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Effect of air gap on the structural response of aluminum foam protected reinforced concrete panels

Capt. Eng. Mohamed M. Mahmoud*, Assoc. Prof. Sameh Y. Mahfouz** and Maj. Gen. (Ret.) Dr. Hassan M. Farag***

ABSTRACT

This paper comprises computational investigation on the effect of air gap clearance on the dynamic behavior of aluminum foam- air gap- reinforced concrete (RC) panel interaction under the effect of various blast loads. A parametric study was performed using hydro-code software (i.e. AUTODYN 3D) in order to investigate the effect of considering material of low mechanical impedance (i.e. Air) between the protection panel and RC panel. The parameters studied are the thickness of aluminum foam, air gap thickness, the weight of explosive charge, and thickness of RC panel. A set of published experimental tests was used to validate the developed numerical models of protected and unprotected RC panels. In the numerical simulations, the dynamic behavior of reinforced concrete and aluminum foam materials as porous materials were defined utilizing different Equations of State (EOS) and strength models. Time-dependent results of the response of the tested RC panels are analyzed, discussed and utilized to obtain the suitable aluminum foam and air gap thicknesses for each case to maintain the maximum deflection of each RC panel within its elastic limit.

KEYWORDS: Concrete slabs, Aluminum Foam, Air gap, blast loadings.

INTRODUCTION

Threats posed by terrorist attacks and accidental explosions demand improvement of the construction materials and techniques used in order to improve the blast resistance of reinforced concrete structures. Therefore, various techniques have been developed to protect buildings against the destructive effect of blast loading with various degrees of success. Researches directed their study to investigate the effect of using different composite materials as protecting layers [1-5]. Another research work [6] directed to invention of light weight protective layers and foam cladding techniques to protect structures from blast loads.

Aluminum foam is a lightweight material with excellent plastic strain energy [7]. The aluminum foam material behaves as a perfect-plastic material. Moreover, aluminum foam can absorb high blast energy at a nearly constant stress level because of its long plastic plateau in compression [6]. The typical behavior of aluminum foam was illustrated by Hanssen et al. [7] and Wu and Hamid [8].

* *Defense Systems Studies Center*

** *Head of Construction and Building Engineering Department, College of Engineering and Technology (Smart Village), Arab Academy for Science, Technology, and Maritime Transport*

*** *Military Technical College*

The characteristics of aluminum foam attract researches to use composite sandwich panels having aluminum cores as sacrificial layers. Among them, Chi et al. [9] experimentally investigated the influence of core height and face plate thickness on the response of honeycomb sandwich panels subjected to blast loading. It was found that increasing the core thickness delayed the onset of core densification and decreased the back plate deflection. Also increasing the plate thickness decreased the back plate deflection.

Full scale explosive tests on protected and unprotected concrete slabs were conducted by Schenker et al. [10] where several layers of aluminum foams were studied. The authors illustrated and verified the effectiveness of the using aluminum foam for reducing the slab response. Based on the previous studies, it can be concluded that aluminum foam can protected RC structures and is able to absorb amount of energy resulted from explosion. In the present study, the effect of an air gap between RC panel and protection layer (i.e. aluminum foam) on the dynamic response of RC panels is investigated. The dynamic response of two RC panels protected with aluminum foam subjected to blast loads are obtained using AUTODYN 3D. the computed results are then utilized to study the minimum thicknesses of aluminum foam and air gap to maintain the maximum deflection of each RC panel within its elastic limit calculated using approximated design method [11]

The idea of this research is based on how the blast pressure is affected with the value of mechanical imedance of the medium which the blast wave transfer through. In case of high explosive detonations, a high pressure blast wave is generated. This wave moves outward in all directions hitting an object. This incident pressure is divided into transmitted pressure and reflected pressure. For blast protection purpose, it is important to study how to reduce the transmitted pressure to a minumum value.

The amount of transmitted or reflected pressure depends on the mechanical impedance (Z) of the medium [12].The Impedance can be expressed in the form [13]:

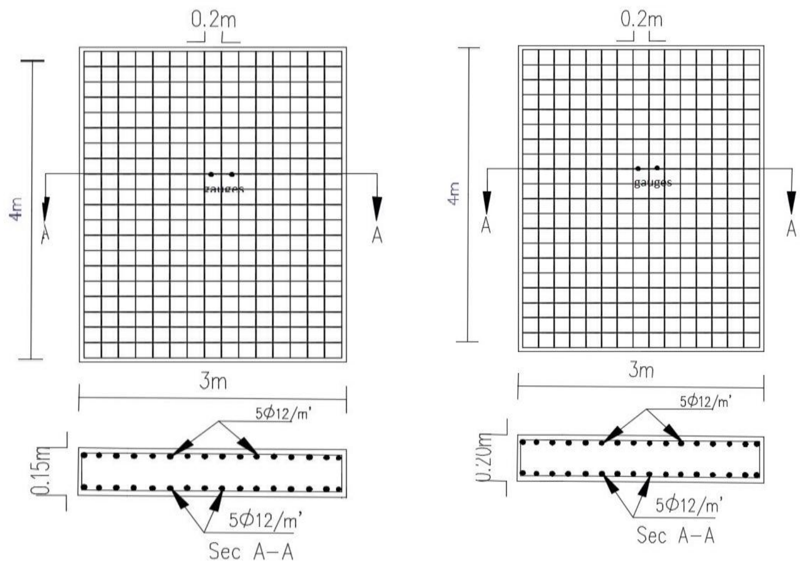
$$Z = \frac{Change\ in\ pressure}{Change\ in\ velocity} = \frac{\Delta P}{\Delta v} \qquad (1)$$

Where, ΔP is the change in pressure and Δv is the change in velocity of the shock wave travelling through the medium.

Preliminary design

The preliminary design of two RC panels A and B are carried out using the approximate design rules defined in TM5 [11]. The panel dimensions are 4000 mm length and 3000 mm width. The panels are fixed from all sides. Panel A is elastically designed to sustain against pressure load resulted from 3 kg TNT at a standoff distance 4 meters. Similarly, panel B is designed considering 5 kg TNT.

The calculated thicknesses of RC panels A and B are 150 mm and 200 mm respectively. The steel reinforcement is double mesh having 5 bars of 12 mm diameter per meter in each direction. The maximum elastic deflections are 5.2 mm and 4.3 mm for panels A and B respectively. The RC panels' geometries as well as steel reinforcement are shown in Fig. (1).



Panel A Panel B

Fig. (1) Geometry and steel reinforcement for RC Panels A and B

Material models

In the present study, equations of state and strength models are used to describe the materials in the numerical simulation. For air, the ideal gas equation of state (EOS) [14] is:

$$P = (\gamma - 1)\rho e + P_{shift} \tag{2}$$

Where, P is the pressure. The adiabatic constant γ equals 1.4 for air behaving like an ideal gas. The air density is ρ and e is a specific internal energy. A small pressure P_{shift} is defined to give a zero starting pressure to avoid complication in problems with multiple materials where initial small pressures in the gas would generate small unwanted velocities. The Jones-Wilkins-Lee (JWL) equation of state is used to describe the explosive, which is in the form:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{3}$$

Where A, B, R_1, R_2, ω are empirically derived constants which depend on the type of explosives, V is the relative volume or the expansion of the explosive product, and E is the detonation energy per initial unit volume. These parameters were derived from Dobratz and Crawford [15].

Herrman (1969) [16] proposed a porous equation of state for concrete and this considered the concrete inhomogeneity and porosity. Equation (4) describes the behavior of fully compacted material while the porous material is scaled using the porosity (α). Thus for the fully compacted material the pressure (P) equals P_{lock} and the porosity α equals 1and the pressure was calculated using the solid polynomial equation as presented in equation (4).For pressure greater than P_{crush} and less thanP_{lock}, the pressure was scaled using equation (5).

$$P = A_1\mu + A_2\mu^2 + A_3\mu^3 + (B_0\mu + B_1\mu)\rho_0 e \text{with} \mu = \frac{\rho}{\rho_0} - 1 \tag{4}$$

$$P = f(\rho, e) \xrightarrow{porus} P = f(\rho\alpha, e) \text{with} \alpha = 1 + (\alpha_{init} - 1)\left[\frac{P_{lock} - P}{P_{lock} - P_{crush}}\right]^n$$

(5)

The data that defines the concrete material in the hydro-code [14] was chosen from the library as (conc-35MPA) and modified to match those used in the experimental work carried by Zhu et al.[17].P-Alpha equation of state and polynomial solid EOS with Riedel, Hiermaier and Thoma (RHT) [18] Concrete strength model were applied. Reference density of concrete equals 2.75 gm/cm^3, Compressive strength equals 3.2e4 kPa and Shear modulus equals 1.67e7 kPa.

The data that defines the steel reinforcement (Steel 1006) material in the hydro-code [14] was chosen from the library and modified. The linear equation of state and strength model Johnson and Cook [19] were applied. The yield stress of steel was assumed 3.5e5 kPa and its shear modulus was 8.18e7 kPa

The dynamic behavior of aluminum foam material as a porous material was described using the approach proposed by Kipp[20] where the equation of state P-α compaction model together with the von Mises yield strength were used. The von Mises yield criterion describes the material elastic limit and its inability to support large shear stresses. Material failure occurred when the material was not able to withstand tensile stresses exceeding the material's local tensile strength. The hydrodynamic tensile model was used for simulation, and the model requires a specified constant hydrodynamic tensile limit to determine failure occurrence. The physical data of aluminum foam inserted in AUTODYN were porous density equals 0.5 gm/cm^3, initial compaction pressure set7 MPa, solid compaction pressure was 133 MPa, compaction exponent considered 1.4, Shear Modulus was 1.88 GPa, Yield Stress proposed 7 MPa, and the Hydro Tensile limit was -2 GPa.

Parametric study

Twenty four models are developed using AUTODYN. The proposed models are composed of RC panel and aluminum foam layer spaced from RC panel. The spacing between aluminum foam and RC panel is filled with air (i.e. air gap) as shown in Fig. (3). A parametric study is conducted for each panel. The parameters are thickness of aluminum foam, air gap thickness, and weight of explosive charge.

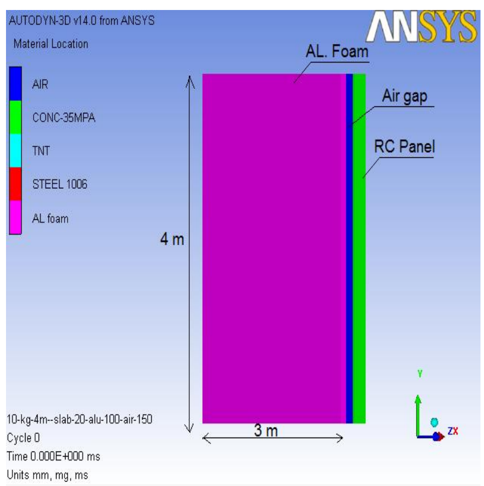


Fig. (3) Geometry of the proposed model

The reinforced concrete panel is totally clamped from all its sides, prevented from translation and rotation in all directions (perpendicular and parallel to its surface) at the perimeter nodes. Aluminum foam panel is fixed with the RC panel at eight points at the edges: four points at the corners and the other four points at the mid-span of the panel's sides.

In AUTODYN, Air domain surrounds RC panel and explosion zone and has boundary condition called FLOW OUT. The flow out permits to translate blast wave to hit the RC panel as in blast field test (i.e. RC panel responds similar to actual practical case). Fig. (4) illustrates the boundary conditions of the panel, the air media, and the explosion sphere. In numerical model, air and TNT are simulated by Euler formulation. Concrete and aluminum foam are simulated by Lagrange formulation. Steel reinforcement bars are modeled as bar elements by using beam solver.

Two blast loads are applied to the reinforced concrete panels. These blast load levels are implemented through the application of 10 and 15 kg of TNT explosive at the same stand-off distance of 4 m. These explosive charges are chosen so that the RC panel's deflection increases to three times its elastic deflection (i.e. μ=3). The pressure-time histories for both charges are illustrated in Fig. (5).

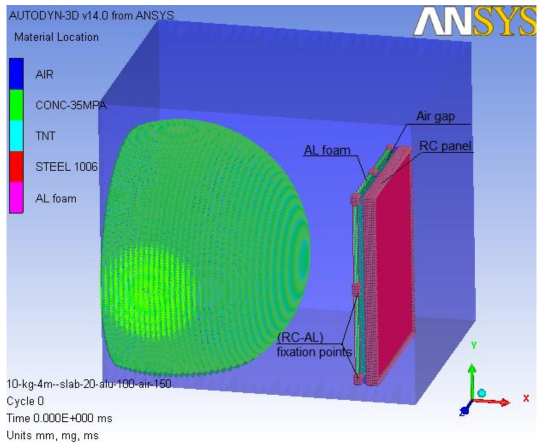


Fig. (4) The boundary conditions, air medium, and explosion sphere.

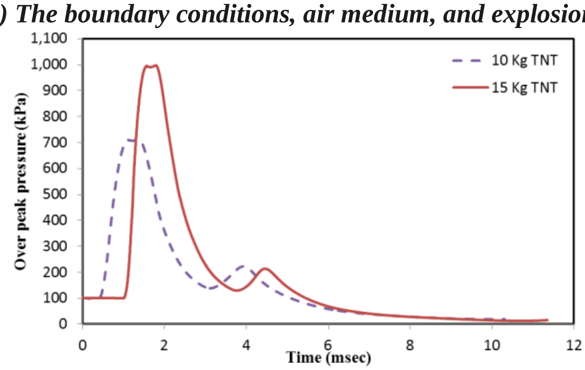
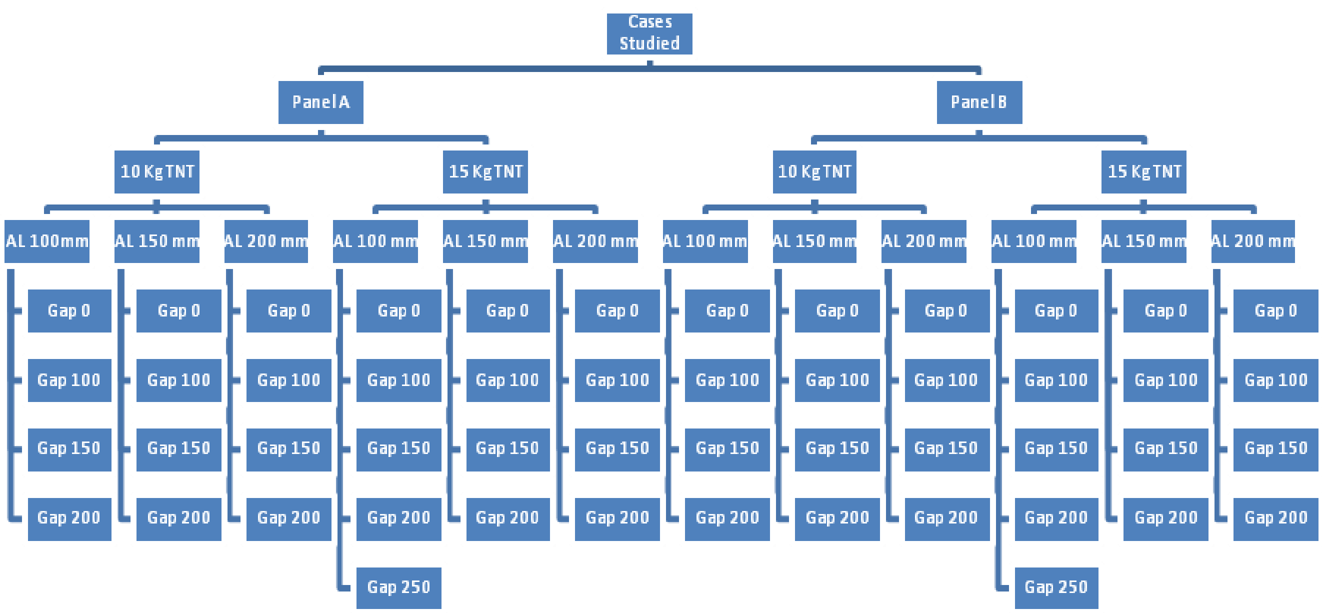


Fig. (5) Pressure-time histories for 10 and 15 kg TNT charges.



Dynamic response of RC panel A

The dynamic response of RC panels protected with aluminum foam is investigated based on air gap between RC panel and the aluminum foam. Here, a parametric study is carried out. The parameters studied are the thickness of aluminum foam and clearance of air gap and TNT charge weight.

Utilizing AUTODYN, the RC panel and aluminum foam are modeled as described before. In the model, a displacement gauge is assigned to capture the displacement-time history at the center of the reinforced concrete panel. Two gauges are added at the mid-span of the front and back face of aluminum foam to monitor the internal energy.

In the current study for panel A, twenty four numerical simulations are carried out on three aluminum foam panel thicknesses (100, 150 and 200 mm) having different clearance of air gap (0, 100, 150 and 200 mm). These models are subjected to different blast loads (i.e. 10 and 15 kg TNT) at stand-off distance of 4 meters.

Fig. (5), Fig. (6), and Fig. (7) illustrate the comparison between the displacement-time histories at the mid-span of RC panel A under the effect of 10 Kg TNT explosion when varying the thicknesses of air gap using aluminum foam panel (100, 150 and 200 mm) thick respectively.Similarly Fig. (8), Fig. (9), and Fig. (10) illustrate the comparison between the displacement-time historiesat the mid-span of RC panel Aunder the effect of 15 Kg TNT explosion at stand off distance 4 meters. In these figures, the displacement-time history of unprotected panel is included. From these figures, it can be noted that as the aluminum foam thickness increases, the displacement decreases at all times. It can be also concluded that using an air gap more than 200 mm has no effect on the response of the reinforced concrete panel. This conclusion is cleared from the result obtained when using 250 mm air gap that gives nearly the same response in case of the 200 mm air gap thickness.

Fig.(11), Fig.(12), and Fig. (13) illustrate the comparison between internal energies at the front and back faces of aluminum foam. It can be shown that aluminum foam was capable of absorbing energy due to its porosity.

Fig. (14)and Fig (15) show maximum displacement versus air gap thicknesses when considering protection layer of aluminum foam having various thicknesses (100, 150, and 200) under the effect of 10 and 15 Kg TNT explosive charge respectively. It can be seen from these Figures that increasing the thickness of air gap decreases the positive displacement significantly. In case of subjecting Panel (A) to 10 Kg TNT explosion charge, it was found that 150 mm air gap thickness is the best thickness used for 100 mm aluminum foam panel to maintain the RC panel A within its elastic deflection. In case of using protection layers of 150 or 200 mm aluminum foam, the air gap thickness of 100 mm is suitable to maintain the RC panel A within its elastic deflection limit. While under the effect of 15 Kg TNT explosion,Itwas found that 200 mm air gap thickness is the best thickness used for 100 mm aluminum foam panel to maintain the RC panel A within its elastic deflection. In case of using protection layers of 150 or 200 mm aluminum foam, the air gap thickness of 150 mm is suitable to maintain the RC panel A within its elastic deflection limit.

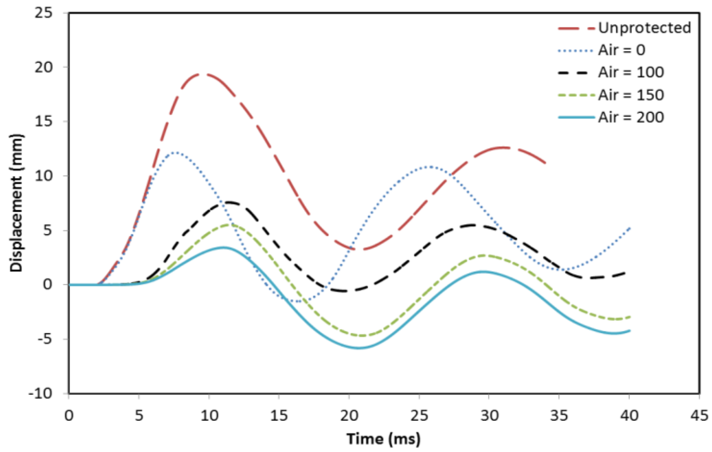


Fig. (5) Displacement-time histories of RC panel A protected by aluminum foam panel of 100 mm thickness considering different air gap thicknesses (scaled distance = 1.86)

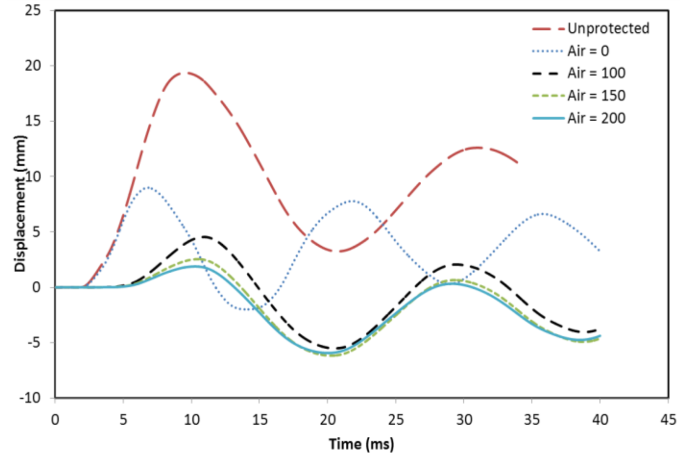


Fig. (6) Displacement-time histories of RC panel A protected by aluminum foam panel of 150 mm thickness considering different air gap thicknesses (scaled distance = 1.86)

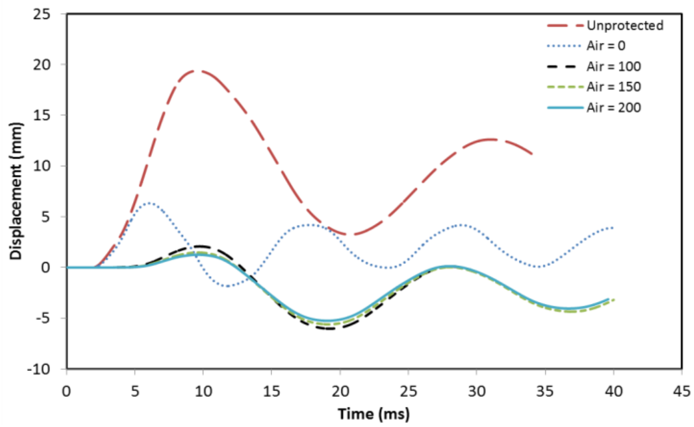


Fig. (7) Displacement-time histories of RC panel A protected by aluminum foam panel of 200 mm thickness considering different air gap thicknesses (scaled distance = 1.86)

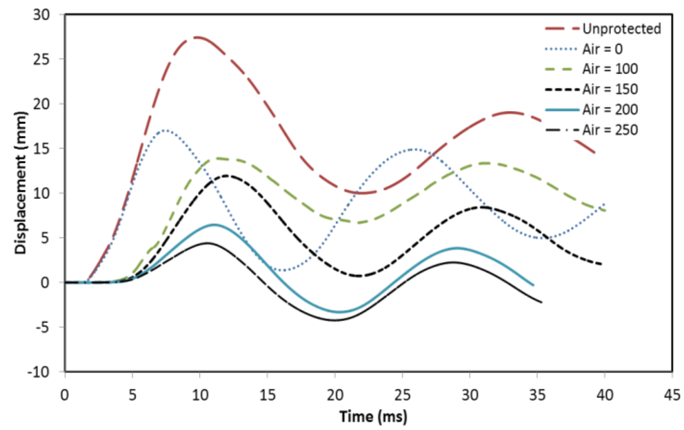


Fig. (8) Displacement-time histories of RC panel A protected by aluminum foam panel of 100 mm thickness considering different air gap thickness (scaled distance = 1.62)

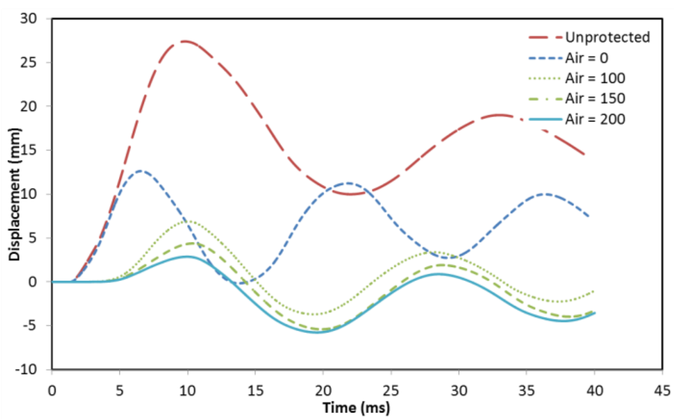


Fig. (9) Displacement-time histories of RC panel A protected by aluminum foam panel of 150 mm thickness considering different air gap thickness (scaled distance = 1.62)

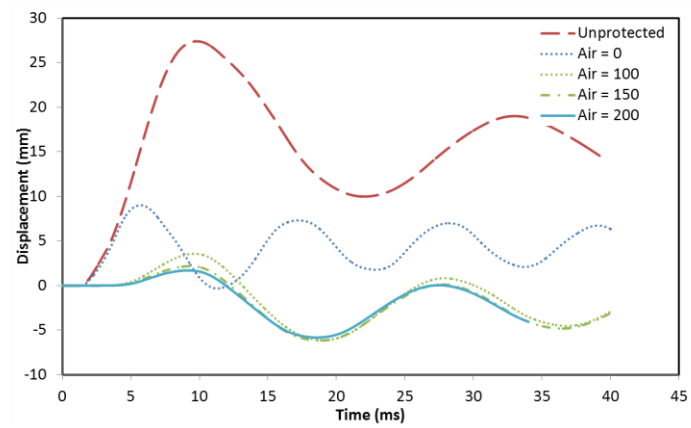


Fig. (10) Displacement-time histories of RC panel A protected by aluminum foam panel of 200 mm thickness considering different air gap thickness (scaled distance = 1.62)

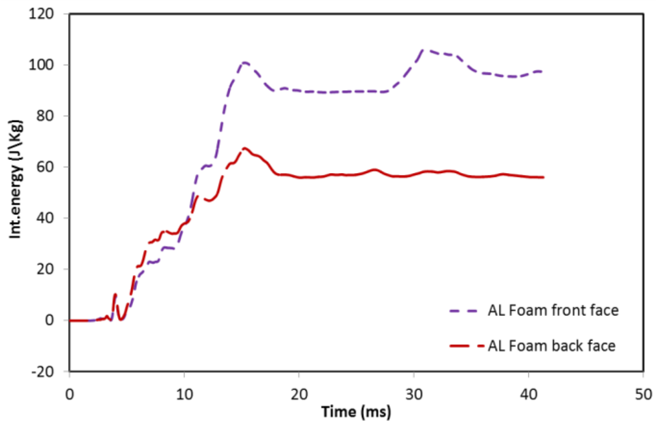


Fig. (11) Internal energy at the front and back faces of 100 mm aluminum foam (scaled distance = 1.86)

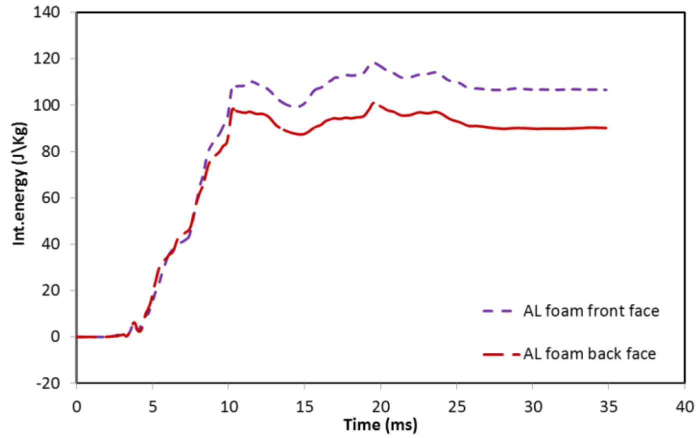


Fig. (12) Internal energy at the front and back face of 150 mm aluminum foam (scaled distance = 1.86)

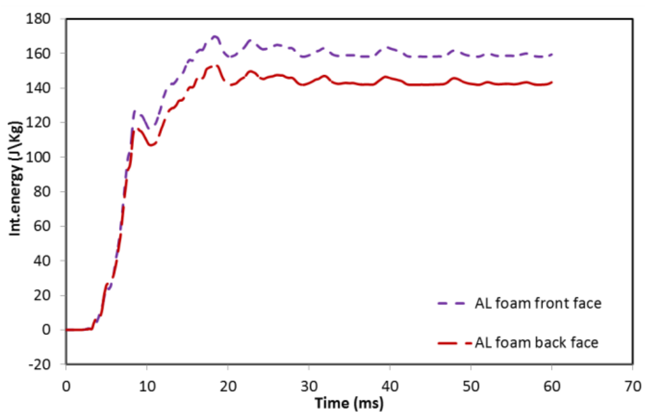


Fig. (13) Internal energy at the front and back face of 200 mm aluminum foam (scaled distance = 1.86)

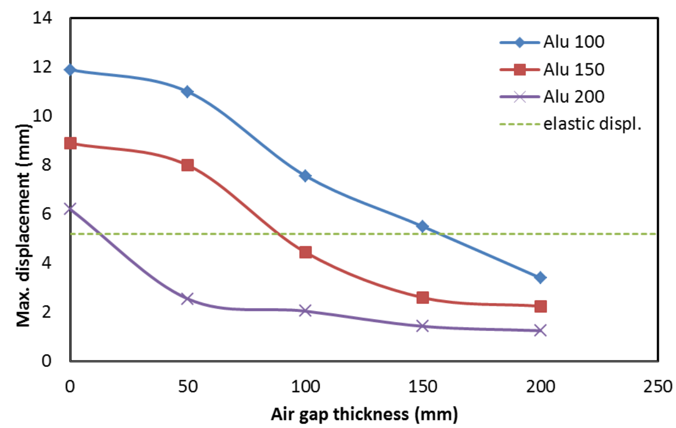


Fig. (14) Maximum displacement of panel A versus air gap thickness (scaled distance = 1.86)

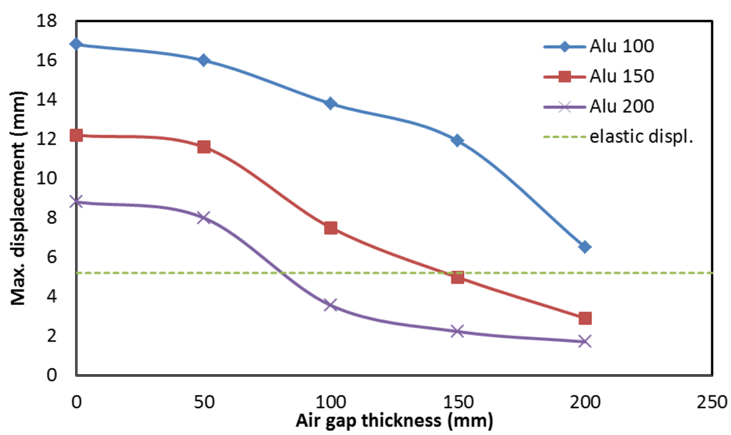


Fig. (15) Maximum displacement of panel A versus air gap size (scaled distance = 1.62)

(a) Air gap 0 *(b) Air gap 100* *(c) Air gap 200*

Fig. (16) Damage patterns for Panel A protected with AL 150 mm subjected to 15 Kg TNT

The effect of existing an air gap between the protective layer (i.e. aluminum foam 150 mm) and the concrete panel A is illustrated in figure (16). This figure shows a comparison between damage patterns of panel B protected with 150 mm aluminum foam layer thickness having various air gap thicknesses and subjected to 15 Kg TNT explosive charge. It can be noticed from the damage patterns figures, that there is no damage occurred and the cracks are minimized and located at the lower and upper edges after adding an air gap between the protective layer and the concrete panel.

Dynamic response of RC panel B

The dynamic response of RC panel (B) protected with aluminum foam is investigated when having air gap between RC panel and the aluminum foam. Here, a parametric study is carried out. The parameters studied are the thickness of aluminum foam and thickness of air gap and TNT charge weight.

In the model a displacement gauge is assigned to capture the displacement-time history at the center of the reinforced concrete panel. In the current study for panel B, twenty four numerical simulations are carried out considering three aluminum foam panel thicknesses (100, 150 and 200 mm) and different thicknesses of air gap (0, 100, 150 and 200 mm). These models are subjected to different blast loads (10 and 15 kg TNT) at standoff distance of 4 meters.

Fig. (17), Fig. (18), and Fig. (19) illustrate the comparison between the displacement-time histories at the mid-span of RC panel (B)under the effect of 10 Kg TNT explosion when varying the thicknesses of air gap using aluminum foam panel (100, 150 and 200 mm) thick respectively.Similarly Fig. (20), Fig. (21), and Fig. (22) illustrate the comparison between the displacement-time historiesat the mid-span of RC panel (B)under the effect of 15 Kg TNT explosion at stand off distance 4 meters. In these figures, the displacement-time history of unprotected panel is included. From these figures, it can be noted that as the aluminum foam thickness increases, the displacement decreases at all times. It can be also concluded that using an air gap more than 200 mm has no effect on the response of the reinforced concrete panel. This conclusion is cleared from the result obtained when using 250 mm air gap that gives nearly the same response in case of the 200 mm air gap thickness.

Fig. (23)and Fig (24) show maximum displacement versus air gap thicknesses when considering protection layer of aluminum foam having various thicknesses (100, 150, and 200) under the effect of 10 and 15 Kg TNT explosive charge respectively. It can be seen from these Figures that increasing the thickness of air gap decreases the positive displacement significantly. In case of subjecting Panel (B) to 10 Kg TNT explosion charge, It is found that 100 mm air gap thickness is the best thickness used for 100 mm aluminum foam panel to maintain the RC panel B within its elastic deflection. In case of using protection layers of 150 or 200 mm aluminum foam, the air gap thickness of 100 mm is suitable to maintain the RC panel B within its elastic deflection limit. While under the effect of 15 Kg TNT explosion,it is found that 200 mm air gap thickness is the best thickness used for 100 mm aluminum foam panel to maintain the RC panel B within its elastic deflection. In case of using protection layers of 150 or 200 mm aluminum foam, the air gap thickness of 150 mm is suitable to maintain the RC panel (B) within its elastic deflection limit.

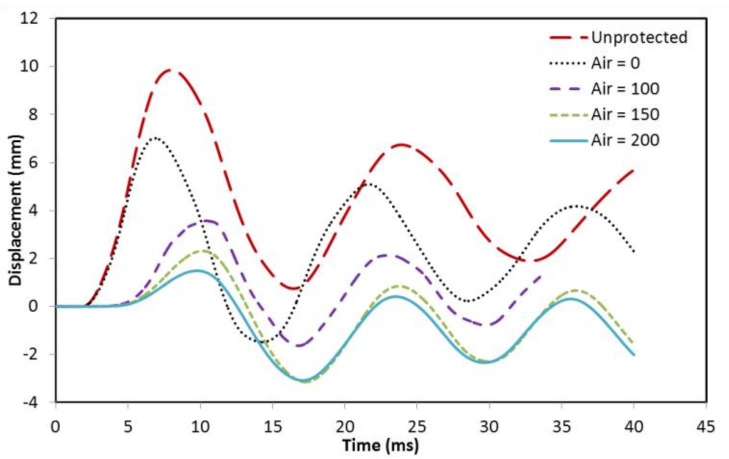


Fig. (17) Displacement-time histories of RC panel B protected by aluminum foam panel of 100 mm thickness considering different air gap thickness (scaled distance = 1.86)

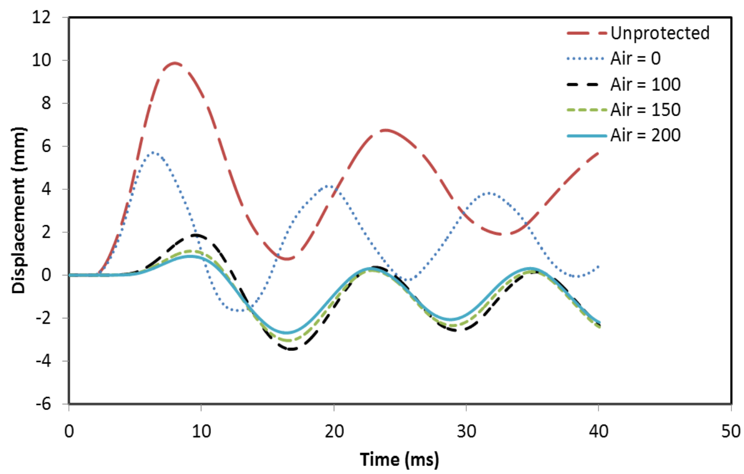


Fig. (18) Displacement-time histories of RC panel B protected by aluminum foam panel of 150 mm thickness considering different air gap thickness (scaled distance = 1.86)

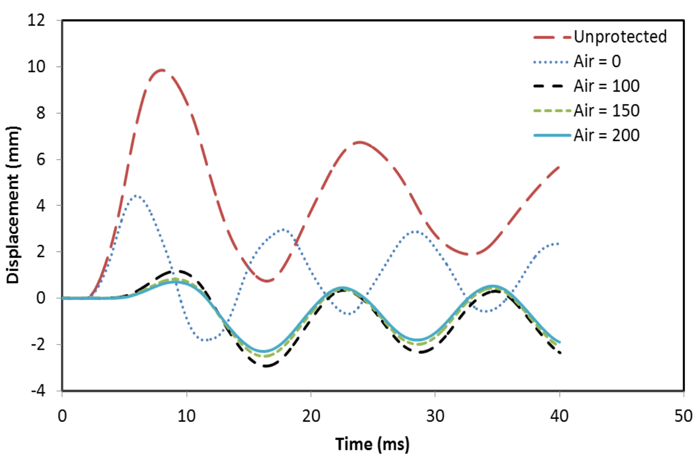


Fig. (19) Displacement-time histories of RC panel B protected by aluminum foam panel of 200 mm thickness considering different air gap thickness (scaled distance = 1.86)

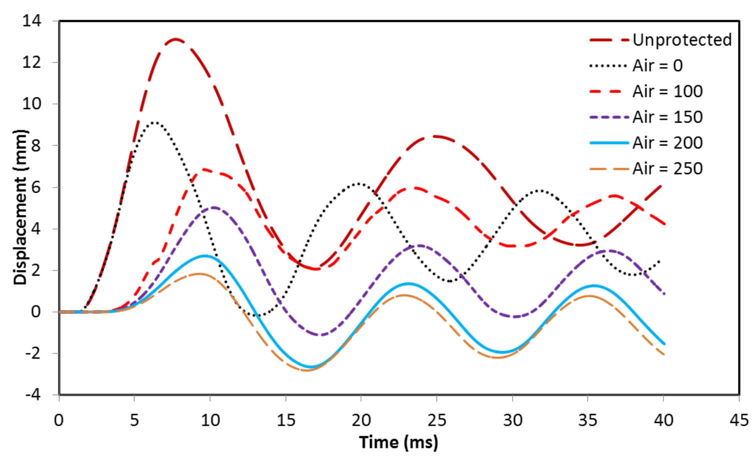


Fig. (20) Displacement-time histories of RC panel B protected by aluminum foam panel of 100 mm thickness considering different air gap thickness (scaled distance = 1.62)

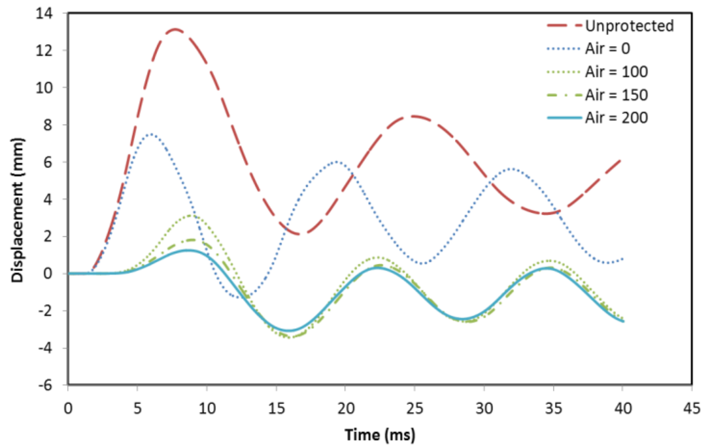


Fig. (21) Displacement-time histories of RC panel B protected by aluminum foam panel of 150 mm thickness considering different air gap thickness (scaled distance = 1.62)

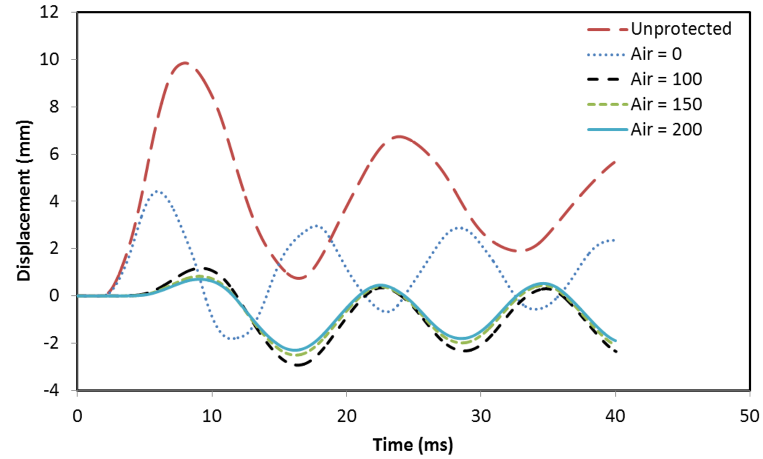


Fig. (22) Displacement-time histories of RC panel B protected by aluminum foam panel of 200 mm thickness considering different air gap thickness (scaled distance = 1.62)

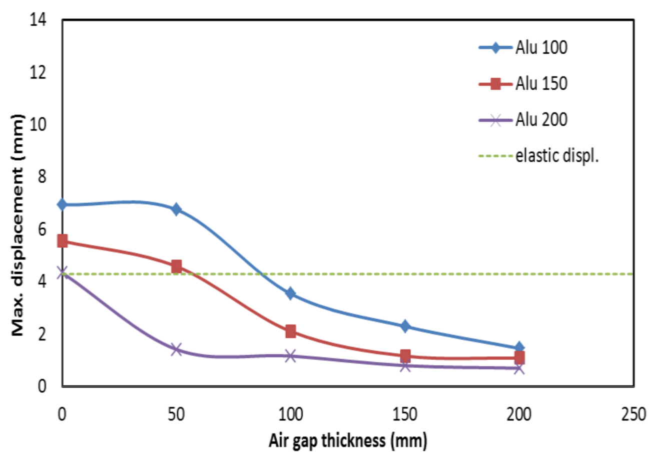


Fig. (23) Maximum displacement of panel B versus air gap thickness (scaled distance = 1.86)

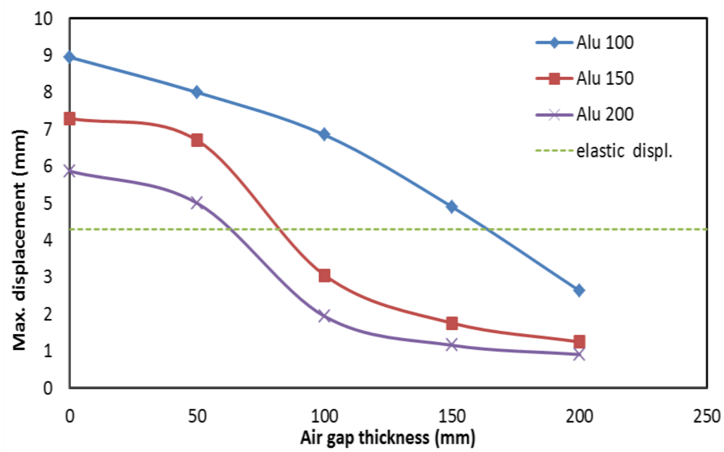
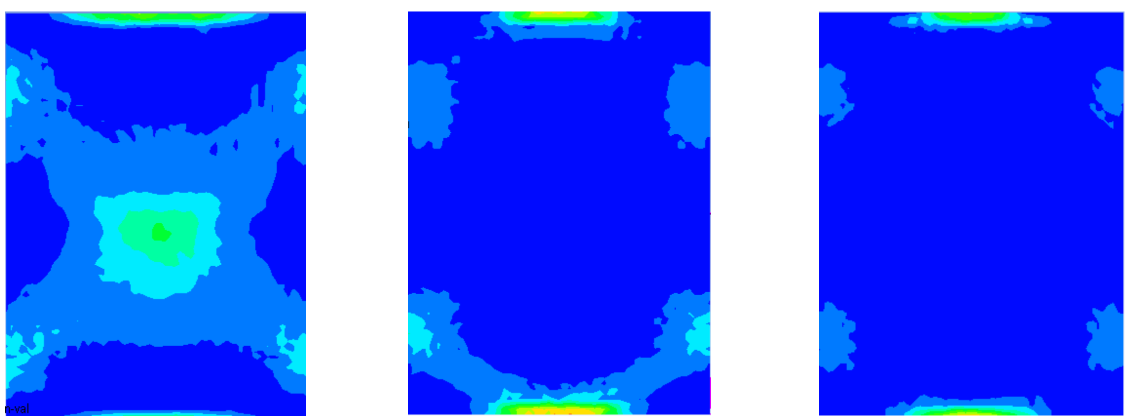


Fig. (24) Maximum displacement of panel B versus air gap thickness (scaled distance = 1.62)



(a) Air gap 0 *(b) Air gap 100* *(c) Air gap 200*

Fig. (25) Damage patterns for Panel B protected with AL 200 mm subjected to 15 Kg TNT

The effect of existing an air gap between the protective layer (i.e. aluminum foam 200 mm) and the concrete panel B is illustrated in figure (25). This figure shows a comparison between damage patterns of panel B protected with 200 mm aluminum foam layer thickness having various air gap thicknesses. It can be noticed from the damage patterns figures, that there is no damage occurred and the cracks are minimized and located at the lower and upper edges after adding an air gap between the protective layer and the concrete panel.

Discussion of Results

This paper presents a parametric study to investigate the effect of aluminum-concrete air gap on the response of reinforced concrete panels subjected to blast loading. The parameters studied are the thickness of aluminum foam, air gap clearance, the weight of explosive charge, and thickness of RC panel. From the obtaining results, it could be concluded that using air gap between aluminum foam and RC panel dramatically decreases the maximum displacement of RC slab by an average value of 60%. For all the cases studied, air gap clearance varied from 150 mm up to 200 mm can decrease the maximum displacement of RC panels to prevent any plastic deformation of the RC panel.

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