PERFORMANCE OF ONE-WAY REINFORCED CONCRETE WALLS SUBJECTED TO BLAST LOADS

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ABSTRACT

The performance of one-way reinforced concrete walls in resisting blast loads is numerically evaluated in this paper. Reinforced concrete wall strips of dimension 4.0 × 1.0 m and different thicknesses and supported on two sides spanning in the long direction are subjected to blast loads produced by the detonation of high explosive charges. The modelling and analysis was carried out using ANSYS AUTODYN solver. The accuracy of the modelling and its parameters is numerically verified against published experimental results of blast load tests on reinforced concrete slabs. The model was capable of simulating the observed damage and displacement with reasonable accuracy. The verified model is then used for extensive parametric study to examine the effect of different design parameters on the performance of reinforced concrete walls under the effect of blast loads. The design parameters considered in this study include the effect of concrete compressive strength of RC wall, the wall thickness, the reinforcement amount and details, and reflected peak pressure. The wall performance was evaluated considering maximum displacement, extent of damage and energy absorbed within the wall through damage.

Keywords: ANSYS, blast load, dynamic, nonlinear numerical modelling, RC wall.

1 INTRODUCTION

Blast load effect on buildings and building components has received considerable attention in recent years [1, 2]. This is mainly due to the increase in blast events resulting from different accidents and terrorism activities targeting important structures in different parts of the world. This paper is concerned with the effect of dynamic loading produced by the detonation of high explosives on one-way reinforced concrete wall (RC wall) elements. Studies have shown that blast loads with short duration and high magnitude influence the response of the structure and modify the material behaviour [3–5]. The results of experimental research on steel [6,7], concrete [8,9] and FRP [10] panels subjected to blast loads are reported in the literature. Beams, slabs and shells under blast loads are mostly studied with limit analysis theory, which assumes rigid-plastic behaviour for the material.

With the rapid development of computer hardware over the last few decades, it has become possible to make detailed numerical simulations of blast loads on personal computers, significantly increasing the availability of these methods. In this paper, the parametric study is conducted using ANSYS AUTODYN Solver provided by Workbench explicit dynamic modules in ANSYS V14.5.

2 NUMERICAL MODEL VERIFICATION

The numerical model developed in this paper is verified against the experimental results of published research on blast-loading response of reinforced concrete panels by

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Razaqpur *et al*. [11]. The control specimens of the experimental program are modelled, and its nonlinear blast response is simulated and compared to the test results. The validation of the numerical model along with detailed parametric study on the behaviour of two-way reinforced concrete slabs subjected to blast load are conducted by the authors of this paper [12].

ANSYS V.14.5 – Explicit dynamics system is used for simulating the response of the control specimen to blast. Solid element was used to simulate both the concrete body and the reinforcing steel bars. The characteristics of the solid element are governed by the mesh type and characteristics. For the simulation of the concrete panel the CONC-40MPA material is used. Furthermore, the STEEL 4340 is assigned to simulate the steel reinforcing bars. To imitate the same boundary condition the mathematical model is assigned to have fixed supports all over the panel edges. The assigned load is chosen to be pressure type and equal to 5.059 MPa in time duration equal to 7.7×10^{-4} sec. Correlating numerical to experimental results reveals that the mathematical model gives reasonably accurate results [12]. Thus, the developed models is adapted in this study.

3 NUMERICAL SIMULATION AND PARAMETRIC STUDY

The developed and verified numerical model is now used for studying the performance of one-way RC walls under the effect of blast loads using numerical simulation. The parameters considered in this research are the concrete compressive strength of RC wall, RC wall thickness, and reflected peak pressure.

A total of 24 RC wall models 4,000 × 1,000 mm, spanning in the long direction, are used with four deferent RC wall thicknesses 200, 300, 400, and 500 mm. Moreover, three reflected peak pressures, 4, 12, and 23.5 MPa were used with 100 kg as TNT explosive discharge. Two concrete compressive strengths were also used: 35 MPa as normal strength concrete and 140 MPa as high strength concrete. For all models, steel reinforcement had yield stress equal to 400 MPa. The numerical models were divided into six groups (A, B, C, D, E, and F) according to concrete compressive strength and reflected peak pressure as shown in Table 1. Furthermore, each group contains four different thicknesses assigned to the RC wall.

Solid element was used to simulate both the concrete body as well as the reinforcing steel bars. Furthermore, the configurations of the solid element are governed by the mesh type and characteristics. The mesh physics preference is set to explicit with coarse relevance centre and triangle surface mesher is program controlled, which leads to tetrahedrons element for the simulation of concrete body and reinforcement steel as shown in Fig. 1. For the simulation of the concrete wall the CONC-35MPA and CONC-140MPA material are used and the STEEL 4340 is assigned to simulate the steel reinforcing bars.

Table 1: Parametric study groups details.

Group ID	RC wall compressive strength (MPa)	Reflected peak pressure (MPa)
Group A	35	4
Group B	140	
Group C	35	12
Group D	140	
Group E	35	23.5
Group F	140	

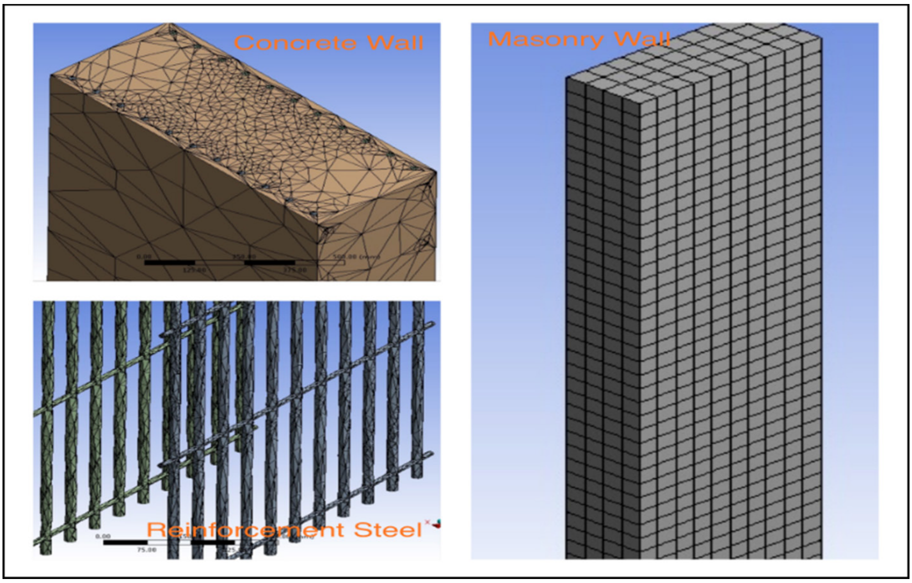


Figure 1: Mesh elements of the numerical models.

The parametric study examines the effect of the different parameters mentioned above on the response measures represented by maximum deformation, strain in steel and concrete body, internal energy of RC wall, and plastic work done by the RC wall.

All the RC walls are fixed at the upper and lower ends. To maintain the one-way analysis case the in-plan and perpendicular to the left and right wall faces transition movements is prohibited by setting it to equal zero during the analysis.

Furthermore, the assigned loads have three scenarios. The first scenario is having a 100 kg as TNT equivalent charge at 6 m stand-off distance. This scenario produces a reflected pressure equal to 4 MPa in time duration equal to 1.48 msec. The second scenario is having a 100 kg as TNT equivalent charge weight at 4 m stand-off distance. This scenario produces a reflected pressure equal to 12 MPa in time duration equal to 0.83. While the last scenario produces a reflected pressure equal to 23.5 MPa in time duration equal to 0.64 msec using a 100 kg as TNT equivalent discharge weight at 3 m stand-off distance.

All the RC walls were designed to meet the Army TM 5-1300 code requirements. The entire RC walls assumed to have an idealized shock wave for the propose of the blast design. Moreover, all the RC walls designed to have a medium protection level against blast load. Figure 2 shows the typical failure modes observed in almost all wall. Ultimately, walls fail due to concrete crushing at the fixed supports and at the mid-span point forming a three hinged mechanism as shown in Fig. 2. Maximum deformation is observed at the mid-span point.

4 RESULTS OF PARAMETRIC STUDY

This parametric study investigates the effect of RC wall thickness, concrete compressive strength, and the reflected peak pressure on the behaviour of RC wall. The failure in the RC wall is represented by the percentage of nodes with strain level exceeding the maximum assigned strain which is 0.003.

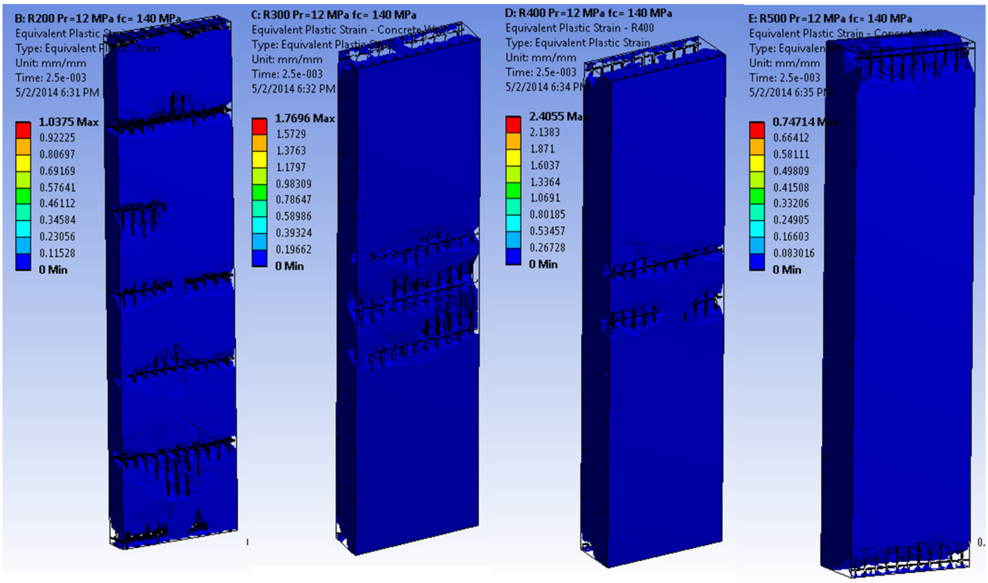


Figure 2: Typical mode of failure for RC walls with different thicknesses.

4.1 Effect of the thickness of the RC wall

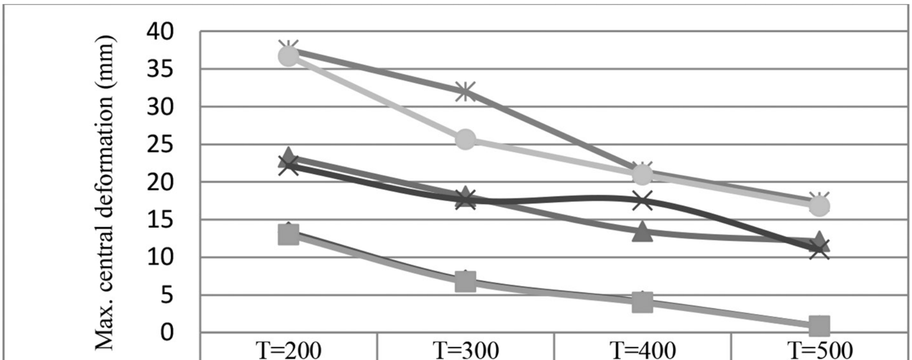
By examining Group A, Group B, Group C, Group D, Group E and Group F to study the effect of RC wall thickness on the behaviour of the RC wall under blast load, the numerical results increasing RC wall thickness decreased the maximum central deformation for all walls in all groups.

Furthermore, the RC walls in Group A increasing wall thickness from 200 to 300 mm decreased the maximum deformation by 48.2%. On the other hand, increasing wall thickness from 200 to 400 mm decreased maximum deformation by 69.2%. Moreover, increasing the thickness from 200 to 500 mm decreased the maximum deformation by 93.7% as presented in Fig. 3.

When examining the effect of RC wall thickness on the failure percentage of the RC wall, the results showed that increasing the thickness of the RC wall decreased the failure percentage. By taking walls in Group A, the results showed that increasing the RC wall thickness from 200 to 300 mm decreased the failure percentage by 33.4% and increasing the thickness from 200 to 400 mm decreased the failure percentage by 85%. While increasing the thickness from 200 to 500 mm decreased the failure percentage by 93.96% as shown in Fig. 4.

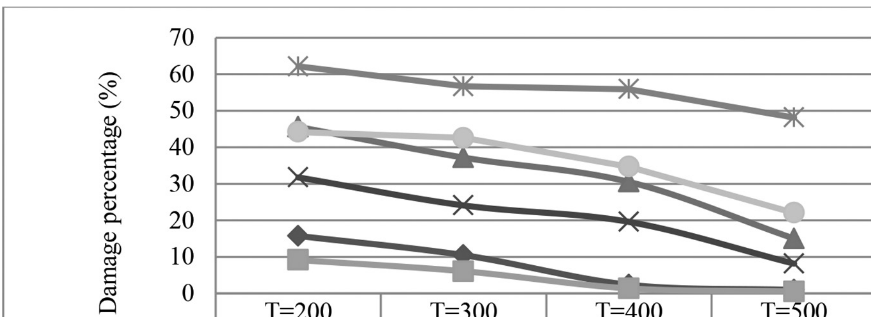
The general behaviour of all RC walls observed a decrease in the internal energy of the RC wall with increasing the wall thickness. On the other hand, when increasing the RC wall thickness, the plastic work done by the RC wall decreased.

By comparing the internal energy and plastic work done by wall R200-A to wall R300-A, the results showed that increasing the wall thickness from 200 to 300 mm decreased both the internal energy and the plastic work by 52.7% and by 21.53%, respectively. While in the case of increasing RC wall thickness from 200 to 500 mm, the results showed a reduction in both



	T=200	T=300	T=400	T=500
Group A	13.31	6.9	4.1	0.84
Group B	12.99	6.72	3.98	0.819
Group C	23.263	18.1	13.45	12.1
Group D	22.126	17.6	17.5	10.975
Group E	37.517	31.944	21.382	17.328
Group F	36.662	25.624	20.924	16.758

Figure 3: Effect of wall thickness on maximum central deflection of RC walls.



	T=200	T=300	T=400	T=500
Group A	15.73	10.47	2.36	0.95
Group B	9.134	6.07	1.37	0.551
Group C	45.55	37.165	30.52	15
Group D	31.745	24.0755	19.591	8.148
Group E	62.12266667	56.68	55.9	48.126
Group F	44.2	42.575	34.6893	22.034

Figure 4: Effect of wall thickness on percentage of damage due to blast loads.

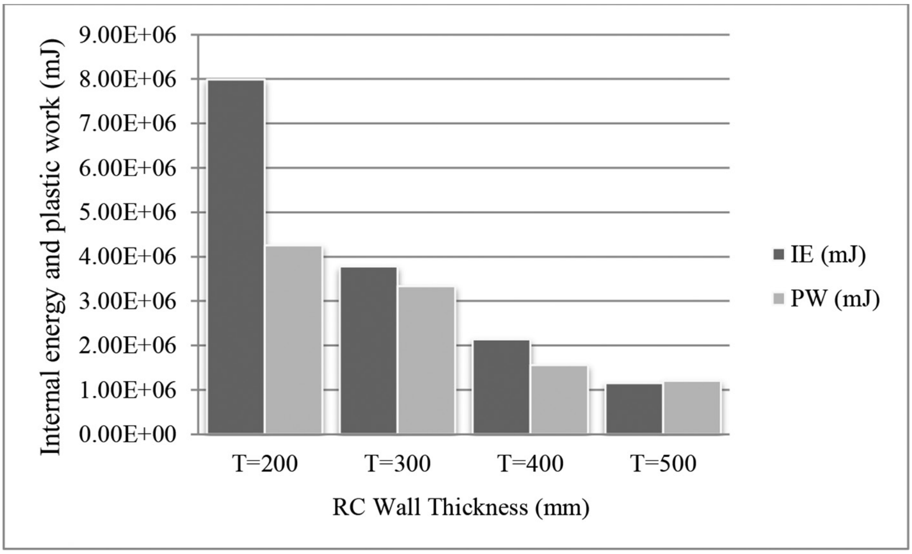


Figure 5: Effect of wall thickness on internal energy and plastic work for RC walls in Group A.

the internal energy and plastic work of RC wall by 85.61% and by 71.8%, respectively, as presented in Fig. 5.

Moreover, in the case of high-reflected peak pressure and by comparing R200-F to R500-F, the results indicated that increasing the RC wall thickness from 200 to 500 mm decreased both the internal energy and plastic work done by 6.55% and by 43.34%, respectively.

4.2 **Effect of compressive strength of the RC wall**

By comparing the numerical results of RC walls in Group A to the results of Group B, it is found that increasing the compressive strength of RC wall decreases the maximum central deformation. For example, increasing concrete compressive strength from 35 to 140 MPa for a RC wall with thickness equal to 200 mm decreased the maximum central deformation by 2.41% and for a 300 mm RC wall the deformation reduced by 2.61%. While in the case of RC wall with thickness equal to 400 mm, the reduction equalled to 2.93%. Moreover, in the case of RC wall with thickness equal to 500 mm, the central deformation reduced by 2.5% as shown in Fig. 6.

When examining the effect of concrete compressive strength on the failure percentage of the RC wall, the results showed that increasing the concrete compressive strength of the RC wall decreasesd the failure percentage. Comparing Group A to Group B, the results showed that increasing the compressive strength of a 200 mm thick RC wall from 35 to 140 MPa decreased the failure percentage by 42%. Almost the same value of reduction in failure percentage due to increasing the compressive strength of concrete from 35 to 140 MPa was observed in all wall thickness 300, 400 and 500 mm as shown in Fig. 7.

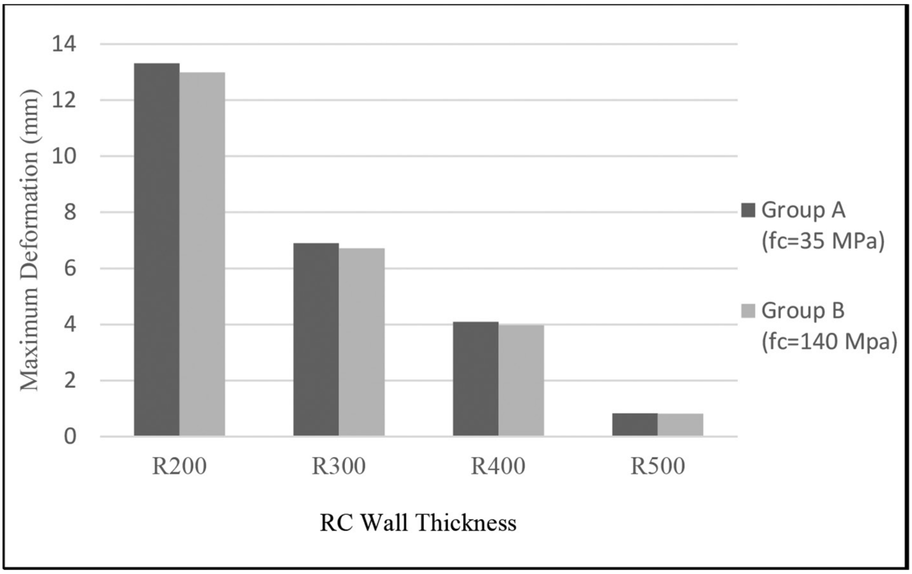


Figure 6: Effect of compressive strength on max deformation for different wall thickness.

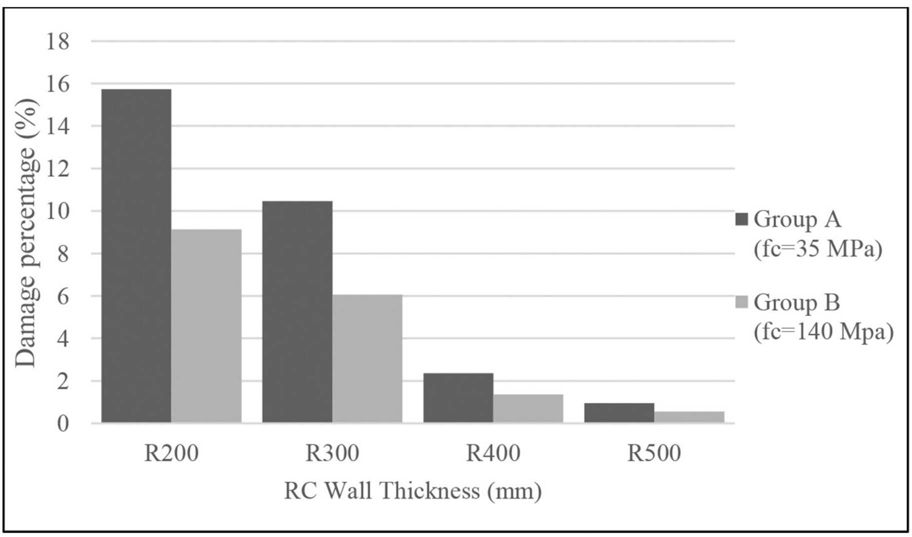


Figure 7: Effect of concrete strength on damage percentage for different wall thickness.

Furthermore the numerical results of all the RC wall groups showed that increasing the concrete compressive strength improved the performance of the RC walls by increasing the internal energy absorbed by the wall by 18% and decreasing the plastic work done by the RC wall by 43.16% as shown in Figs 8 and 9.

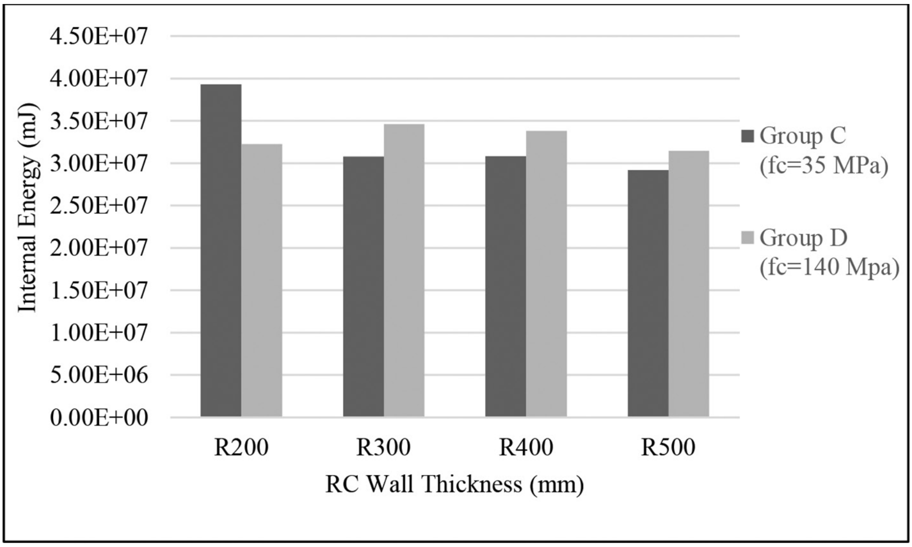


Figure 8: Effect of concrete strength on internal energy for different thicknesses.

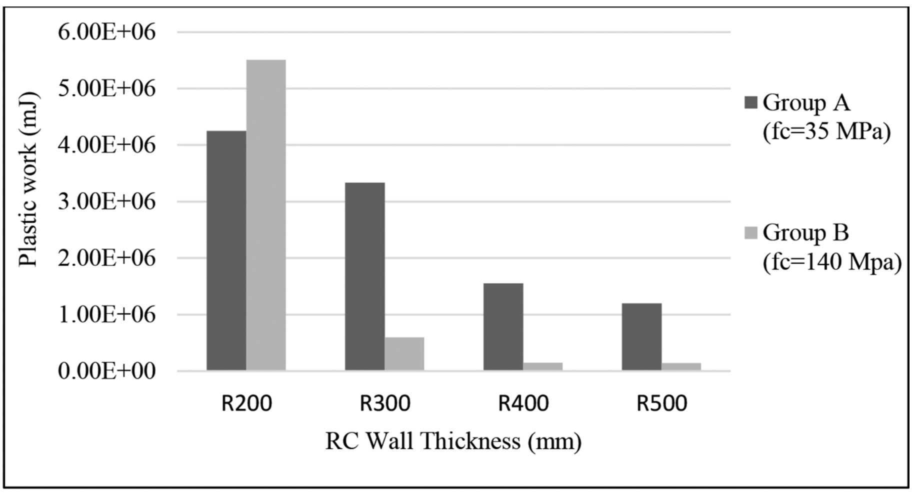


Figure 9: Effect of concrete strength on plastic work for different thicknesses.

4.3 **Effect of reflected peak pressure**

To fully analyse the effect of reflected peak pressure on the behaviour of RC walls under blast loads the results of Group A (Pr = 4 MPa), Group C (Pr = 12 MPa), and Group E (Pr = 23.5 MPa) were compared to each other as well as the results of Group B (Pr = 4 MPa), Group D (Pr = 12 MPa), and Group F (Pr = 23.5 MPa).

By comparing the numerical results of RC walls in Group A (fc = 35 MPa), Group C (fc = 35 MPa), and Group E (fc = 35 MPa) it is shown that increasing the reflected peak pres-

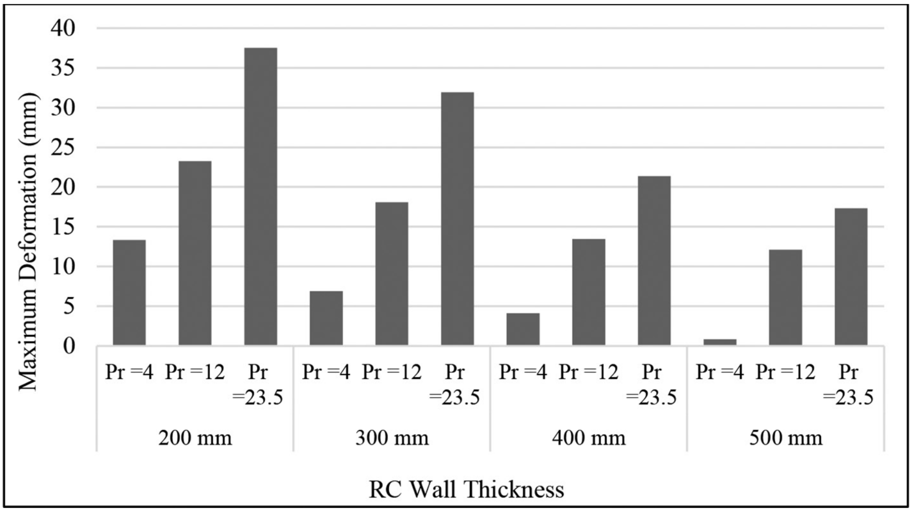


Figure 10: Effect of reflected peak pressure on maximum deformation for different wall thicknesses.

sure of a 200 mm thick RC wall from 4 MPa to 12 MPa increased the maximum central deformation by 74.8%. This increase becomes 181.9% with increasing the reflected peak pressure from 4 MPa to 23.5 MPa. While increasing the reflected peak pressure of a 200 mm RC wall from 12 MPa to 23.5 MPa increased the maximum deformation by 61.3% as shown in Fig. 10.

The same set of RC walls groups was used to examine the effect of reflected peak pressure on the failure percentage of RC walls. By comparing the numerical results of RC walls in Group A (fc = 35 MPa), Group C (fc = 35 MPa), and Group E (fc = 35 MPa), it is shown that increasing the reflected peak pressure of a 200 mm thick RC wall from 4 to 12 MPa increased the failure percentage of RC wall by 189.6%, and the increase becomes 294.9% for the case of increasing reflected peak pressure from 4 to 23.5 MPa. While increasing the reflected peak pressure from 12 to 23.5 MPa increases the failure percentage of RC wall by 36.4% and 220.8% as shown in Fig. 11.

Furthermore by comparing the numerical results of RC walls in Group A (fc = 35 MPa), Group C (fc = 35 MPa), and Group E (fc = 35 MPa), it is shown that increasing the reflected peak pressure of a 200 mm thick RC wall from 4 MPa to 12 MPa increased both the internal energy and plastic work by 391.9% and 349.4%, respectively. While for the same 200 mm RC wall increasing reflected peak pressure from 4 to 23.5 MPa increases both the internal energy and plastic work by 715.5% and 987.6%, respectively. This increase becomes 65.8% and 142% of the internal energy and plastic work in the case of increasing reflected peak pressure from 12 to 23.5 MPa as shown in Fig. 12.

5 CONCLUSIONS

The behaviour on one-way RC walls under the effect of blast load is studied in this paper. Different parameters are studied in this paper including the wall thickness and the peak pressure. Four wall thicknesses are considered, i.e. 200, 300, 400 and 500 mm. The walls are

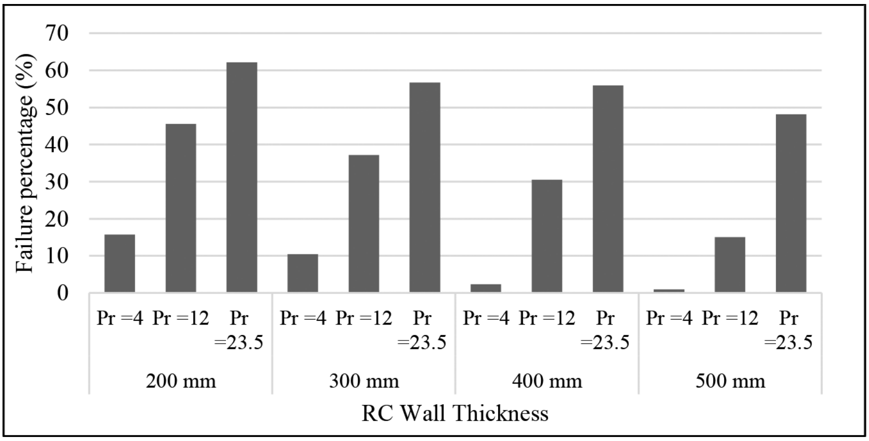


Figure 11: Effect of reflected peak pressure on failure percentage of normal strength RC walls for different thickness.

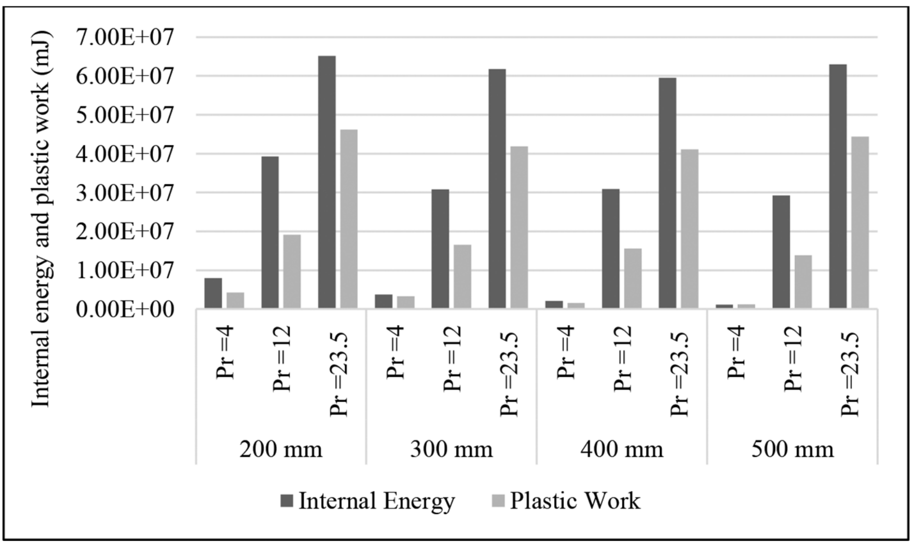


Figure 12: Effect of reflected peak pressure on internal energy and plastic work on normal strength RC walls.

subjected to three different levels of reflected peak pressure: 4, 12 and 23.5 MPa representing three different levels of threat. The performance parameters studied in this papers are the maximum wall deformation, the level of damage, the internal energy absorbed by the wall and the plastic work. The general behaviour of the walls at failure is characterised by concrete crushing at the fixed ends and at the mid-span forming a three hinged failure mechanism.

It is found that the most important parameter affecting the wall performance is the wall thickness. Increasing the wall thickness from 200 to 500 mm reduces the maximum deformation and the percentage of damage to less than half for all considered walls. Moreover, increasing the RC wall thickness decreases the internal energy and plastic work done by the RC wall. At the same time, increasing RC wall thickness increases the upper and the lower support reactions of the RC wall.

Concrete compressive strength has less significant effect on the maximum central deformation. For example, increasing the compressive strength of the RC wall from 35 MP to 140 MPa reduces the maximum central deformation of the RC wall by 10%. Using high strength RC walls instead of normal strength RC walls reduces the failure percentage of RC wall by at least 40%. Moreover, it also improves the behaviour of RC wall by increasing internal energy absorbed and decreasing plastic work done by the wall. Furthermore, increasing the compressive strength of RC wall increased the upper and lower support reactions up to 42.5% due to the reduced damage of the RC wall.

Reflected peak pressure has a strong effect on the behaviour of the RC wall. Increasing reflected peak pressure from 12 to 23.5 MPa increases maximum central deformation by 65% and the damage by 50%. This incense reaches 190% for deformation and 400% for damage for the case of increasing reflected peak pressure from 4 to 23.5 MPa.

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