation in numerical simulation, FE model adopts xz plane (y=0) as the symmetrical plane, and adopts two spans and a half (2m+2m+1m) for the numerical simulation calculation, as shown in Figure 1. The support member is established by beam element, and the fiber cloth is established by shell element[7,8]. The shell element and beam element share the same nodes. The nodes that connect the horizontal joining beam and the ground are imposed restriction. The cross section of the vertical beam is in the shape of I, and the cross section of the sloping beam is in the shape of rectangle. The cross section of the horizontal joining beam is hollow tube. The shape and sizes of the beam cross section are defined in key words.

To the air field of simulation, the xz plane (y=0) is also adopted as the symmetrical plane, and the sizes of the air field on x×y×z direction are 3.5m×5.1m×7.0m. The outer boundary of air field adopts transmission boundary to simulate infinite air field. TNT explosives of different weights are all concentrated on the ground where the symmetrical plane passes, and is 3m away from the surface of the wall facing the blast. The ground to put the explosives is rigid, and the other boundaries adopt symmetrical boundaries. The calculation model is shown in Figure 2.

To compare the effect of large rigidity of flexible anti-blast wall, numerical analysis of rigid anti-blast wall constructed by reinforced concrete is conducted. The rigid anti-blast wall is 5m long, 2.5m tall and 0.4m thick. The wall and the FE analysis model are shown in Figure 3 and Figure 4.

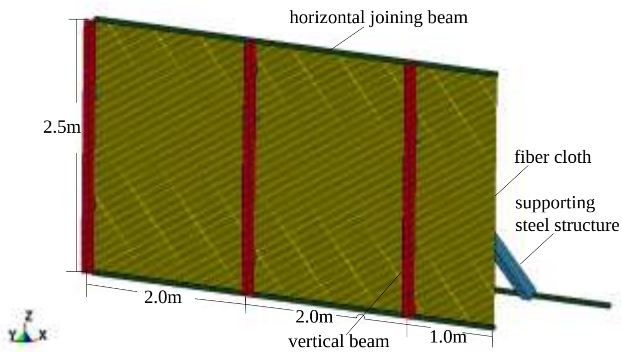


Fig. 1: FE model of flexible anti-blast wall

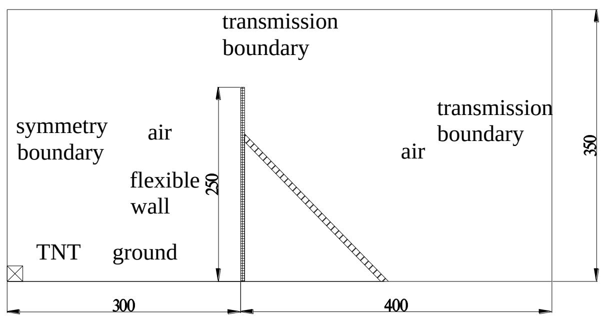


Fig. 2: Lateral view of flexible anti-blast wall (cm)

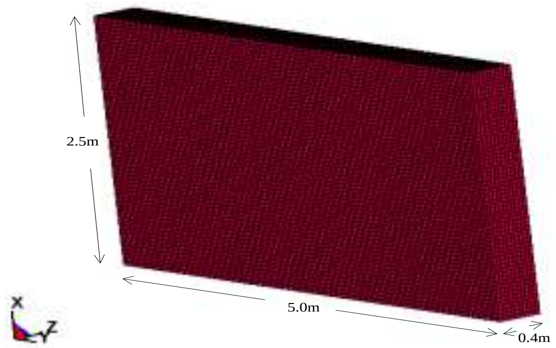


Fig. 3: FE model of rigid anti-blast wall

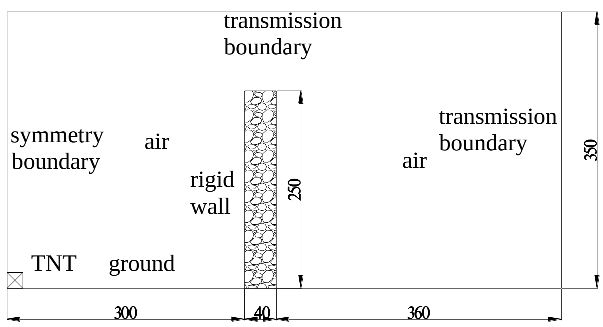


Fig. 4: Lateral view of rigid anti-blast wall (cm)

The support and connection members of the flexible wall adopt PLASTIC_KINEMATIC material model, and the main parameters are shown in Table 1:

The fiber cloth adopts MAT_ELASTIC material model, and the main parameters are shown in Table 2[9]. Its planar density is 220g/m^2 and its volume density is 970kg/m^3. The thickness of flexible wall made of 12 layers of fiber cloth is 2.7mm. To simplify analysis, the material of rigid wall also uses MAT_ELASTIC model, and the main parameters are shown in Table 2:

Table-1:Parameters of steel

ρ/(kg/m^3)	E / Pa	pr	$sigy$ / Pa	$beta$
7.8e+3	2.0e+11	0.25	4.68e+8	0

Table-2:Parameters of fiber and concrete

material	ρ/(kg/m^3)	E / Pa	pr
fiber	0.97e+3	0.95e+11	0.34
concrete	2.50e+3	4.0e+10	0.18

TNT explosives adopt MAT_HIGH_EXPLOSIVE_BURN model. The parameters of explosive density ρ, Chapman-Jouguet pressure P_{cj} and detonation wave speed D, etc. need to be defined. JWL state equation is used to describe the relationship among the blast product pressure, internal energy and relative volume. JWL state equation is as follows:

$$P = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \text{ ---------------------------(1)}$$

In the equation, A, B, R_1, R_2 and ω are all material constants, V is relative volume, and E is initial internal energy density. The main parameters of TNT explosive are shown in Table 3:

Table-3: Parameters of TNT

ρ/(kg/m^3)	E /(J/m^3)	Pcj / Pa	D/(m/s)	A	B	R_1	R_2	ω
1.64e+3	6.0e+9	2.10e+10	6930	3.74e+11	1.39e+9	4.15	0.9	0.32

The air adopts MAT_NULL model and chooses linear polynomial state equation to describe. The pressure is calculated as per the following formula:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E \text{ ------------（2）}$$

Where, $\mu = \rho/\rho_0 - 1$, ρ/ρ_0 is the ratio between current density and initial density. When the air is regarded as the ideal gas, $C_0 = C_1 = C_2 = C_3 = C_6 = 0$, $C_4 = C_5 = \gamma - 1$. γ is the specific heat capacity of the air, and its value is usually 1.4. The air density ρ is 1.292kg/m^3, and the initial internal energy density e_0 is 0.25MJ/m^3.

DIFFRACTION AND TRANSMISSION OF SHOCK WAVE

Diffraction and transmission phenomena

To analyze the influences of different thicknesses of flexible wall on the flow field of shock wave behind wall, the pressure distributions of shock wave behind the flexible walls of 7 different thicknesses are calculated, and compared with that of the rigid walls.

Figure 5 and Figure 6 show the interactions between shock waves and rigid wall (40cm)/flexible wall (2.5cm) when 20kg explosives explode on the ground.

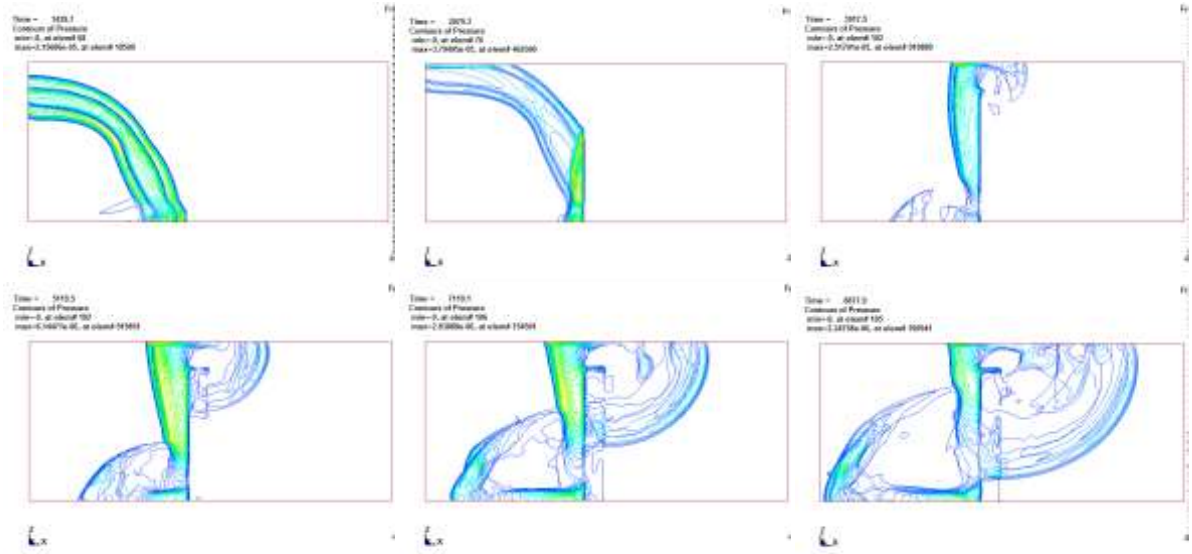


Fig-5: **Flow fields after shock wave impact on rigid wall**

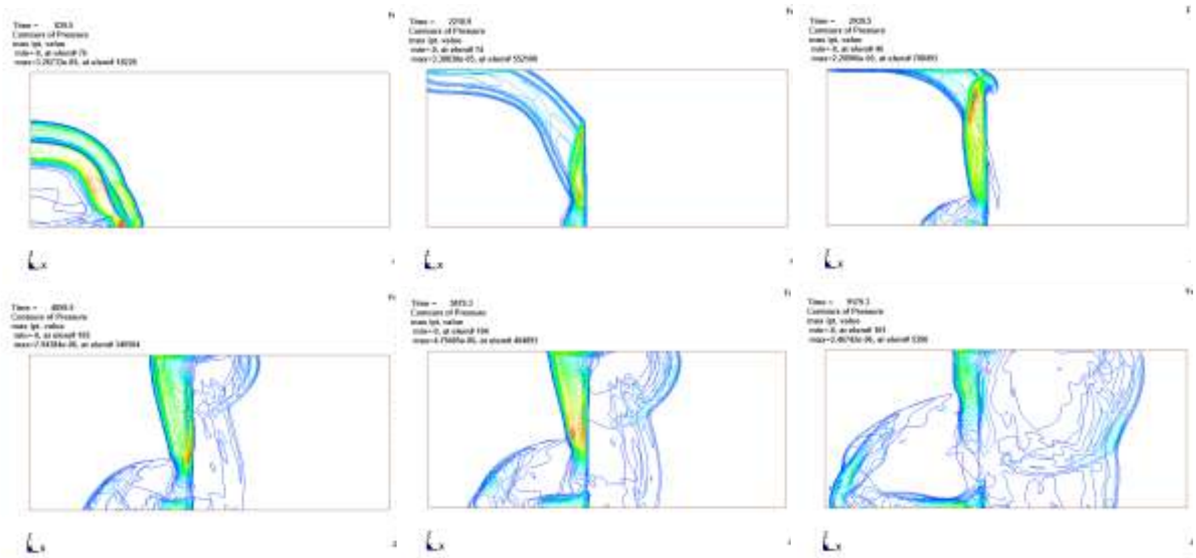


Fig-6: **Flow fields after shock wave impact on flexible wall**

It can be seen from Figure 5 that the shock wave will flow around the rigid wall after meeting it, while the rigid wall does not move or deform, and there is no wall's perturbation to the air behind the wall. The incidence shock wave only arrives at the back of the wall by climbing over the top of the wall (i.e. diffraction), and there is only one peak of wave behind the wall, thus the corresponding pressure is called diffraction pressure. From Figure 6, it can be seen that the wall will deform when the shock wave impacts on the flexible wall. The quick deformation of the wall will strongly perturb the air behind the wall, and produce a new wave, which can be called induced shock wave. Something like that the incidence shock wave will go through the flexible wall to travel. This kind of induced shock wave is called transmission wave. Apart from transmission, the incidence shock wave when impacting on the flexible wall will still produce diffraction along the top of the wall. The transmission wave arrives at the back of the wall earlier than the diffraction wave, and will have interactions with the diffraction wave when it continues to travel. On the pressure waveform behind the flexible wall, there will be a second peak, as shown in Figure 8 and Figure 9.

Figure 7 and Figure 8 show the pressure time histories of the same air elements 20cm over ground and 1.5m/2m behind the wall surface facing the blast when 20kg TNT explode on the ground.

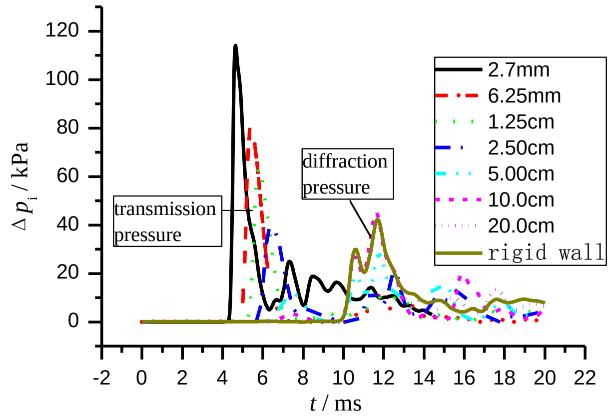


Fig-7: Pressures of the gauge 1.5m behind the wall

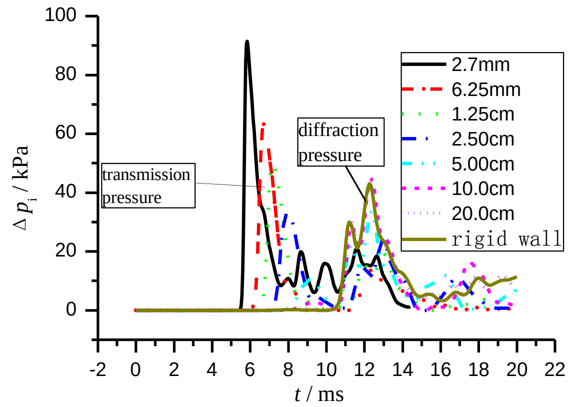
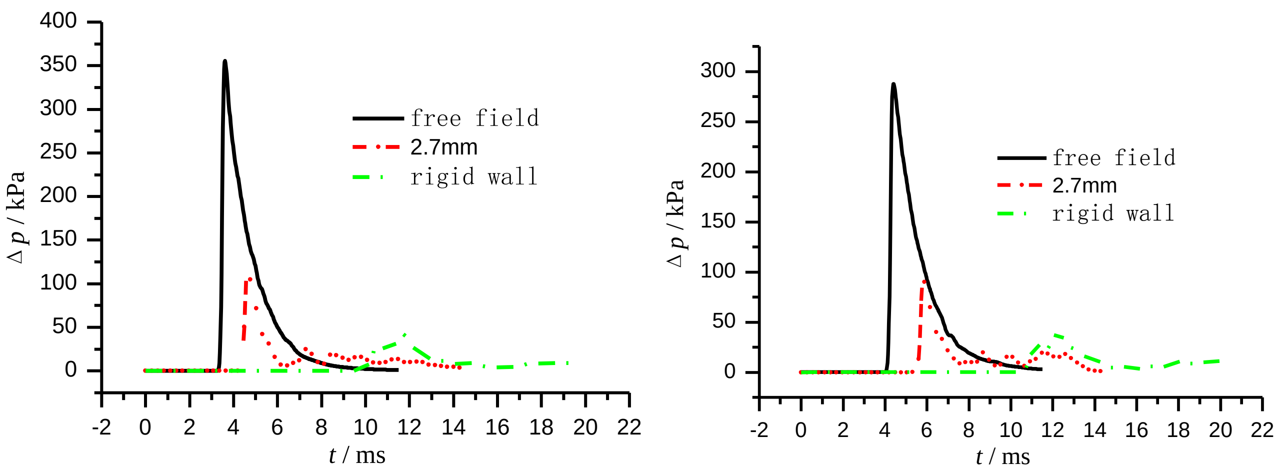


Fig-8:Pressures of the gauge 2.0m behind wall

From Figure 7 and Figure 8, it can be seen that there are two pressure peaks: the first pressure peak is produced by transmission wave, which appears earlier, and the pressure peak decreases as the thickness of the wall increases; the second pressure peak is produced by diffraction wave, which appears later. It appears at almost the same time as the pressure peak of the diffraction behind the rigid wall appears, and the pressure peak increases as the thickness of the wall increases. As the travel distance of the shock wave increases, the wave fronts of transmission wave and the diffraction wave will gradually merge. When the thickness of the flexible wall is over 10cm, the transmission pressure behind the wall is very small, and the diffraction pressure is close to that of the rigid wall.

Differences in pressure waveforms

As for the 20kg TNT blast on the ground, we draw the pressure waveforms of the air elements 1.5m and 2.0m (both are at the heights of 0.2m away from the ground) behind the wall surface facing the blast under the three conditions of free field, rigid wall and flexible wall (2.7mm thick), as shown in Figure 9. From this figure we can see that the arrival time of the pressure behind the flexible wall is earlier than the arrival time of pressure behind the rigid wall on the same gauges. The arrival time of the pressure behind both flexible wall and rigid wall is later than the arrival time of free field shock wave. The peaks of both are lower than the peak of free field shock wave on the same distance.



(a) Pressure waveform 1.5m behind the wall (b) Pressure waveform 2.0m behind the wall

Fig- 9: Pressure time histories behind rigid and flexible wall

Pressure distribution rules of transmission and diffraction

Figure 10 and figure 11 are the calculations of peak pressure variations behind flexible walls of different thicknesses when 20kg TNT explodes on the ground 3m away from the wall. In Figure 10, Δp_t refers to transmission pressure. In Figure 11, Δp_r refers to diffraction pressure, and r is the horizontal distance between the gauge and the wall surface facing the blast.

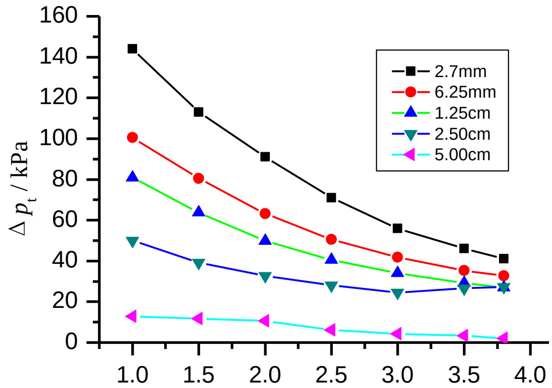


Fig-10: Transmission pressure behind flexible walls

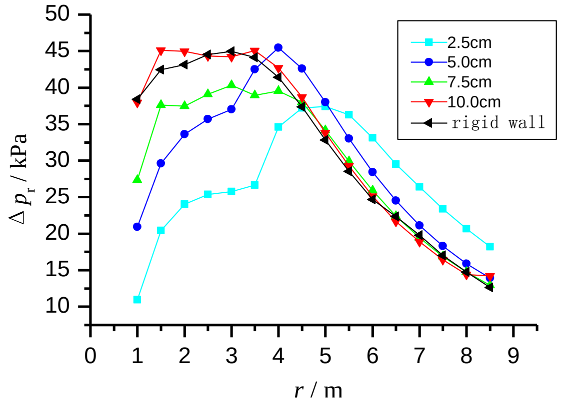
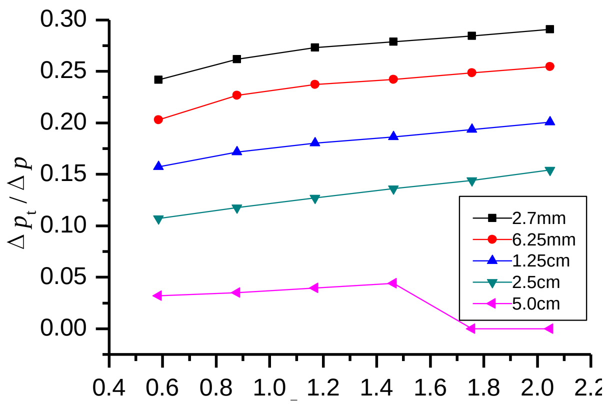


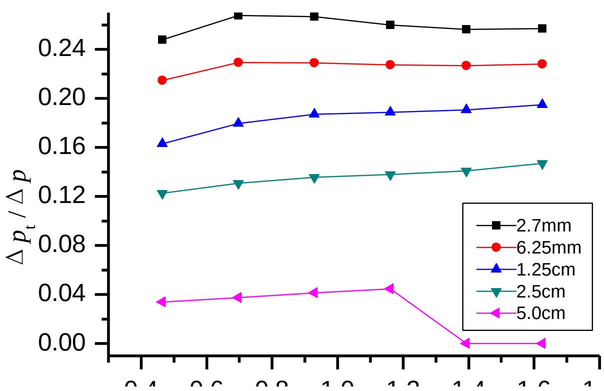
Fig-11: Diffraction pressure behind flexible walls

By comparing Figure 10 and Figure 11, we can see that the transmission pressure and diffraction pressure have different rules with blast distances. The transmission pressure decreases with the increase of distance, and decreases with the increase of wall thickness at the same distance. The diffraction pressure increases gradually with the increase of distance within certain range behind the wall, and starts to decrease at about 4m behind the wall (about 1.6 times of the height of wall), and increases with the increase of wall thickness at the same distance. When the flexible wall is 10cm thick, the diffraction pressure is close to that of the rigid wall. The above phenomena are caused by different mechanisms. The analysis of pressure distributions behind the flexible wall should be carried out separately by transmission and diffraction. According to the numerical simulation, when the largest pressure behind the wall is transmission pressure, the wall thickness is below 2.5cm; when the largest pressure behind the wall is diffraction pressure, the wall thickness is larger than 5cm. The analysis of peak pressure behind the flexible wall can be carried out according to the above distinction.

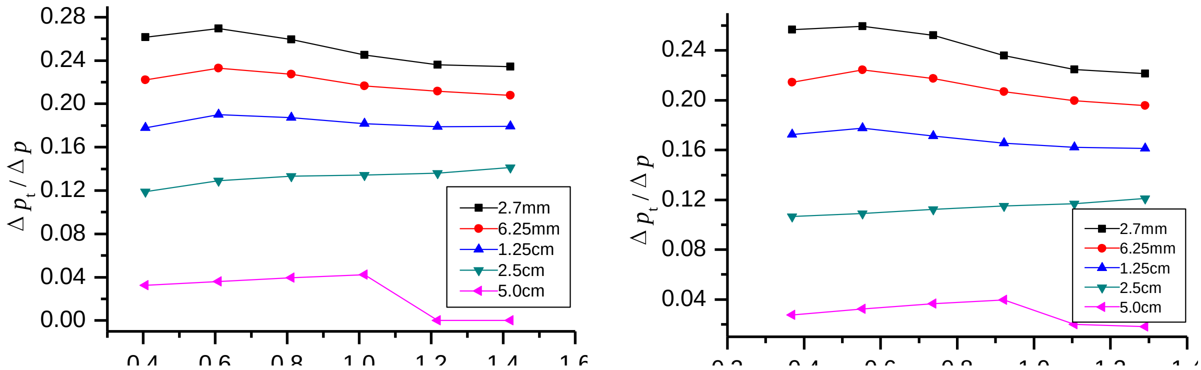
Figure 12 is the variation laws of transmission pressure behind the flexible wall under four different charges of TNT. In the figure, Δp_t and Δp are respectively the transmission overpressure behind the wall and free field incidence overpressure, $\bar{r}$ is the horizontal scaled distance between the gauge and the wall surface facing the blast. From the figure, we can see that the ratio between transmission pressure and incidence pressure behind the flexible wall is changing with the thicknesses of wall. The thicker the wall is, the smaller the value of $\Delta p_t / \Delta p$, and the value of $\Delta p_t / \Delta p$ does not change much with the scaled distance behind the wall of the same thicknesses.



(a) 5kg



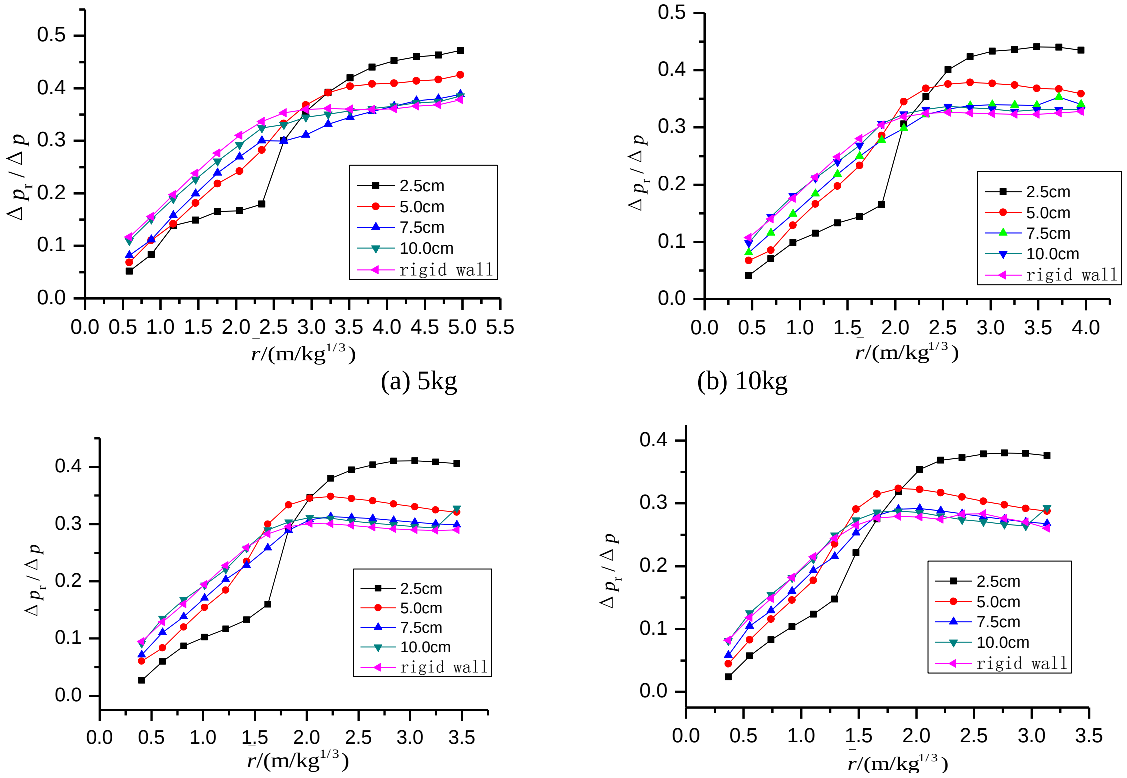
(b) 10kg



(c) 15kg (d) 20kg

Fig-12: Variations of $\Delta p_t / \Delta p$ with wall thicknesses and scaled distances

Figure 13 shows the variation laws of diffraction pressure behind the flexible wall under four TNT charges. Δp_r and Δp in the figure are diffraction overpressure and free field incidence overpressure behind the wall. From the figure, it can be seen that the ratio between the diffraction pressure and the incidence pressure behind the flexible wall also change with the thickness of the wall. Within certain scaled distance, the $\Delta p_r / \Delta p$ will increase with the increase of the wall thickness. Over certain scaled distance, the $\Delta p_r / \Delta p$ value will decrease with the increase of wall thickness, and finally tends to become the same as the $\Delta p_r / \Delta p$ behind the rigid wall.



(a) 5kg (b) 10kg

(c) 15kg (d) 20kg

Fig-13: Variations of $\Delta p_r / \Delta p$ with wall thicknesses and scaled distances

CONCLUSION

The following conclusions can be drawn through numerical simulation analysis in this paper:

(1) Both transmission and diffraction waves will be produced behind the flexible wall under the impact of blast shock wave, but in different ways. When the thickness of flexible wall is smaller than certain value, the transmission pressure is larger than the diffraction pressure; when the thickness of flexible wall is larger than certain value, the diffraction pressure is larger than the transmission pressure.

(2) The variation laws of the transmission pressure and diffraction pressure behind the flexible wall are different. The transmission pressure behind the flexible wall decreases when the thickness of the wall increases, while the diffraction pressure behind the flexible wall increases when the thickness of the wall increases and tends to become the same as the diffraction pressure behind the rigid wall.

(3) At the same scaled distance, the peak pressures behind both flexible wall and rigid wall are lower than the free field incidence peak pressure. The peak pressure behind the flexible wall might be higher or lower than that behind the rigid wall (it depends on the thickness of the flexible wall), and the arrival time of pressure behind the flexible wall is earlier than that behind the rigid wall, and later than the free field.

(4) When the shock wave pushes its obstacle to move, transmission wave will be induced when the velocity of deformation or movement of the obstacle reach certain value, i.e., it appears so-called transmission phenomena.

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