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NUMERICAL INVESTIGATION OF REINFORCED CONCRETE BARRIERS SUBJECTED TO BLAST LOADING

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ABSTRACT

People's lives are threatened by explosions; the tragic terrorist attacks have forced the governments to consider the importance of dealing with these attacks. With the rising threat of terrorism, protecting critical civil infrastructure such as embassies, governmental buildings, and airports against bomb attacks has become a critical issue. In the current research, reinforced concrete barriers subjected to blast loading are numerically investigated using Applied Element Method "AEM". The blast loads adopts the ASCE guidance for design of blast-resistant buildings in petrochemical facilities. Fully nonlinear dynamic analysis was considered where the barriers thickness and reinforcement, end connections were parametrically investigated. It was found that the thickness and reinforcement of the barriers affect the barriers' response, where the most significant parameter was the wall thickness.
Keywords: blast loads, applied element method, reinforced concrete barriers.

1. INTRODUCTION

1.1 Background

The importance of taking blast loads effects on buildings into consideration has been increased greatly in the last few decades. Several blast hazards have occurred in the last few years. In April 1983 the United States embassy in Beirut, Lebanon was subjected to a car bombing attack, which killed 63 people. Murrah federal building was bombed in Oklahoma in April 1995, killing 168 people and injuring about 680 people. Bombing of the Khubar towers in Saudi Arabia in June 1996 lead to killing 19 people and injured about 372 people (Rigby, 2014). Eventually, the total collapse of the World Trade Centre (WTC) towers in New York City has raised the importance of the priority of protection of infrastructure against blast hazards.

1.2 Characteristics of the blast wave and its relation with load parameters

The principal parameters of the blast wave that define the blast loading for a building's components are: (1) Peak side-on positive overpressure, P, (2) Positive phase duration, t_d and (3) Positive impulse, I. Any blast is defined by charge weight of the blast (W) based on TNT equivalence (the amount of trinitrotoluene which will produce similar effects as the actual explosive material under consideration), the radial distance from the epicenter of the explosive to a particular location on the structure (R) and the scaled distance parameter (Z). To simplify the blast resistant design procedure, the generalized blast wave profiles are usually idealized, or linearized, as illustrated in Figure 1 for a shock wave and pressure wave.

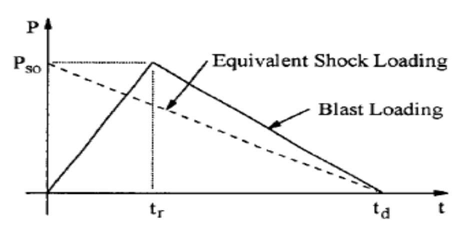


Figure 1: Idealized Blast Load (ASCE, 1997)

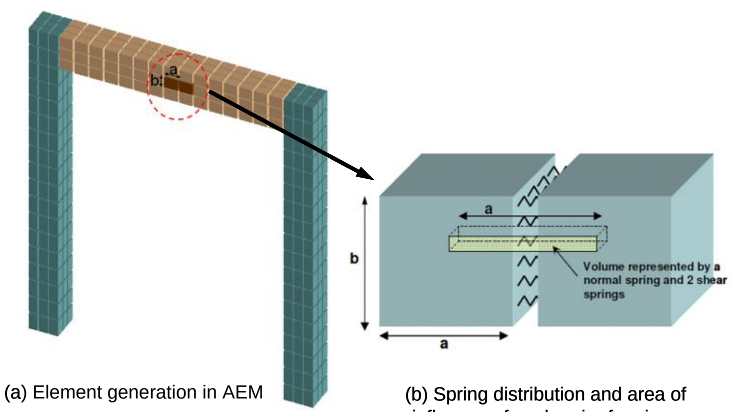
2. APPLIED ELEMENT METHOD

2.1 Overview

In the Applied Element Method "AEM", the structure is modeled as an assembly of relatively small 3D elements. The elements are connected together along their surfaces through a set of normal and shear springs. Each single element has six degrees of freedom: three for translations and three for rotations. The springs are responsible for transfer of normal and shear stresses among adjacent elements. Each spring represents stresses and deformations of a certain volume of the material as shown in Figure 2. Each two adjacent elements can be completely separated once the springs connecting them are ruptured. AEM is capable of predicting the discrete behavior of the structures to a high degree of accuracy.

Fully nonlinear path-dependant constitutive models are adopted in the AEM. For concrete in compression, elasto-plastic and fracture model is adopted (Maekawa and Okamura, 1983). When concrete is subjected to tension, linear stress-strain relationship is adopted until cracking, where the stresses drop to zero. Since the method adopts discrete crack approach, the reinforcing bars are modeled as bare bars for the envelope (Okamura and Maekawa, 1991) while the model of Ristic *et al.* (1986) is used for the interior loops.

The AEM was proven to be capable of following the deformations of a structure subjected to extreme loads to its total collapse. Therefore, and since the goal of the current study is to investigate the behavior of reinforced concrete structures under severe loads resulting from tsunami action, it was decided that the AEM is the most appropriate numerical tool for such investigation. Although the Finite Element Method (FEM) is a robust and well established structural analysis method, it is not the optimum solution for the scope of progressive collapse analysis. Many drawbacks are associated with the FEM progressive collapse analysis. The elements damage, separation, falling and collision with other elements are very difficult. Hartmann et al. (2008) showed that the computations associated with the simulation of collapses of real world structures based on conventional FEM are very costly, and therefore followed another approach based on multibody models.



(a) Element generation in AEM

(b) Spring distribution and area of influence of each pair of springs

Figure 2: Modeling of structure using AEM

2.2 Software used in progressive collapse analysis

The Extreme Loading for Structures (ELS®), which was developed using the theory of Applied Element Method (AEM), will be used in this study. The ELS is a sophisticated software package that is capable of analyzing the structure to its total collapse (Tagel-Din and Meguro, 2000, Meguro and Tagel-Din, 2001, Tagel-Din, 2002, Meguro and Tagel-Din, 2003, Sasani and Asgitoglu, 2008, Salem et al., 2011, Park et al., 2009, Helmy et al., 2009, Helmy et al., 2012, Sasani, 2008, Wibowo, 2009, Salem 2011, Salem and Helmy, 2014, Salem et al., 2014).

3. ASCE REPORT 1997 SOLVED EXAMPLE

The American report "Design of Blast Resistant Buildings in Petrochemical Facilities." solved an example –in chapter 11- studying the behavior of structural members under the effect of a desired blast load. In this section, the example of the report is modeled using ELS program and the results of the ELS model is compared to the report results.

The structure of the example in the report is made of cast –in- situ concrete walls of a span 20.12m*28.04m. The vertical loads are resisted by a structural steel frame and the blast load is resisted by concrete walls of 25 cm thickness, Figure 3 shows the cross section of the reinforced concrete wall.

The yield strength of the structural steel used is 248 N/mm^2, the reinforcing steel yield strength is 414 N/mm^2 and the characteristic strength of concrete used is 27.6 N/mm^2.

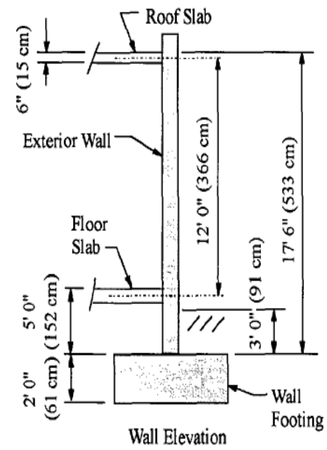


Figure 3: Reinforced concrete wall cross section

The reflected overpressure P_r = 0.095 N/mm^2, effective duration t_e = 0.042 sec, the reflected overpressure versus time is shown in Figure 4:

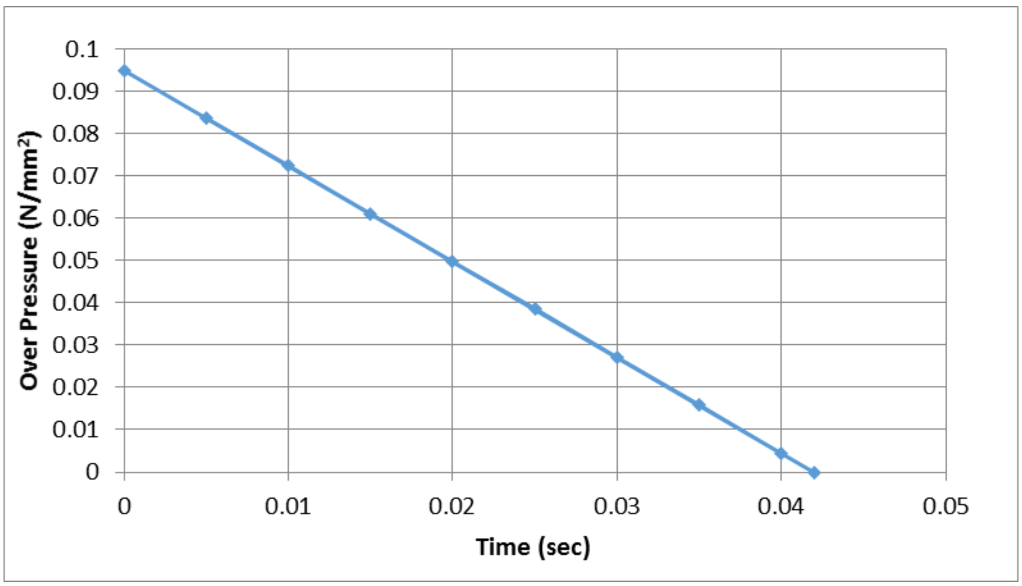


Figure 4: Reflected overpressure VS effective duration

The thickness of the walls is 25 cm and the reinforcement is 7φ16/m, the steel columns are W10x45, girders W21x111 and beams W14x38, the roof slab and slab on grade thickness is 15cm and the slabs reinforcement is 6φ12/m.

The structure is analyzed in the report example using SDOF method. The maximum deformation of the wall is 2.27 cm, and the rotation of the wall is 0.71^o, the results show that the behavior of the wall is considered as a low response range (less than 2^o).

4. MESH SENSITIVITY ANALYSIS

The same example of the report is modeled using ELS program. Mesh sensitivity analysis is conducted to optimize the solution time with a good accuracy. Four models with different mesh sizes are used to model the front barrier as shown in Table 1.

Table 1 Mesh distribution for the front wall

Model number	Wall mesh in x direction	Wall mesh in y direction	Wall mesh in z direction	Number of elements
1	11	2	36	792
2	23	2	36	1656
3	47	3	36	5076
4	61	3	36	6588

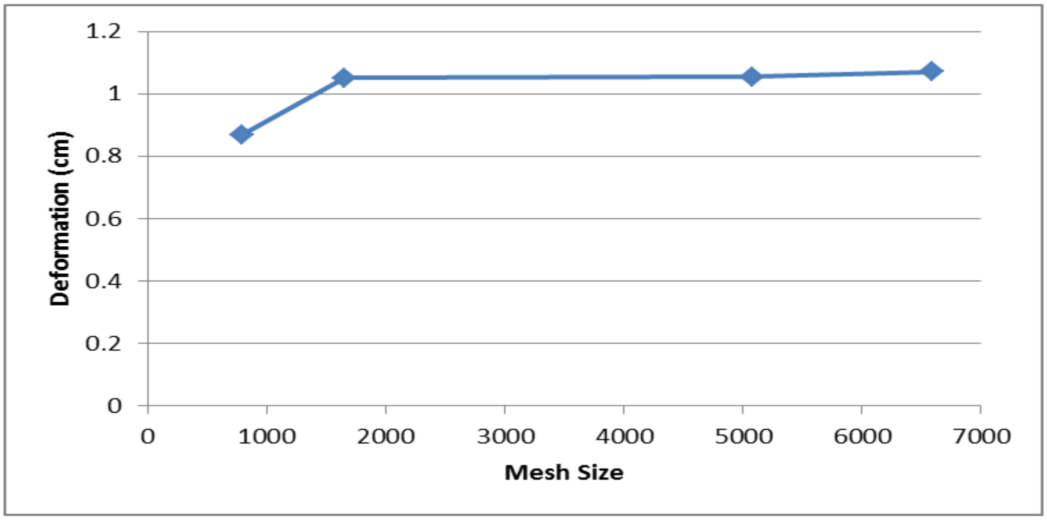


Figure 5: mesh sensitivity analysis for the front wall

Based on the deformations obtained for the 4 models as shown in Figure 5, the model number "2" is used in the current study. It's obvious that the deformation obtained from the ELS analysis is much less than the SDOF method adopted by the report (1.09 cm vs 2.27 cm). This is attributed to the fact that the ELS model uses the integrity of the whole structure in resisting the blast pressure. Figure 6 shows the modeling of all structural members using ELS.

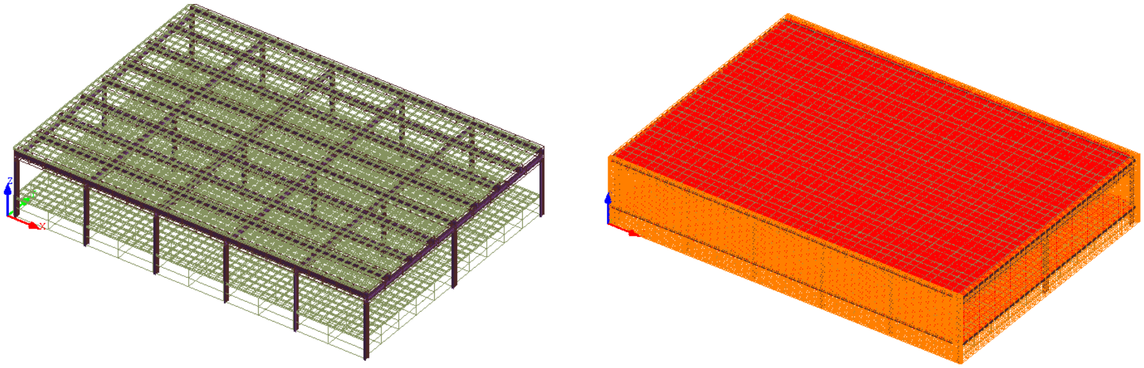


Figure 6: ELS model for the steel structure, the top slab, slab on grade and the barriers

Since the current study is focusing mainly on the behavior of the front wall, and to reduce the time of computations, a small model is considered, in which only the front wall in addition to one meter of the side walls, top slab and slab on grade are modeled. The results of the small model are compared to the full model representing and mesh sensitivity analysis is applied as shown in Figure 7.

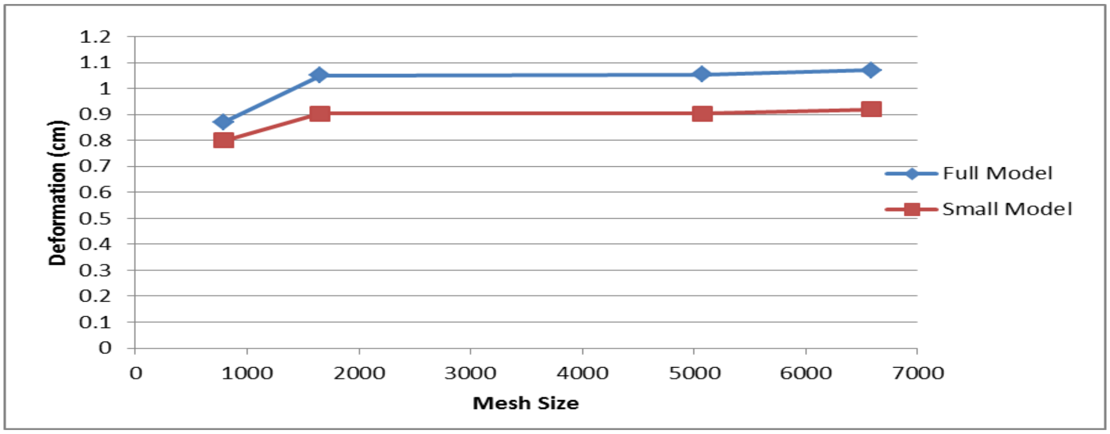


Figure 7: Comparison between small and full barrier models

Since the difference between the maximum deformation for the small model compared to the full barrier model is 3.6%, it is acceptable to study the behaviour of the front wall based on the small model analysis.

5. PARAMETRIC STUDY

The parameters of this case study are the properties of the wall are the wall thickness and reinforcement as well as the connection details. The thicknesses studied are 15, 20, 25 and 30 cm, the reinforcements of the wall are set to be 7φ12/m and 7φ16/m. the connection between the barrier and the slabs is considered in the parametric study. Five different reinforcement details are analyzed for each parameter as shown in the Figure 8 and Table 2.

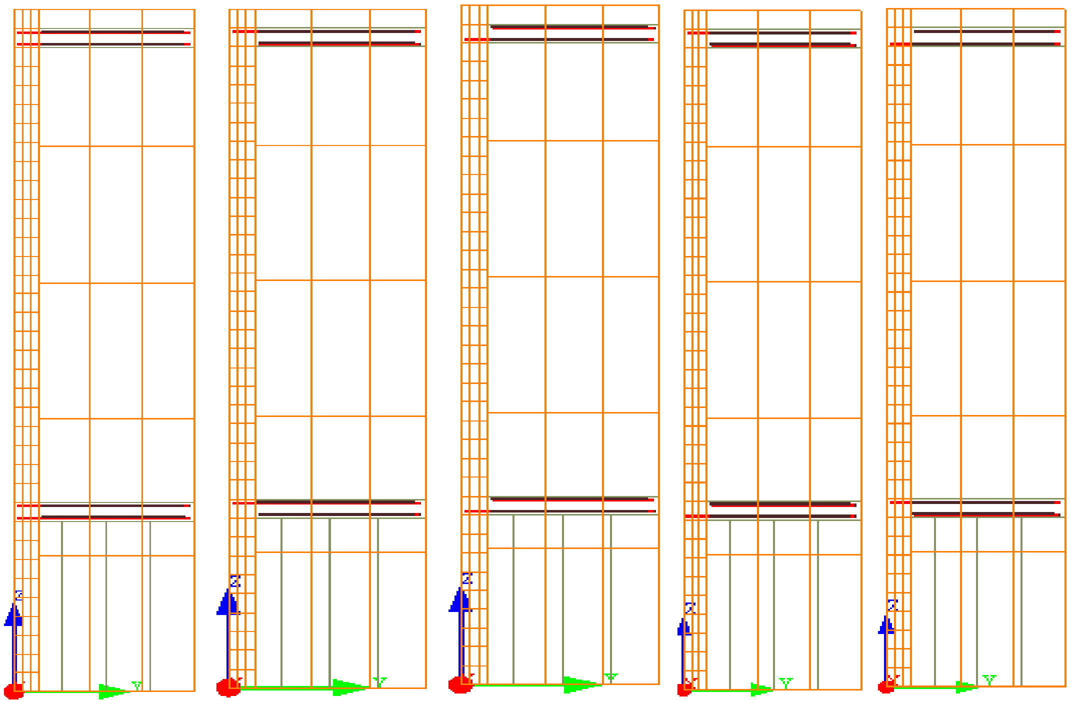


Figure 8: Reinforcement extension from slabs to wall

The description of the five cases is summarized in the following table:

Table 2: Description of slabs reinforcement extension to the front wall

Case	Description	Abbreviation
A	Both of bottom and top reinforcement of top slab and slab on grade are extended to the front wall	XX
B	Top reinforcement only of both of top slab and slab on grade is extended to the front wall while the bottom reinforcement is not extended	XS
C	Bottom reinforcement only of both of top slab and slab on grade is extended while the top reinforcement is not extended	SX
D	Top reinforcement of the top slab and bottom reinforcement of the slab on grade extends to the front wall while the bottom reinforcement of the top slab and the top reinforcement of the slab on grade is not extended.	H
E	Bottom reinforcement of the top slab and top reinforcement of the slab on grade extends to the front wall while the top reinforcement of the top slab and the bottom reinforcement of the slab on grade is not extended.	F

5.1 Thickness

The thickness parameter is studied by changing its value from the report example which is 25cm to 15cm, 20cm and 30cm.The reinforcement of the wall is assumed to be 7φ16/m, the characteristic strength of the concrete used is 25N/mm^2 and the density of concrete is 25 KN/m^3. Five different reinforcement details are used for each thickness.

5.2 Reinforcement of the wall parameter

The reinforcement of the wall parameter is studied by changing its value from the report example which is7φ16/m to 7φ12/m. The concrete specific weight is 25 KN/m^3, the thickness of the wall is 25cm and concrete characteristic strength is 25 N/mm^2. Five different reinforcement details are used for each thickness.

6. ANALYSIS AND DISCUSSION OF RESULTS

6.1 Effect of wall thickness

As mentioned above, the thickness effect is studied by changing its value from the report example (which is 25cm) to 15cm, 20cm and 30cm.

Except the extension of the slabs reinforcement to the wall which is shown in Fig. 16, the other parameters are assumed to be constant; the reinforcement of the wall is assumed 7φ16/m, the characteristic strength of the concrete used is 25 N/mm^2 and the density of concrete is 25KN/m^3.

The maximum allowed deformation of the wall can be calculated as 6.385 cm as indicated in the ASCE report. The effect of changing the wall thickness on the maximum deformation of the wall compared with the allowed deformation is shown in Figure 9. It can be concluded that the wall thickness is so effective on the maximum deformation occurs during the time studied (1.2 seconds).

The end conditions of the barriers have no significant effect on the barrier deformation. When the barrier thickness is 15 cm, the fixed end condition gives a 14 % higher deformation value than the hinged end condition. While at thickness equals 30 cm, the difference is almost 0.3%.

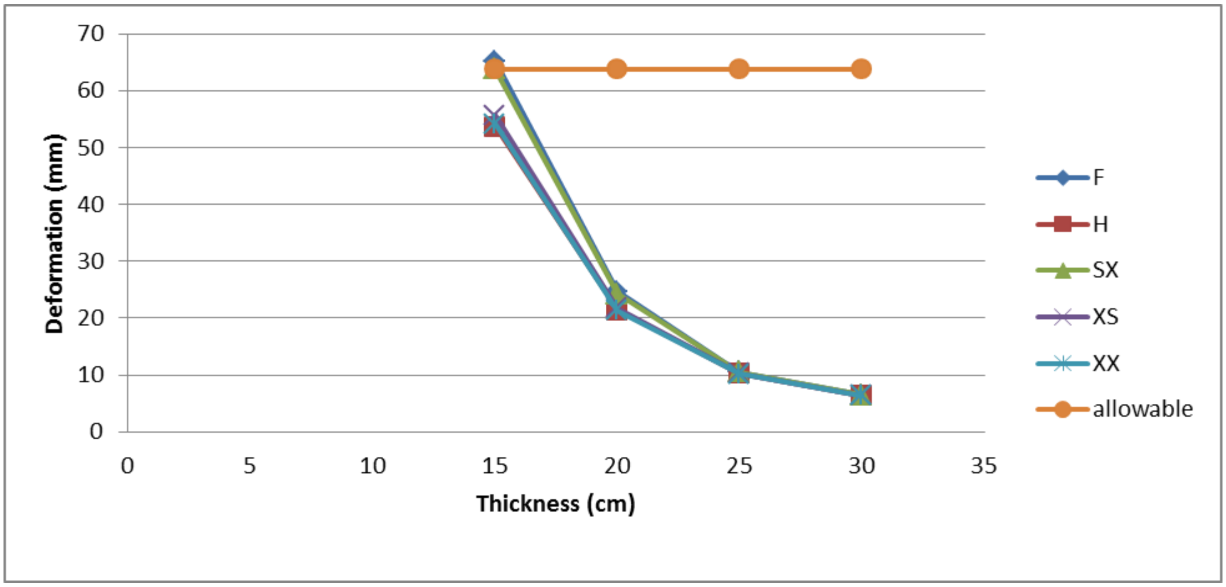


Figure 9: Maximum deformation of the wall versus wall thickness

6.2 Effect of wall reinforcement

The effect of changing the reinforcement of the wall on the maximum deformation of the wall is shown in Figure 10. The maximum deformations obtained are safe to a very far extent (i.e. the maximum deformation among all the models is 1.92 cm and the allowed deformation is 6.385 cm). It can be concluded that the effect of the reinforcement of the wall on the maximum deformation is significant.

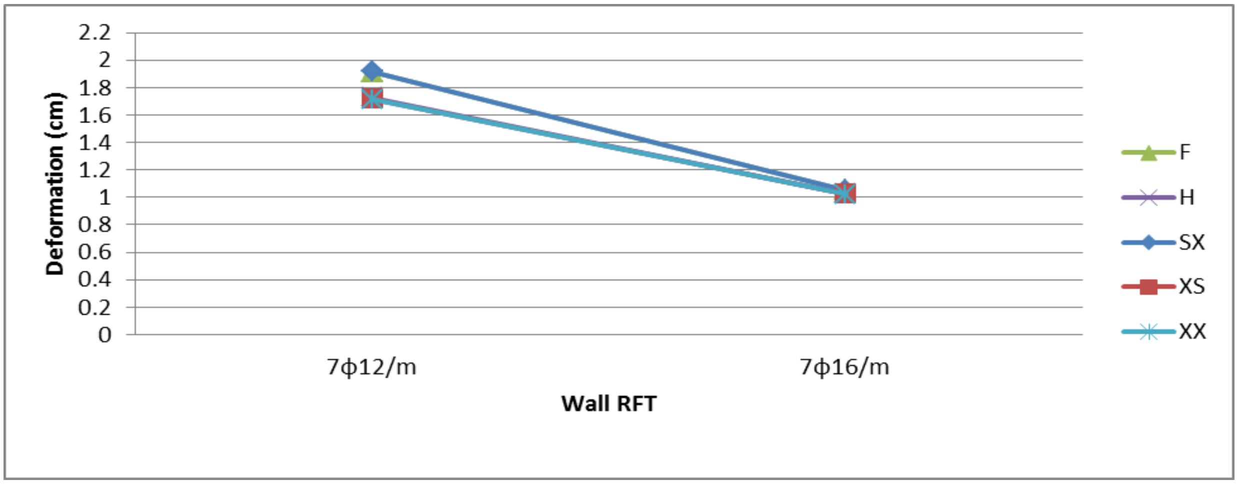


Figure 10: Maximum deformation of the wall versus wall reinforcement

6.3 Effect of end conditions

The end conditions of the barriers have no significant effect on the barrier deformation. When the barrier reinforcement is 7ϕ12/m, the fixed end condition gives a 9.5 % higher deformation value than the hinged end condition. While at reinforcement equals 7ϕ16/m, the difference is almost 0.12%. Figure 11shows the variation of the top deformation of the barrier with the different the end conditions.

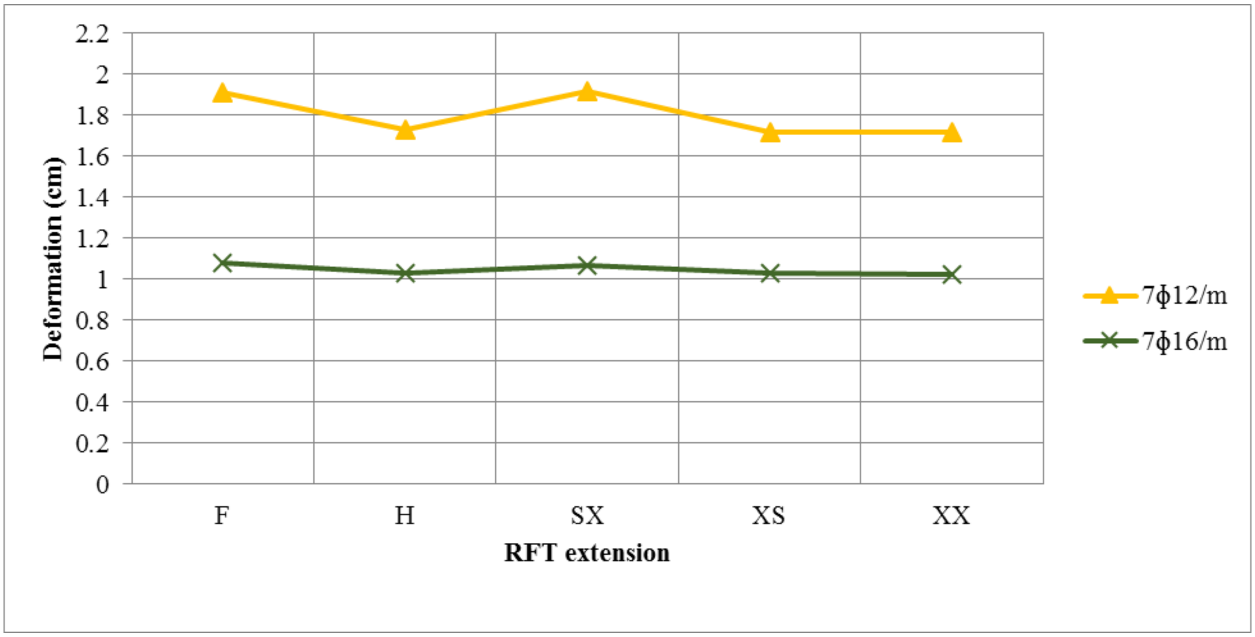


Figure 11: Maximum deformation of the wall versus end conditions

7. CONCLUSIONS

Based on the AEM analysis for the reinforced concrete barriers under blast loading, the following conclusions are obtained:

1. Applied Element Method "AEM" can predict the overall response including any potential partial or total collapse which cannot be predicted by SDOF component by component method. In other words, SDOF method could be sometimes unconservative method.
2. The end conditions of the barriers have no significance effect on its behaviour.
3. The reinforced concrete barriers behavior is greatly affected by its thickness, An increase of 5 cm in the thickness reduces the deformation of the barriers by 52%
4. The behavior of the barriers is affected by the barriers reinforcement, decreasing the barrier RFT by from 7ϕ16/m to 7ϕ12/m increases the maximum deformation by 44 %.

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