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Assessment of Blast Induced Damage in Concrete Walls of Urban Metro Stations Using the Finite Elements Method

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Abstract- Structural engineers are faced with many different challenges when designing structures, especially in important reinforced concrete buildings that could be subjected to blast loads. The response of structures due to explosions are controlled by some parameters, such as mass and standoff distance of charge, dimensions and direction of structure, adjacency to other buildings, and important properties of the land. A common lateral load resisting system that is particularly vulnerable to blast loads is the internal reinforced concrete shear wall in urban metro stations. This study investigated the dynamic behavior of the internal wall in a metro station in the effect of blast loading. To assess the progressive collapse of these structures, the damaged walls should be modeled in software. The modeling of damage walls is complicated; therefore, in this study, after analysis of the area of damage, an equal wall was proposed to substitute for the damaged wall.

Keywords: Blast, Shear Wall, Finite Elements, Metro Station

1. Introduction

The subway metro is heavily used in urban transportation; thus, the possibility of explosions in stations, caused by terrorist attacks, also increases with the development of the subway and other underground structures (Feng et.al, 2015, Dowding, 1996). In some cases, metro stations are connected to important structures by a directly enclosed hallway. Consequently, the analysis of these structures due to explosion loads has great significance. Engineers have design concerns for explosions in recent years. In the design of structures that are resistant to explosions, it is important to prevent progressive collapse (Drake and Little, 1983; Buonsanti and Leonardi, 2012; Razaqpur et.al, 2007).

Several experiments and simulations have been conducted in recent years on the consequences of explosive charge detonation in underground tunnels and structures. Also, the ISC (Interagency Security Committee) of the GSA (General Services Administration) recently outlined specific standards for all leased buildings, which will affect any existing building considered for lease by the GSA (Wheaton, 2005; Dept.of Defense, 2005; Gen.Ser.Admn, 2003). In most studies that investigate the dynamic behavior of walls due to a blast, only the flexural behavior of the wall was considered, and the effect of the shear failure mechanism was not observed. This causes differences between the analyzed and real responses (Bao and Kunnath, 2010; Orakcal et.al, 2004; Dick, 2012; Baker, 1973).

This study assessed blast-induced damage in reinforced concrete walls of an urban metro station. Four different charge weights of TNT were modeled at a standoff distance of 3.5 meters from the reinforced concrete wall. ANSYS AUTODYN (Autodyn, 2009) was used to model and simulate the behavior of models that is subjected to air blast loading. There are no studies concerning the determination damage ratio of walls in metro stations due to a blast. This paper presents a

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method to determine equivalent of damaged walls of buildings. An equal wall with an opening was proposed to substitute for the damaged walls for modeling in nonlinear software. For modeling, the openings for the damaged area in models, three damage zones (heavy damage, moderate damage, and light damage) were identified in the results. Each zone is characterized by the damaged area, defined as the difference in the cross-section before and after the blast. The results of this research can be used to assess the progressive collapse and to retrofit reinforced concrete wall structures.

The architectural design of subway metro stations is a significant factor to decrease the impact of significant circumstances, such as blasts, as well as fire, which may also be involved.

For this study, a station of an urban metro that contains some interior walls was selected. Fig.1 shows the plan of the selected station in the lower level. In this station, the passengers stand between two trains. The metro station structure was three stories high with shear walls located in, around, and inside the station. The general view of the station is shown in Fig. 2.

2. Structure modelling

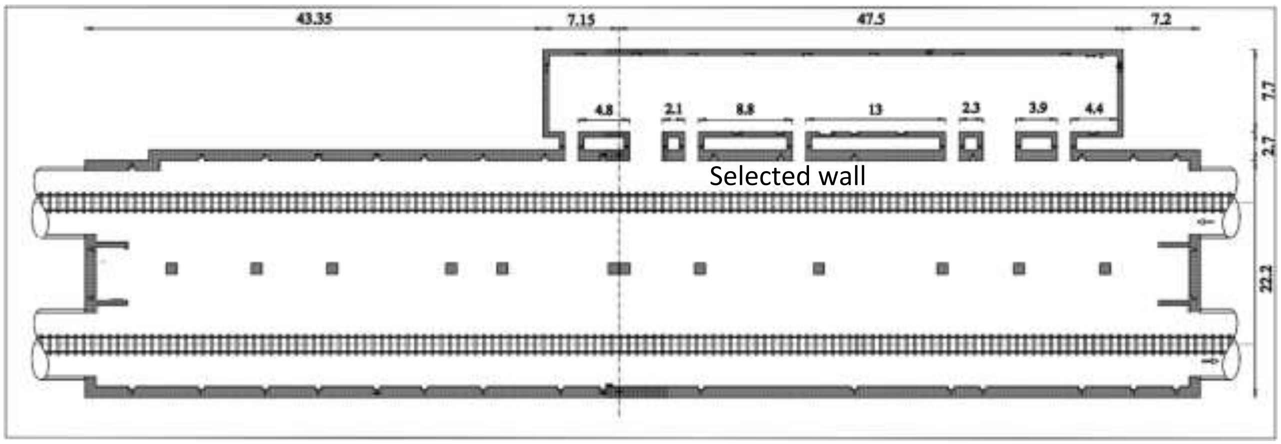

Fig.1. Plan of metro station

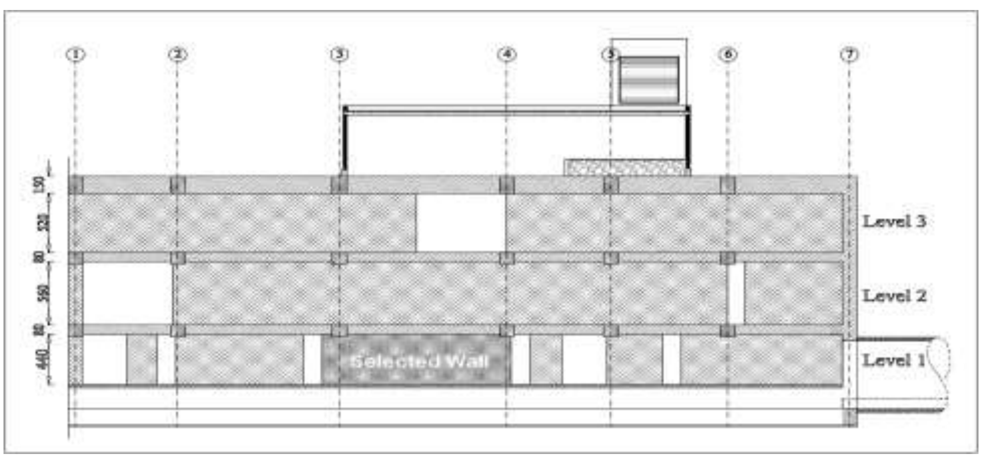

Fig.2. Elevation view of station

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According to Figs. 1 and 2 one of the internal walls was selected. The geometry and detail of the selected wall is shown in Fig 3.

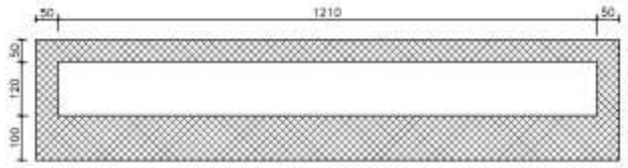

Figure 3. Geometry of selected wall

This wall has a box shape. The steel bars were a standard diameter 25 mm rebar with a nominal tensile strength of 60 ksi and a modulus of elasticity of 29,000 ksi. Each side of the wall contained two mats, and rebar was spaced at 25cm.
Autodyn is finite element software for analyzing non-linear systems including the resultant stresses emanated from explosive materials using the empirical Jones-Wilkins-Lee (JWL) equations. While reinforced concrete shear wall systems have been used to successfully resist the effects of lateral loads, such as earthquakes and the wind, the resistance to explosive loads has not been comprehensively examined. Shear walls are conventionally designed to resist lateral loads through in-plane action; however, blast forces typically generate out-of-plane loads. The large surface area of a wall provides an ideal area to capture blast pressures, resulting in a complex, dynamic structural response (Orakcal et.al, 2004; Mitelman and Elmo 2014).

A Lagrange sub-grid was used to model the reinforced concrete wall, while a Euler sub-grid solid element was used to model the air and the explosive. Material models are shown in Table 1.

Table 1. Material model used in the simulation

Material	Equation of State	Strength model	Density $g.cm^{-3}$	Shear Modulus kPa
Concrete 35Mpa	P-alpha	RHT	2.75	1.67e+7
Steel	Linear	Johnson Cook	7.9	8e+7

The equation for the RHT model that describes the behavior of concrete is shown in Eq. 1.

$$Y_{fail} = f_c(A\left(\frac{p}{fc} - \frac{PHTL}{fc}.\ F_{rate}\right)^N)R_3(\theta)F_{rate}(\varepsilon)\ (1)$$

Where: fc is the compressive strength; PHTL is the tensile strength; A and N are the constant value; P is hydrostatic pressure; F_{Rate} is the strain rate factor, and $R_3(\Theta)$ is the internal resistance force for the concrete.
The yield stress of steel reinforcement in the Johnson Cook material model, subjected to an explosion, is shown in Eq. 2.

$$\sigma_y = (A + B\varepsilon^n)(1 + C\ ln\frac{\varepsilon^p_{eq}}{\varepsilon_0})(1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m)\ (2)$$

Where: A, B, C are the constant value; T_m is the melting temperature of the material, and T_r is the reference temperature [11].

3. Impact Scenarios

An explosion is a very fast reaction that produces hot gasses; the hot gasses force the air around those gasses outwards, and these gasses are the outer most or top layer of the blast wave (Berg and Weerheijm 2006; Parisi, 2015). The outwards motion compresses the air that surrounds the gasses; the compressed air contains energy as a form of pressure from the explosion. As this explosion wave travels through the air, it decreases in energy as it travels further from the center of the explosion. According to Fig. 4, the momentum of the upper layer of gasses causes the air to over expand, causing the pressure to decrease below atmospheric conditions at the tail end of the blast wave (Jiang and Zhou, 2012; Lam and Mendis, 2004).

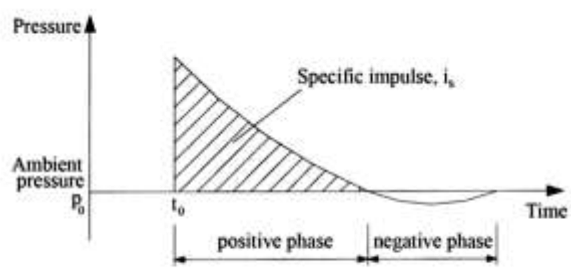

Fig. 4. Blast wave pressures

Drake and Little (1983) concluded that the pressure-time histories consist of a compressive pulse with a short rise

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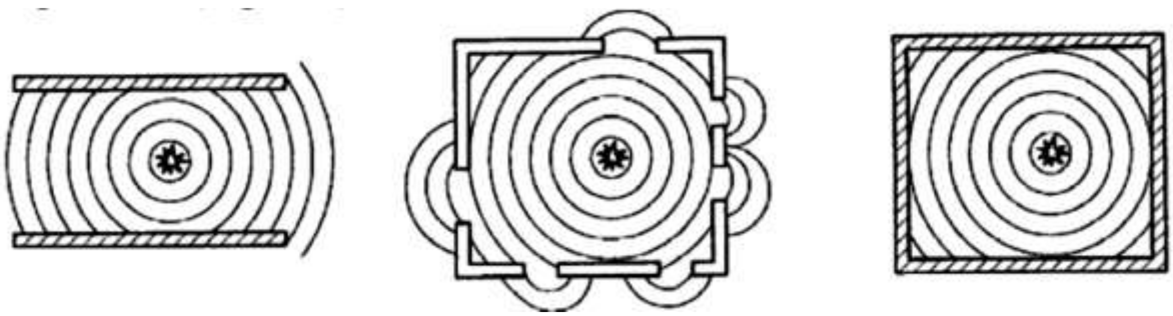
time followed by a negligible negative tensile pulse. The last major ingredient needed in the model is the blast action. Its load is defined by a pressure law that depends on time and position for each quantity of explosive. Defining the blast load is important to describe the damage from each blast and to predict how a panel will respond. Eq. 3 shows the normalized standoff distance.

$$Z = R / W^{\frac{1}{3}} \quad (3)$$

Where: Z is the normalized standoff distance, R is the standoff distance, and W is the weight of the TNT (Brode, 1955). This ratio normalizes the blast standoff distance to the weight of the charge (Tedesco et.al, 1987). According to Fig. 5, depending on the extent of venting, various types of confined explosions are possible (Ngo et. Al, 2007; Baker et al, 1983).



(a) (b) (c)

Fig.5. Various types of confined explosions a) Fully vented, b) Partially, vented c) Fully confined

The metro stations in the lower level are fully vented. The weight of the charge for this study was presented in the equivalent weight of TNT. The first steps of this study concluded that an explosion due to a less than 150 kg charge had no important effect on the damage of the selected wall. The minimum distance of the explosion to the selected wall is 3.5 meters, so four different charge weight of TNT was modeled at a standoff distance of 3.5 meters in front of the wall. The weight of the charge was modeled by 150, 200, 250, and 300 kg in Models 1 to 4.

In the modeling of the blast pressure, the TNT and air properties are based on the Autodyn material library and presented in Table 2. The equation of state for air is the ideal gas equation. The internal energy corresponding to the atmospheric pressure is assigned to the air material as an initial condition.

Table 2. TNT and air material properties

Material	Equation of State	Density g.cm^{-3}
TNT	JWL	1.63
Air	Ideal Gas	1.225

To model the expansion of explosive detonation of the charge, the JWL equation shown in Eq. 4 was used.

$$P = A\left(1 - \frac{w}{R_1 v}\right)e^{-R_1 v} + B\left(1 - \frac{w}{R_2 v}\right)e^{-R_2 v} + \frac{wE}{v} \quad (4)$$

Where: A, B, w, R_1 and R_2 are the empirically derived constants; v is the volume of the material at pressure divided by the initial volume of a unreacted explosive, and E is the internal specific energy (AUTODYN, 2009).

Kuhlmeyer and Lysmer (1973) concluded that in order to obtain acceptable results in dynamic simulations, the mesh size of the model should not be larger than one-eighth of the minimal wavelength. This criterion is used to select the mesh size for models. The hypothesis is also validated by performing a mesh sensitivity analysis, and results converged at a mesh size of 20 cm.

4. Analysis of models

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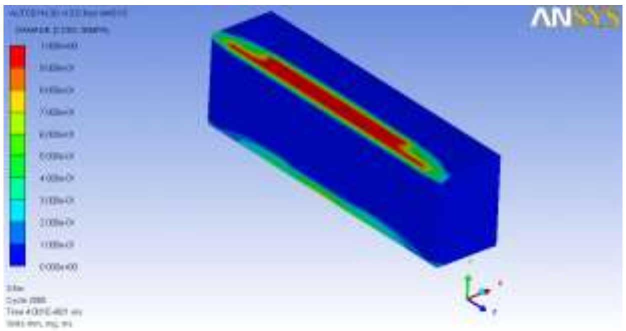
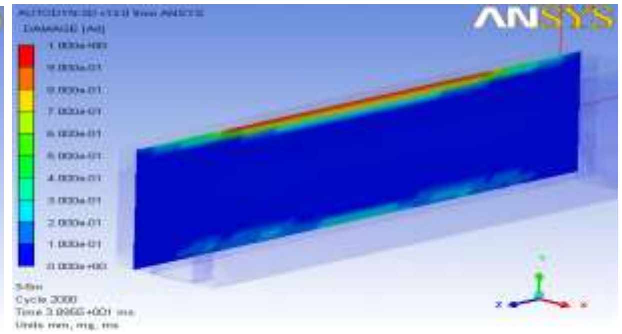
The damage ratios of each scenario in four models are shown in Figs. 6-9.



(a)



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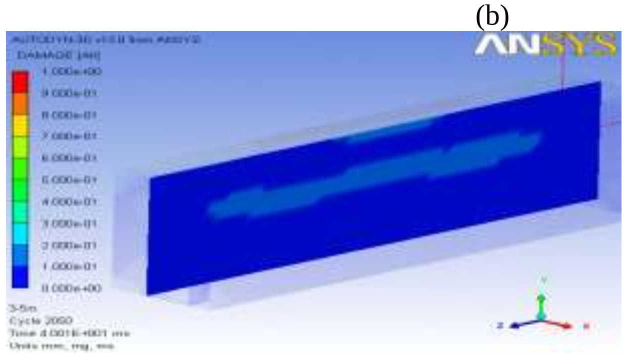
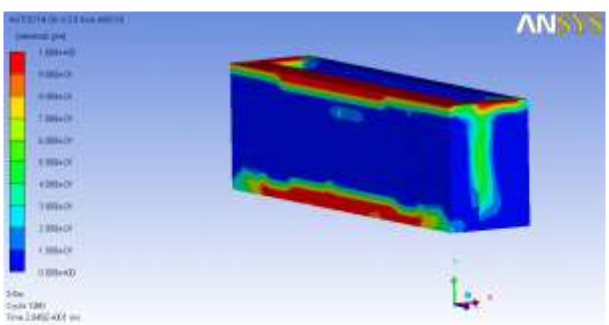
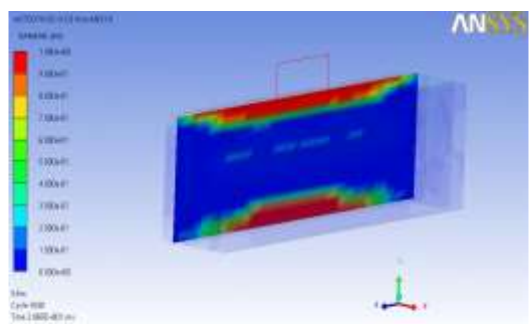


(C)

Fig. 6. Damage results of model 1 a) front, b) middle, and c) back



(a)



(b)

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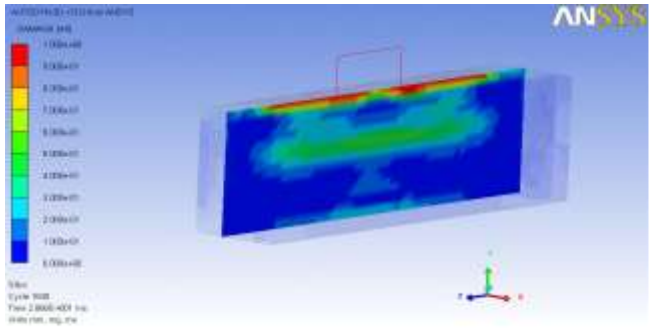
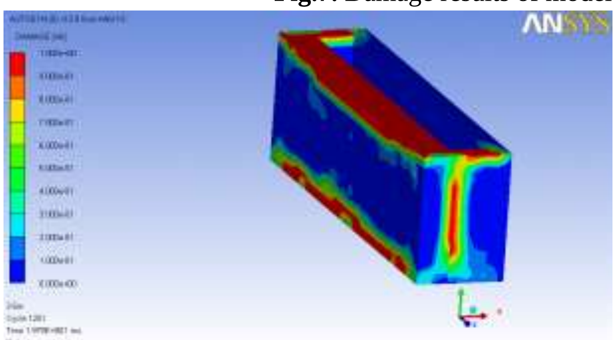
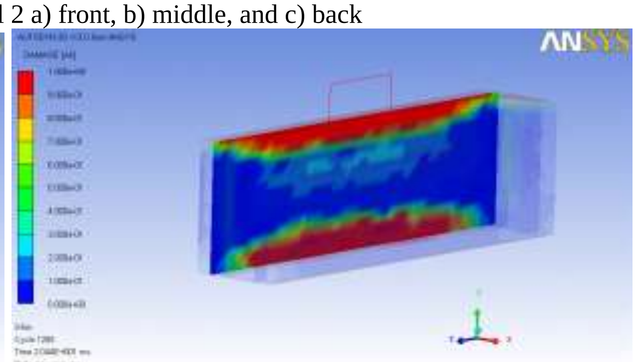


(c)

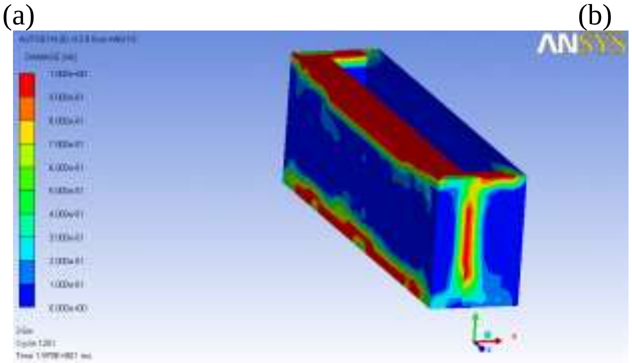
Fig.7. Damage results of model 2 a) front, b) middle, and c) back



(a)



(b)



(c)

Fig. 8. Damage results of model 3 a) front, b) middle, and c) back

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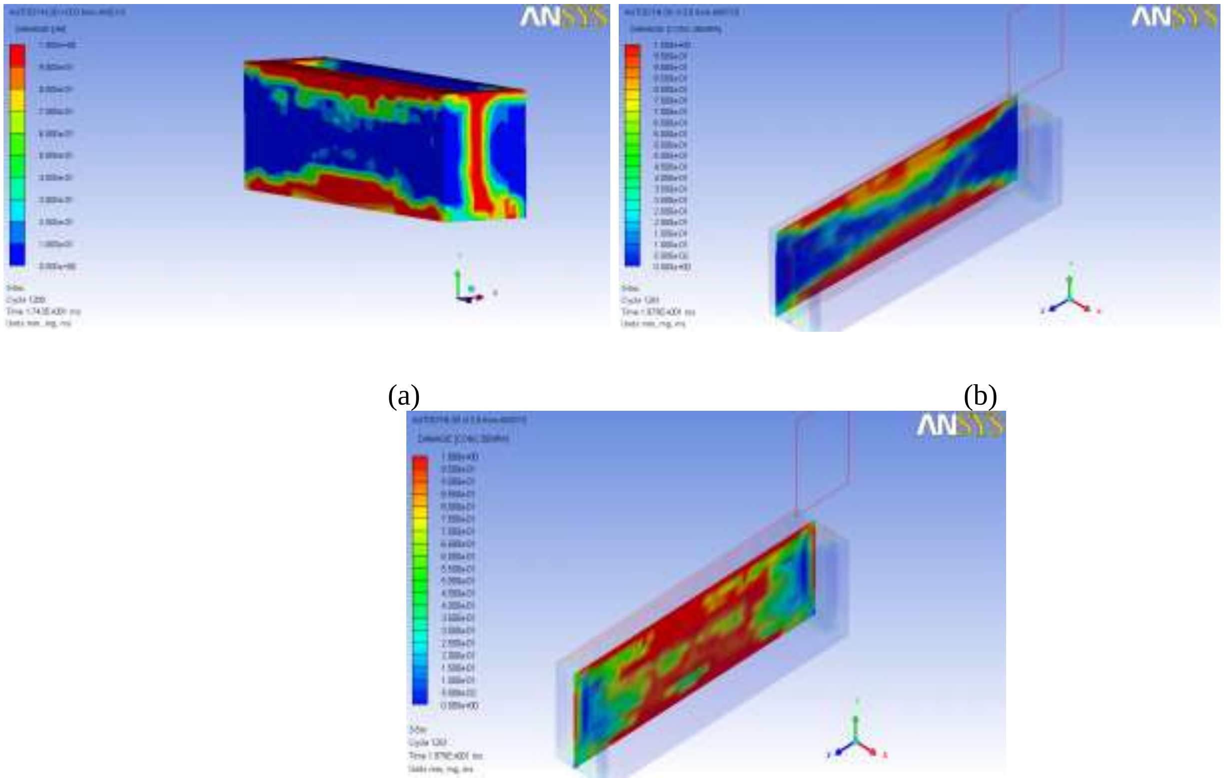

(a) (b)

(c)

Fig. 9. Damage results of model 4 a) front, b) middle, and c) back

One can conclude from the damage ratio of models that the applied blast pressure is greater on the top and bottom part of the wall and then decreases outwards from the ends. To model the openings for the damaged area in the models, three damage zones were identified in the results. The zones are categorized as follows:

(1) Zone 1: heavy damage (damage ratio more than 70%);

(2) Zone 2: moderate damage (damage ratio between 60% and 40%);

(3) Zone 3: light damage (damage ratio less than 30%).

Each zone is characterized by the damaged area, defined as the difference in cross-section before and after the blast. Table 3 shows the percentage of damage to the three sides of the walls (front, middle, and back) in each zone. Fig. 10 shows the damage ratio and scattering damages in each side of models. The modeling of damaged walls in design software is complicated. According to the damage ratio of the models, the equal wall presented in Figure 11.

Table 3. Damage ratio of the models

	Model 1			Model 2			Model 3			Model 4		
	Front	Middle	Back	Front	Middle	Back	Front	Middle	Back	Front	Middle	Back
Zone1	3.2	2.1	0.5	12.9	18	12	27.4	22	13.2	32	31	62
Zone2	11.2	6	2	13.3	13	35.4	16.2	10	39	23	24	27.7
Zone3	85.6	91.9	97.5	73.8	69	52.6	56.4	68	47.8	45	45	10.3

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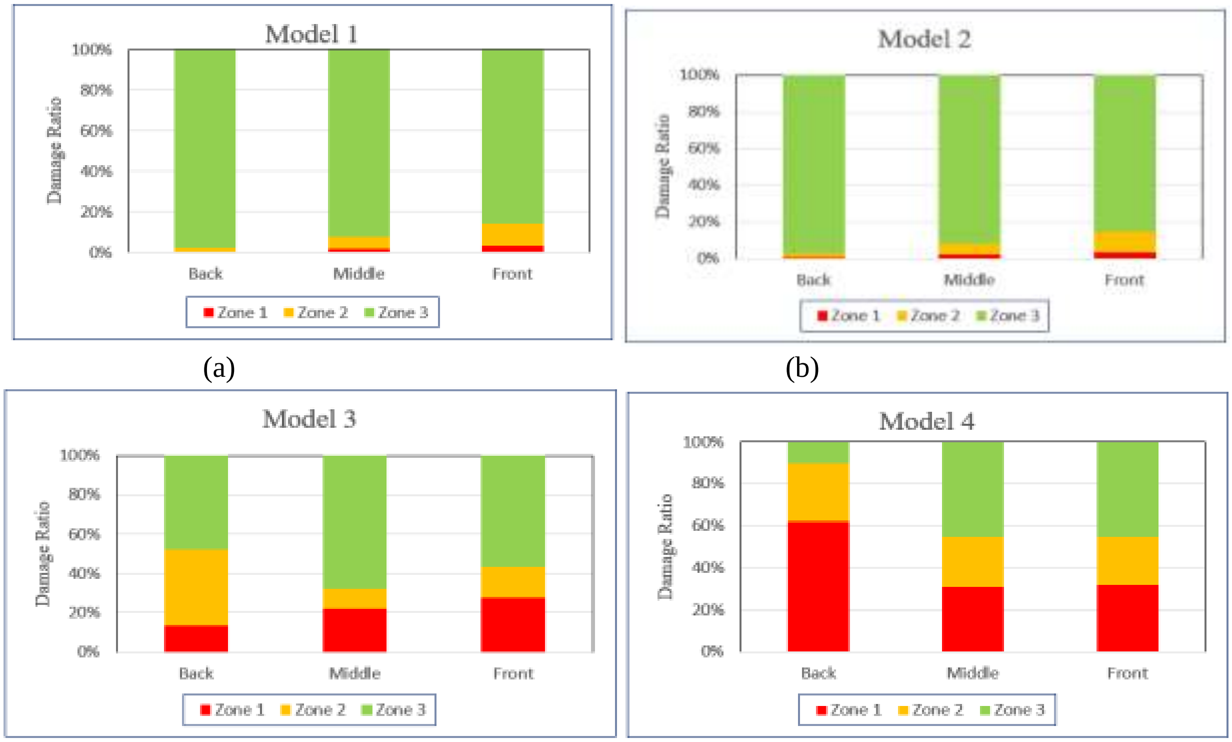
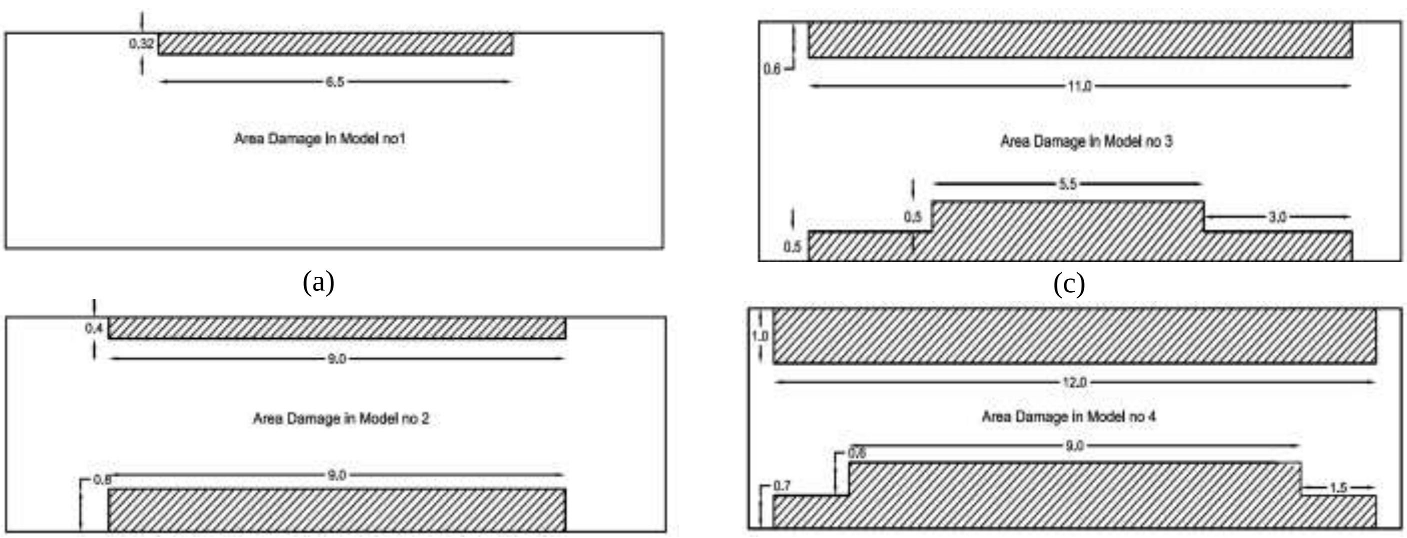


(a) (b)

(c) (d)

Fig. 10. Damage ratio of the models



(a) (c)

(b) (d)

Fig. 11. Equal wall proposed for damaged models a) model 1, b) model 2, c) model 3, and d) model 4

The nonlinear behavior of a structure can be assessed by modelling the proposed damaged wall in software such as SAP2000, OpenSEES, or Perform 3D.

5. Conclusions

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Traffic infrastructure in urbanized areas is increasingly projected in urban subway metro. This development has significant consequences for the risks associated with terrorist attacks. It is obvious that the inner shear walls in subway metro stations are important structural elements. The loss of each of the inner walls will cause failure in a large area of the slab. To improve the performance of such structures, there are some solutions, such as anchoring the floor to the comer wall, designing the slab in cantilever conditions, or retrofitting the shear wall. Therefore, before conducting any rehabilitation methods, one must assess how the wall will be damaged and what amount of failure is associated with a given blast. This study examined the shear wall system in a metro station. Consideration was given to develop an efficient method that can be replicated in practice to model the damaged walls.

In the current study, the blast was modeled inside the structure; in another study, the behavior of the roof could be assessed by an external explosion. For future research, the shape of the wall can be changed, and more studies can concentrate on steel shear walls.

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