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FEA modelling prediction of the transmitted overpressure and particle acceleration within a frame subjected to shock tube blast loadings

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Abstract: Blast shock waves can cause primary blast lung injury and incapacitation. It has been established that a number of physical parameters, such as peak overpressure, positive phase duration, and the rate of displacement of the thoracic wall may be considered as predictors of non-auditory blast injury. In order to reduce the peak transmitted overpressure through the human body and the peak acceleration of the thoracic wall, it is necessary to develop various advanced blast protective materials and body armor systems.

In this paper, a two-dimensional (2D) finite element analysis (FEA) model, previously developed and verified by the authors for predicting the peak transmitted overpressure in a water block, was modified by introducing a polyurethane frame. This frame was employed as a simple approximation of a human thoracic wall, which contains the water block and is subjected to various levels of shock tube blast loadings. Both the water block and frame were modelled using the Mie-Gruneisen equation of state. Flow-out and transmit boundary conditions were respectively applied to the outer perimeter of the air surrounding the end of the shock tube and that of the polyurethane frame so as not to reflect energy back into the computational grid. Using this modified 2D FEA model, the peak transmitted overpressure and particle acceleration in the frame were obtained for various shock tube blast loadings. It was noted from the numerical study that the arrival time of the peak transmitted overpressure was close to that for the peak particle acceleration. This was expected.

In order to reduce the peak transmitted overpressure and particle acceleration that occurred in the simplified thoracic wall frame, various single- and multiple-layer blast protective material panels were alternatively placed on the left surface of the frame. The effects of the major parameters on the peak transmitted overpressure and particle acceleration measured in the frame are discussed. The parameters considered here include the thickness and material properties of selected blast protective panels, the shock tube blast loading conditions, the existence of an air gap and the presence of low density (LD) foam within a multiple-layer panel.

For the single-layer case, placing aluminium, high density polyethylene (HDPE) or Kevlar panels on the left surface of the frame decreased the peak transmitted overpressure and particle acceleration. LD foam increased the peak transmitted overpressure and particle acceleration in the frame. With an increase in panel thickness, the peak transmitted overpressure decreases for aluminium, HDPE and Kevlar. These findings are consistent with those obtained using the 2D FEA model developed previously for simulating the peak transmitted overpressure in a water block. As the panel thickness increases, the peak particle acceleration decreases for the aluminium panel. However, it is interesting to note that the effect of the panel thickness on the peak acceleration is not significant for HDPE and Kevlar. For the LD foam, the peak transmitted overpressure and acceleration increase with the panel thickness until it attains 9mm, beyond that both peak transmitted overpressure and acceleration remain almost unchanged.

The numerical study has also included multi-layer cases, and identified the significant role of an air gap and LD foam in mitigating the peak transmitted overpressure and particle acceleration. The limitations and future improvements of the simplified frame model are also discussed.

Keywords: *Finite element analysis (FEA) model, blast protection, transmitted overpressure, particle acceleration, shock tube blast loadings.*

1. INTRODUCTION

When an explosive detonates, there is a sudden and dramatic release of considerable amounts of energy. Their deleterious effects on human organisms are embodied by blast injury. Currently, blast injuries have become one of the main threats in the battle field and in regions of political conflict. Hence, understanding of the blast injury mechanism is critical for the development of effective blast protective materials and ensembles. It is also useful in helping doctors to manage and deal with the blast injury.

Over the past four decades, various blast injury criteria and thresholds have been studied and established by researchers. For example, a blast injury criterion, which was based on empirical studies of the biological effects of the blast wave and associated peak overpressure and positive phase duration, has been proposed by Bowen et al. [1] and further extended by Bass et al. [2-3].

A relationship between the lung injury and peak acceleration of the lateral thoracic wall of anesthetized pigs, which were subjected to short duration blast loadings, was obtained by Cooper [4]. Cooper [4] found that under short duration blast wave loadings, the direct coupling of the incident shock wave into the thorax, which was achieved by the initial rapid acceleration of the thoracic wall, was the principal injury mechanism. For the purpose of decoupling the incident shock wave, Cooper [4] suggested that a decoupling layer could be used for reducing the peak transmitted overpressure. This decoupling layer is composed of a material of high acoustic impedance (*Z=product of the speed of sound in the material and its density*) backed by a material of very low *Z* such as foam with high compliance and high air content.

For the purpose of reducing the severity of internal blast injuries such as primary lung injury, it is necessary to develop blast protective materials, which will help to effectively reduce the peak transmitted overpressures and accelerations of the thoracic wall subjected to blast loadings. FEA modelling is one of the cost-effective and efficient means to simulate the performance of blast protective materials against blast loadings.

The present paper aims at simulating and improving the blast protective behaviours of selected materials and ensembles under various blast loadings. It was conducted by using a 2D FEA model, which was generated using the FEA software Autodyn [5]. In this paper, a 2D FEA model [6], which was previously developed and verified by the authors for predicting the transmitted overpressure within a water block, was briefly outlined. This was followed by modifying the 2D FEA model for predicting the peak values of transmitted overpressures (P_t) and particle acceleration in the x direction (a_x) within a polyurethane frame. The frame considered here was employed as a simple approximation of a human thoracic wall. A parametric study was carried out to study the effects of major parameters on the peak values of P_t and a_x in the frame. The parameters considered include the thickness and material properties of selected blast protective panels, the initial driver section pressure (P_0), and the existence of an air gap and LD foam within a multiple-layer panel.

2. OUTLINE OF THE PREVIOUS 2D FEA MODEL

For investigating the blast protective performance of selected materials and ensembles, a 2D FEA model having the configuration shown in Fig.4 in [6] was developed previously using the Autodyn software [5]. In this model, a water block subjected to shock tube blast loading was employed as a simple approximation of a human body. It was modelled using a Mie-Gruneisen form of equation of state (EOS) [7], which is written as

$$P = P_H + \Gamma\rho\left[e - e_H\right] \tag{1}$$

where P is pressure and Γ is the Gruneisen Gamma, ρ is the density, e is the specific internal energy, and the functions P_H and e_H are described in [8]

For the purpose of reducing the peak value of P_t, several blast protective materials, such as aluminium, LD foam *I* and HDPE, were respectively placed on the top surface of the water block. Similarly to water, these three types of material were also modelled using a Mie-Gruneisen form of EOS. Kevlar was modelled using the Puff EOS, which is given below,

$$P = (A_1\mu + A_2\mu^2 + A_3\mu^3)(1 - \Gamma\mu/2) + \Gamma\rho e \tag{2}$$

where A_1, A_2 and A_3 are constants and $\mu = \frac{\rho}{\rho_0} - 1$, ρ_0 is the initial density.

The parameters required for generating the 2D FEA model using Autodyn are listed in Table 1, in which Γ_0 is the initial Gruneisen Gamma. The parameters c_0 and s are obtained from the corresponding material shock Hugoniot curve in the shock-particle velocity plane.

For generating the shock tube blast loadings, a light gas of helium was used as the driver gas and air was used for the driven gas. Both helium and air were modelled as ideal gases, which followed the equation as listed below,

$$P = (\gamma - 1)\rho e \tag{3}$$

where γ stands for ratio of specific heats. It is a constant equal to $1+R/c_v$, where constant R may be taken to be the universal gas constant R_0 divided by the effective molecular weight of the particular gas and c_v is the specific heat at constant volume [6]. The values of γ and ρ for helium are 1.66 and 0.1787kg/m^3 respectively, while those for air at standard atmospheric conditions are 1.44 and 1.225kg/m^3.

Table **1**. The required parameters for the Mie-Gruneisen and Puff EOS [5, 9-10]

Water				Aluminium			
Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s	Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s
0.28	1000	1483	1.75	2.0	2785	5328	1.338
LD foam *I*				HDPE			
Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s	Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s
1.18	80	884.6	0.6466	1.64	954	3250.1	1.426
Steel				Polyurethane			
Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s	Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s
2.17	7896	4569	1.49	1.55	1265	2486	1.577
Foam *II*				Foam *III*			
Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s	Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s
1.18	100	723.3	0.6931	1.18	150	496.8	0.6973
Foam *IV*							
Γ_0	ρ_0 (Kg/m^3)	c_0 (m/s)	s				
1.18	200	21.6	0.8002				
Kevlar							
ρ_0 (Kg/m^3)	Expansion coefficient	Γ	Sublimation energy (J/Kg)	A_1 (kPa)	A_2 (kPa)	A_3 (kPa)	
1290	0.25	0.35	8.23×10^6	8.21×10^6	7.036×10^7	0	

For the sake of allowing the outward blast wave to pass through a boundary without reflecting energy back into the computational grid, a flow-out boundary condition was applied to the outer perimeter of the air surrounding the end of the shock tube. Also, a transmit boundary condition was applied to the outer perimeter of the water block. A pressure gauge was placed at a distance of 10mm from the top surface of the water block to obtain the required peak values of P_t. For taking into account the interactions of the blast wave, air, blast protective panels and the water block, Euler Lagrange Interactions were prescribed during the model set-up.

For increasing confidence in using the 2D FEA model for simulating the performance of materials against blast loadings, a 2D FEA model was generated based on the panel configuration and steel support used by Ouellet et al. in their chamber tests [11]. Its configuration was shown in Fig.8 in [6]. The Mie-Gruneisen form of EOS was employed for modelling aluminium, LD foam and steel. The parameters required for the corresponding 2D FEA models are listed in Table 1. A comparison of the *Diff* values, which are the percentage differences of the peak transmitted overpressure, between the cases with and without blast protective materials, was carried out for the FEA model and the Chamber tests (see Table 2 in [6]). A reasonably good agreement was noted between the two sets of results.

3. 2D MODIFIED FEA MODEL FOR PREDICTING THE TRANSMITTEED OVERPRESURE AND PARTICLE ACCELERATION IN A FRAME

It was noted from the literature that some blast injury criteria were developed based on the peak transmitted overpressure or acceleration of the thoracic wall. For simulating the behaviour of the thoracic wall subjected to blast loadings, a rectangular polyurethane frame representing a human chest wall was added to the 2D FEA model outlined in section 2, as shown in Fig.1.

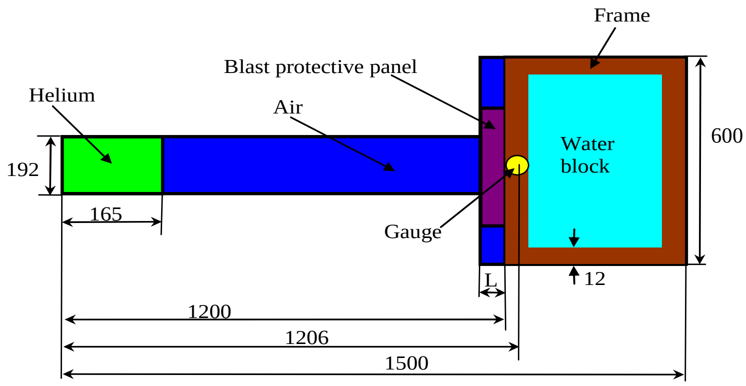


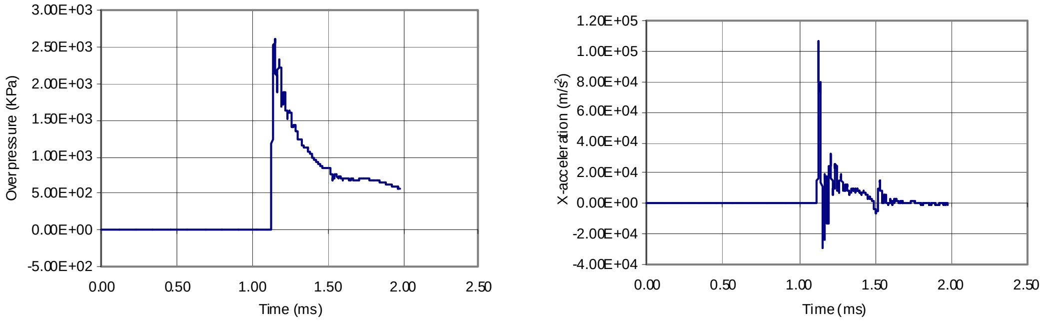
Figure 1. A schematic of the 2D FEA model with a water block surrounded by a frame (The unit used in this diagram is mm. The diagram is not to scale.)

A gauge was located at a distance of 1206mm from the left surface of the shock tube for obtaining the required peak values of P_t and a_x in the frame. The value of a_x at a selected node, can be obtained by

$$a_x = \frac{F_x}{m_p} \tag{4}$$

where F_x is the net component of nodal force in the x direction, and m_p is the mass attributed to the node. The magnitude of m_p was taken to be the sum of the masses of the surrounding quadrants of the neighbouring zones. Each quadrant is assumed to have one quarter of the mass of the relevant zone so the magnitude of m_p is equal to one quarter of the sum of the four surrounding cell masses.

Figure 2 shows the variation of P_t and a_x with time for the frame subjected to P_0= 2MPa. It was noted that the arrival time for the peak value of P_t is close to that of a_x. This is expected because the nodal force F_x depends on the overpressure and the value of a_x is related to F_x by equation (4).



(a) P_t vs time (b) a_x vs time

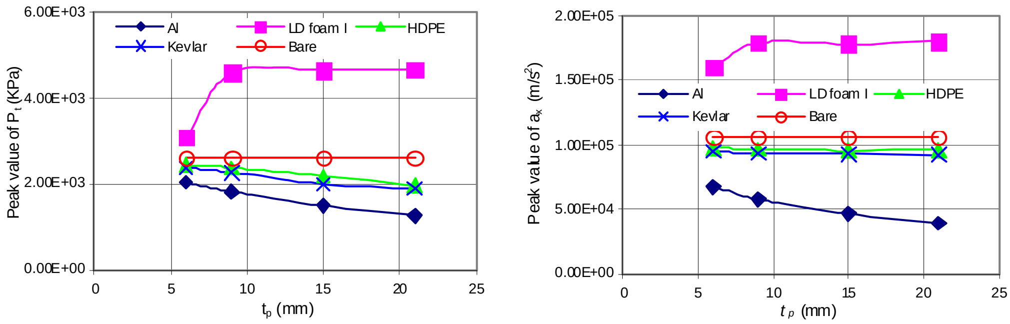
Figure 2. Variation of P_t and a_x in a frame subjected to P_0=2MPa

4. PARAMETRIC STUDY

For the purpose of investigating the performance of the blast protective layer systems against blast loadings, both single-layer and multiple-layer panel systems were considered.

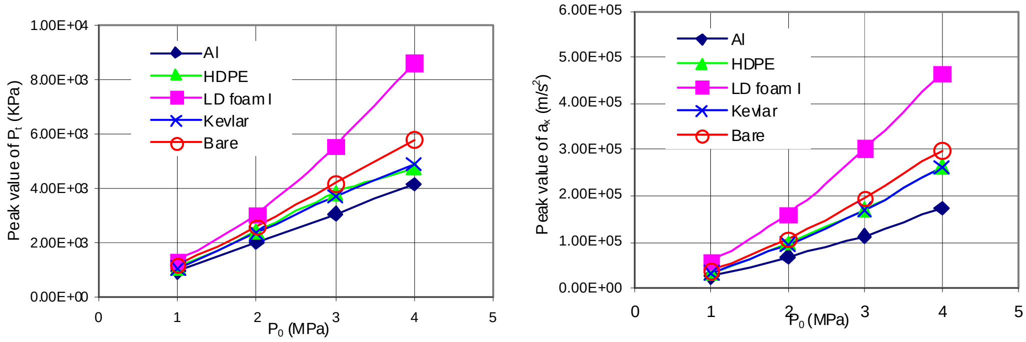
4.1 Single-layer panels

For investigating the effects of the single-layer panel thickness (t_p) and initial driver section pressure (P_0) on the peak values of P_t and a_x, the values of t_p and P_0 were varied in individual simulations: blast protective panel thicknesses of 6, 9, 15, 21mm and initial driver section pressures of 1, 2, 3, 4MPa were used. The corresponding variation of the peak values for P_t and a_x with t_p and P_0 were plotted in Figs. 3 and 4, respectively. For comparison, results for the bare case are also shown in Figs. 3 and 4.



(a) Peak value of P_t vs t_p (b)Peak value of a_x vs t_p

Figure 3. Variation of the peak values of P_t and a_x with t_p (for the case of P_0=2MPa)



(a) Peak value of P_t vs P_0 (b) Peak value of a_x vs P_0

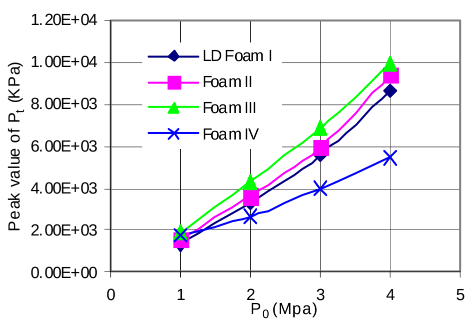
Figure 4. Variation of the peak values of P_t and a_x with P_0 (for the case of t_p=6mm)

It may be noted from Figs.3(a) and (b) that with an increase in t_p, the peak value of P_t for the aluminium panel decreases significantly, while that of HDPE or Kevlar panel decreases slightly. These findings are consistent with those reported in [6] where only a water block was considered. However, it is interesting that for the aluminium, the peak value of a_x decreases significantly with t_p, while the effect of t_p on the peak value of a_x is not significant for HDPE or Kevlar. For the LD foam *I*, the peak values of P_t and a_x increase with t_p until it attains 9mm, beyond that both peak transmitted overpressure and acceleration remain almost unchanged. Figure 4 revealed that for all single-layer panels considered here, an increase in P_0 results in significant increases in the peak values of P_t and a_x. These findings are consistent with those for the peak values of P_t available in [6] for the case without a frame.

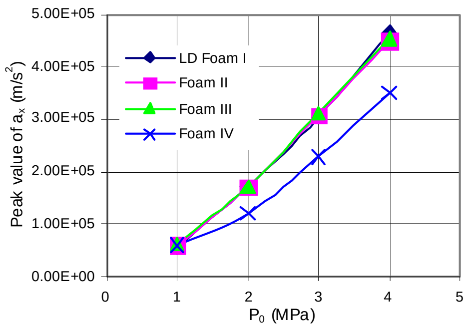
It is interesting to note from Figs. 3 and 4 that placing an LD foam *I* panel on the left surface of the frame amplified the peak values of P_t and a_x. For discussing the effects of foam properties on the peak values of P_t and a_x, another three types of foam, namely foam *II*, *III* and *IV*, were considered. Their corresponding parameters for the Mie-Gruneisen form of EOS were listed in Table 1.

Figure 5 illustrates the variation of the peak values of P_t and a_x with P_0 for the foam *II*, *III* and *IV*. For comparison, the corresponding variation for LD foam *I* was also plotted in Fig. 5. It was noted from Fig.5

that from the point of view of reducing the peak values of P_t and a_x, the performance of foam *IV* , having the lower value of $\rho_0 c_0$ compared to other three types of form, is better. This may imply that the value of $\rho_0 c_0$ may play an important role in mitigating the peak values of P_t and a_x. This finding is consistent with that the shock pressure depends on the shock impedance, which increases with the value of $\rho_0 c_0$ [12]



(a) Peak value of P_t vs P_0



(b)Peak value of a_x vs P_0

Figure 5. Comparison of the peak values for P_t and a_x vs P_0 for foams *I* to *IV*

4.2 Multiple-layer panels

In this study, three different types of multiple-layer blast protective panel, including triple-layer, four-layer and five-layer panel (Fig.6), were considered. The value of P_0 was chosen to be 7, 10, 13 and 16MPa, respectively. The variation of the peak values of P_t and a_x vs P_0 are illustrated in Fig. 7. Results for the bare case are also plotted in Fig. 7 for comparison. It is noted from Fig. 7 that for the triple-layer panel, the peak values of P_t and a_x increase almost linearly with P_0. For the four-layer panel, the peak values of P_t and a_x increase with P_0 until P_0 attains 13MPa, beyond which they change slightly. For the five-layer panel, the effect of P_0 on the peak values of P_t and a_x is not significant. Hence, it may be concluded that the existence of an air gap and LD foam *I* plays an important role in attenuating the peak values of P_t and a_x. This is consistent with the finding reported by Cooper [13] that a copper with larger *Z* value facing on FOAM R with smaller *Z* value significantly reduced the peak transmitted overpressure. For those multiple–layer panels with an air gap, numerical results showed that shock loading reduced the thickness of the air gap with time. Hence, it must be noted that the results presented here only considered the behaviour of the panel while an air gap still exists.

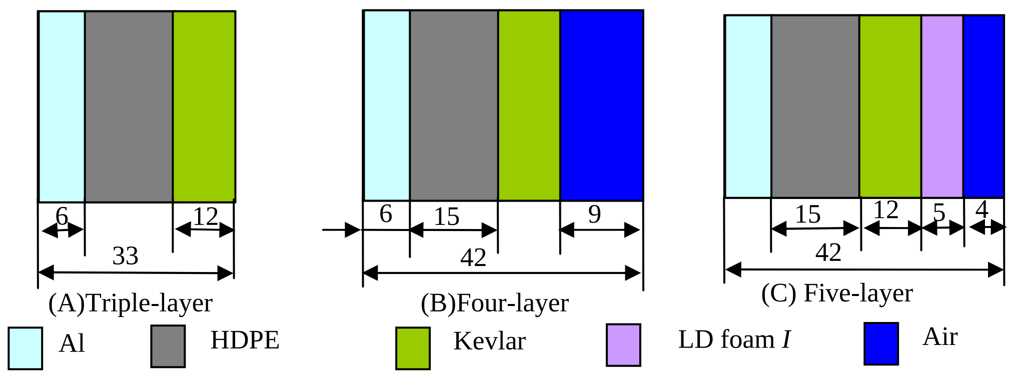
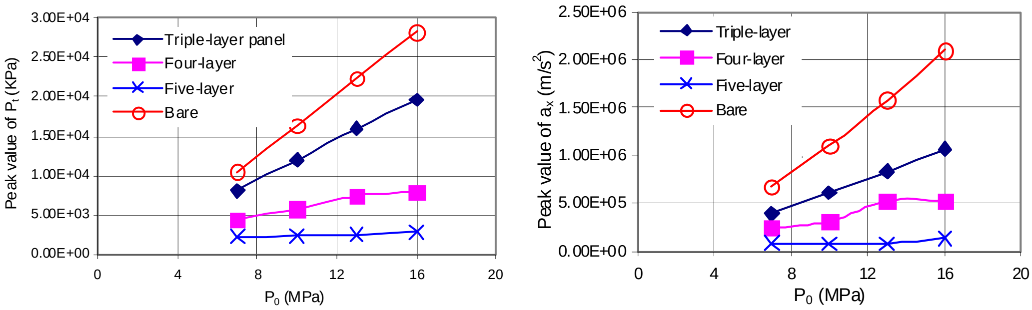


Figure 6. Three typical configurations for the multiple-layer panels



(a) Peak value of P_t vs P_0 (b) Peak value of a_x vs P_0

Figure 7. Variation of the peak value of P_t and a_x *vs* P_0 for multiple-layer panels

5. CONCLUSIONS

In this paper, a 2D FEA model, developed previously, was modified to evaluate the values of P_t and a_x in a polyurethane frame subjected to various shock tube blast loadings. An investigation of mitigating the peak values of P_t and a_x by placing various single- and multiple-layer panels on the left surface of the frame was also carried out. For the single-layer panels, it was revealed from the parametric study that as t_p increases, the peak value of P_t decreases for the aluminium, HDPE or Kevlar panel. The peak value of a_x decreases with t_p for the aluminium panel. The effect of t_p on the peak value of a_x is not significant for the HDPE or Kevlar panel. For the LD foam *I* panel, the peak values of P_t and a_x increase with t_p until t_p attains 9mm, beyond that they remain almost unchanged. The parametric study also revealed that the peak values of P_t and a_x may be significantly reduced by selecting a foam with suitable value of $\rho_0 c_0$. For all cases considered, the peak values of P_t and a_x increase significantly with P_0, except for the five-layer panel with LD foam *I* and an air gap. The peak values of P_t and a_x for the five-layer panel change slightly with P_0. Hence, it may be pointed out that the existence of an air gap and LD foam plays an important role in attenuating the peak values of P_t and a_x. It is worth mentioning that for more realistically modeling the human torso, the shapes of the rectangular frame and water block need to be modified to cylinders.

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