Numerical Prediction of Cantilevered Reinforced Concrete Wall Subjected to Blast Load

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Abstract. Aggressor attack using improvised explosive not the only source for blast load. Some commercial equipment and daily activities can contribute as well, such as electrical transformers, gas pipelines and industrial plants. Normally, reinforced concrete wall is used as the protection. Therefore, it is vital to estimate the structure damage. In this paper, the behaviour of cantilevered reinforced concrete (RC) wall subjected to blast load is investigated through numerical simulation. A three-dimensional solid model, including explosive, air and RC wall is simulated. The wall has a cross-sectional dimension of 1829 mm × 1219 mm with wall thickness of 152 mm and 305 mm thickness of strip footing. It is subjected to 13.61 kg Trinitrotoluene (TNT) explosive at 1.21 m standoff distance from the centre. Concrete and steel material model behaviour considers the high strain rate effect and dynamic loading. The Arbitrary Langrange Euler (ALE) coupling interface between air and solid are applied to simulate the damage mechanism of RC wall. A Comparison between experimental data on blast pressure and damage pattern shows a favourable agreement. The numerical result shows, the displacement-time history on each side is in a contrary direction. A permanent deformation is occurred and, the blast pressure near to the wall base is the highest.

Introduction

Study on the structure with the capable of withstanding blast load in the construction industry around the world became important since the last decade due to the September 11, 2001 attacks in New York. Besides the terror attacks and other acts of war, accidental explosions due to civilian accident and commercial equipment occurring in urban areas or close to facilities such as building and protective structures may cause tremendous damage and loss of life. Due to space constraint, residential homes, commercial and utilities building are developed just next to traffic access such as road, highway and railways in the most major cities. Those mentioned situations are prone to dynamic loading due to transformer explosion, vehicle and train accident. As one of the effective approaches, barrier walls can be constructed to ensure the safety of civilian. Experimental and numerical analysis have demonstrated that a barrier wall can effectively protect nearby building from external explosion [1]–[3].

RC is widely used as the principal construction material for urban environment, infrastructure or as different types of civilian and military facilities. Generally, plain concrete is known to have a relatively high blast resistance compared to other construction material. However, the plain concrete of higher strength will lead to a more brittle failure compared to ordinary concrete. Therefore the combination of using proper amount of steel reinforcement and the right concrete strength will result a ductile concrete, hence limit the structural damage in RC structural element. Series of the experimental and numerical have been conducted to investigate the damage due to blast load in different scope of works. The investigation lead to the scope for strengthening the strength of ordinary reinforced concrete structure with different method such as retrofitted the concrete material with steel fiber [4]–[7]; replaced the normal strength steel with enamel coated steel [8] or retrofit the structure with different material such as aluminium foam [9]. However, in the attention to strengthen the reinforced concrete, some of the experimental test show a mixed result or worse than the ordinary reinforced concrete. For example, the usage of glass fiber reinforced polymer to retrofit reinforced panel found, in some cases the retrofitted panel performed better than unretrofitted panel while in other cases the opposite are occurred [10]. In the case of carbon fibre reinforced polymer plate used to retrofit on compression and tension side of the panel, it was found, the post impact of scabbing hole in the retrofitted was significant larger than the unretrofitted panel [11]. Also, the usage of high strength concrete on structure did not improve the performance remarkably when subjected to blast load [12]. Although, RC slab panel can be simplified as RC wall with designed restrain either in the experimental or numerical, to appraise the cantilevered reinforced concrete wall with strip footing, the actual structure is required. This is because, with the wall base, the main steel in the wall needs to be hooked into its base. However, there is lack of intensive studies on the structure due to blast load. Normally, for the blast studies, the sample size is small to ensure the blast load can give an impact on structure. Besides, the cost of blast test can be reduced.

Currently, numerical simulation is an alternative method to replace an expensive blast test. As example, AUTODYN simulation package has been used for the current research. The AUTODYN is an integrated explicit analysis tool program specially designed for modelling non-linear dynamic problems that uses finite elements (FE), finite volume (CFD) and mesh-free particle (SPH) to solve nonlinear dynamic problems of solid, fluids, gas and the interaction between them. Besides modelling non-linear dynamic problems, AUTODYN offers multi-solver coupling for multi-physic including coupling between FE, CFD and SPH. The available concrete and reinforcement steel material model in AUTODYN is used because it considers the strain rate effects and the appropriate coupling between air-solid interface. The numerical results are compared with available experimental data.

Experimental setup and structural geometry

In the present study for instance in Yan et al. [8], the cantilevered reinforced concrete wall were reinforced with 16 mm diameter on vertical reinforcement and 10mm diameter on transverse stirrups, both at 152 mm spacing. The concrete cover on all sides of the walls is 25 mm thick. The cylinder compressive strength of the concrete was 44 MPa with standard deviation of 1.38 MPa; the Modulus of Elasticity is 31.5 GPa with a standard deviation of 827 MPa. The reinforcement had yield strength of 619 MPa and Young's modulus of 200 GPa. The walls have a cross-sectional dimension of 1829 mm × 1219 mm with wall thickness of 152 mm and 305 mm thickness of strip footing. According to the experimental, the wall was tested with 4 lbs., 10 lbs. and 30 lbs. TNT charge weight with 4 ft. standoff distance from the centre of the wall. Pressure transducer was placed at 18 ft. away from the centre of the charge weight. The blast test reveals that the visible cracks were clearly observed on the front and the back of the wall only after the third test with 30 lbs charge weight. Therefore in the present study, the highest charge weight is considered in the following numerical simulation.

AUTODYN analysis of cantilevered wall under blast load

A series of numerical simulations using developed and tested computational material models has become powerful measurement in design process of a structure especially subjected to blast load. Also a detail investigation of structure physical, response and failure mechanism can realistically simulate by adopting a three-dimensional (3D) numerical simulation. In the current study, a 3D numerical simulation is employed to investigate the damage for reinforced concrete wall.

A proper model that reflect concrete material behavior characteristic at high strain rate is vital to obtain a reliable prediction of concrete behavior under blast loads. The material model developed by Riedel, Hiermayer and Thoma (RHT) [13] is adopted for this study. The RHT concrete model is an advanced plasticity model for brittle materials. This model is particularly useful for modelling the dynamic loading of concrete. As it also takes into account pressure hardening, strain hardening, strain rate hardening, third invariant dependence for compressive and tensile meridian and strain softening. This model also employs *p-α* equation of state (EOS) to represent the concrete thermodynamic behavior at high stress, it provides a reasonably detailed description of the compaction behavior at low stress ranges. In the present simulation, the material data for CONC-35MPA [14] is employed, the modification is made accordingly base on experimental data. Johnson-Cook material model [15] was used to describe the behavior of the reinforcing steel. This model represents the strength of material behavior subjected to large strain, high strain rates and high temperature, typically metal. In the current simulation, the typical data for STEEL 4340 is employed [14]. The ALE is the numerical approach for the interface analysis between the air and structure. Using this approach, different part of the solvers such as structure, fluids and gases can be modeled simultaneously using Lagrange and Euler approaches. These different solvers are then coupled together in space and time. The air is modelled by an ideal gas EOS while, the high explosives of TNT is typically modelled by using the Jones-Wilkins-Lee (JWL) EOS.

Numerical simulation

In order to study the free propagation of the blast waves in the air, a 1 m x 1m x 5.5 m volume of air was numerically simulated for 30 lbs as shows in Figure 1(a) below. The wedge consists of blast pressure history is created before the application remap function in AUTODYN, as it is used to apply the effect of explosion in 3D model. Gauge 1 and 2 located at 4 ft. and 18 ft. respectively away from centre of the charge weight. Flow out of air is allowed in all the model borders. It is found for Gauge 1 the peak incident overpressure is 2.40 MPa at 1.43 msec, while for Gauge 2 is 0.51 MPa at 4.62 msec as shows in Figure 1(b). From the blast test conducted [8], the peak incident overpressure pressure at 18 ft. away from centre of explosive recorded is 0.49MPa at 4.64msec. Therefore, the numerical results on peak incident overpressure for free field agree well with the experimental conducted.

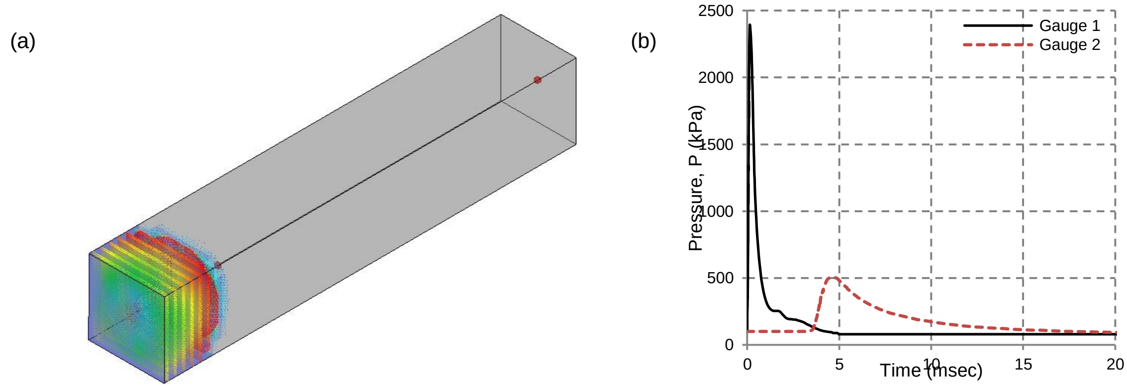

Figure 1: (a) Blast simulation in free field (Type 1) (b) Blast overpressure-time history

The same wedge used for remap function in free-field is considered in the numerical simulation of an actual blast test. Figure 2(a) shows the location of the gauges in 2.5 m x 2.0 m x 7 m volume of air with the consideration of reinforced concrete wall in the simulation. Three gauges are placed on the wall, which are 4 ft. away from the centre of charge weight. It is placed at the height of 538 mm, 1041 mm and 1795 mm respectively from the ground level. Accordingly, at the same height from the ground level, three gauges are placed perpendicular but on the free side and 4 ft. away from charge weight. Gauge 2 is placed at 18 ft. away and perpendicular to the centre of charge weight. It is found that the simulated data for Gauge 2 is 0.38 MPa at 4.9 msec and the positive duration is 25 msec. Type 3 model for an actual blast test as shows in Figure 2(b) is considered due to positive duration.

Table 1 shows the comparison of pressures from Autodyn (Type 1), A.T. Blast computer software and measured peak pressure of [8] at the location of 18 ft. away. The studies found that with the caped nodes up to 32,000 nodes, the grid size and the proper grid arrangement on I,J,K directions of the air model play an important role in predicting the blast parameters. From series of simulations, the grid arrangement of I,J,K (18,22,72) is considered for further analysis. According to the time of arrivals, it indicates a great discrepancy exists, whereas the maximum peak pressure is in good agreement. Therefore, the peak pressure on the structure at dedicated locations is able to appraise with Autodyn.

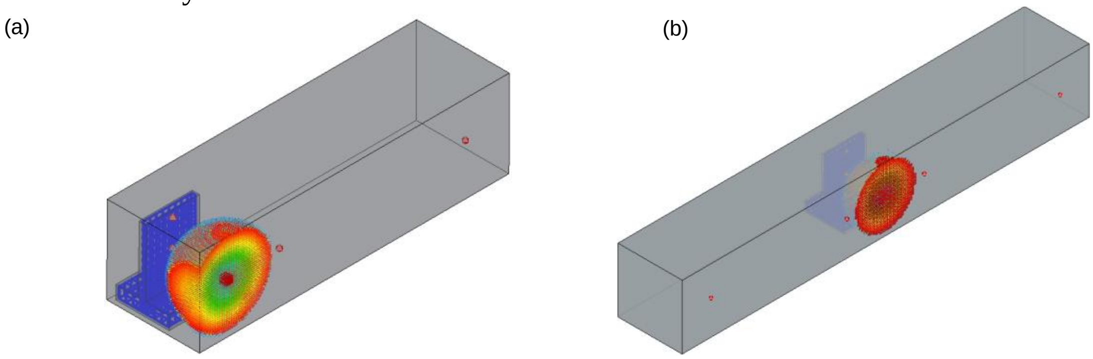

Figure 2: Model of an actual blast test (a) Type 2 (b) Type 3

Table 1: Comparison of pressure at the location of 18 ft. away

A.T. Blast		Autodyn (Type 1)		Measured	
Peak pressure (MPa)	Time of arrival (msec)	Peak pressure (MPa)	Time of arrival (msec)	Peak pressure (MPa)	Time of arrival (msec)
0.48	5.98	0.38	4.86	0.49	4.64

Figure 3(a) and 3(b) shows the pressure result, as can be seen in Figure 3(a) for the gauge 18 ft. away, the peak pressure is identical with 0.38 MPa at 4.86 msec and 0.37 MPa at 5.30 msec for Type 2 and Type 3 respectively. According to Figure 3(b), it is found that the highest blast pressure on the structure side at the bottom part of the wall with 6.91 MPa at 0.32 msec, followed by the gauge at the center and at the top with 5.40 MPa at 0.18 msec and 3.74 MPa at 0.29 msec respectively. For the blast pressure 4 ft. away on the free side, it is found that the blast pressure with the consideration of the structure compared to free field simulation is 28.6 % higher than others with 3.20 MPa at 0.13 msec as shown in Figure 3(b). This might happens due to the rigid structure imposed in the air domain. Also, it is revealed, with the extension of the air domain as shown in Figure 3(a) to 3(b) with the grid on I,J,K (50,50,200) directions respectively. The positive duration in the simulation is reduced from 25 msec to 20 msec as shown in Figure 3(a).

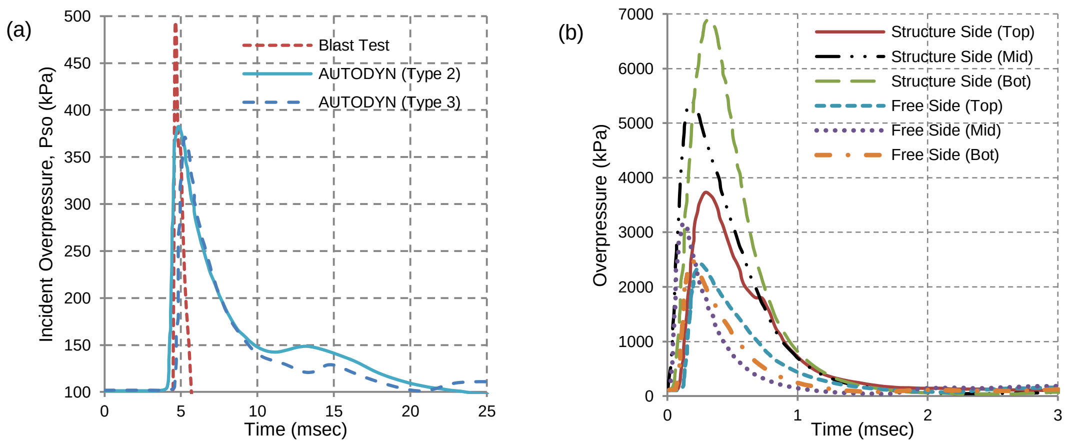

Figure 3: Blast overpressure-time history (a) At 18 ft. away (b) Type 2 at 4 ft. away

Figure 4(a-i) and 4(b-i) shows the RC wall after imposed with the blast load, it is found that the back face of the wall experienced more visible cracks compared to the front face of the wall. As the shock front is engaged with a concrete wall and generates compressive stress on the concrete in contact. The concrete on the front face of the wall and the shock front is locally subjected to bending as the stiffness of the front reinforcement grid suddenly change, potentially causing concrete crack. It is clearly indicated, the cracks basically follow the pattern of the steel reinforcement grid in the reinforced concrete wall. A few more cracks also appear at the lower part of the wall and fewer cracks particularly at the upper part of the wall [8]. The behavior of this crack pattern is agreed well with the numerical simulation as shown in Figure 4(a-ii) and 4(b-ii) where, the damage indicator appears accordingly at the steel reinforcement grid. As can be seen, on the front-side of the crack for the test, the crack is horizontal, while for the simulation the damage location follows on both direction of the reinforcement grid. On the back-side, both numerical and experimental show the patterns of the reinforcement grid in both directions. The slight difference might be cause by the boundary condition. The boundary condition in the experimental might be ‘softer’ than that in the numerical condition, which makes the damage in the numerical results more than the experiment. The material constant is another possible factor, which are not based on real material test, but based on the reasonable assumptions. Moreover, the boundary condition in the numerical simulation is fixed all the times, whereas in the experiment it is loosened. Besides those possible factors, the RC wall experienced for three different blast loads in experiment, while for the numerical simulation it experienced only for the highest blast load.

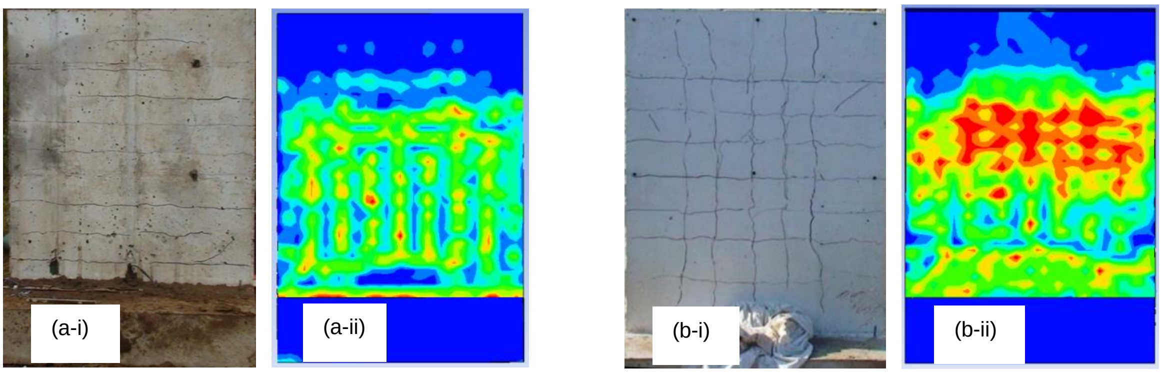

Figure 4: Experimental and numerical cracks on the wall (a)Front side (b)Back side

According to the comparison on blast pressure and crack pattern, the deflection-time history is able to predict. Three gauges are placed at height of 1 m, 2 m and 2.5 m from the center wall base on the back-side. The deflection-time history shows in Figure 5(a), it can be found that, the maximum deflection at the top of the structure is 145.3 mm at 35.3 msec, few displacement oscillation cycles occurred until there is no further wall movement at 500 msec onwards. Permanent deformation is occurred at the end of simulation. Figure 5(b) shows the movement for one cycle until 90 msec, as can be seen, the wall movement in not symmetrical where when the one side is on the front movement while on the other side is on backward movement.

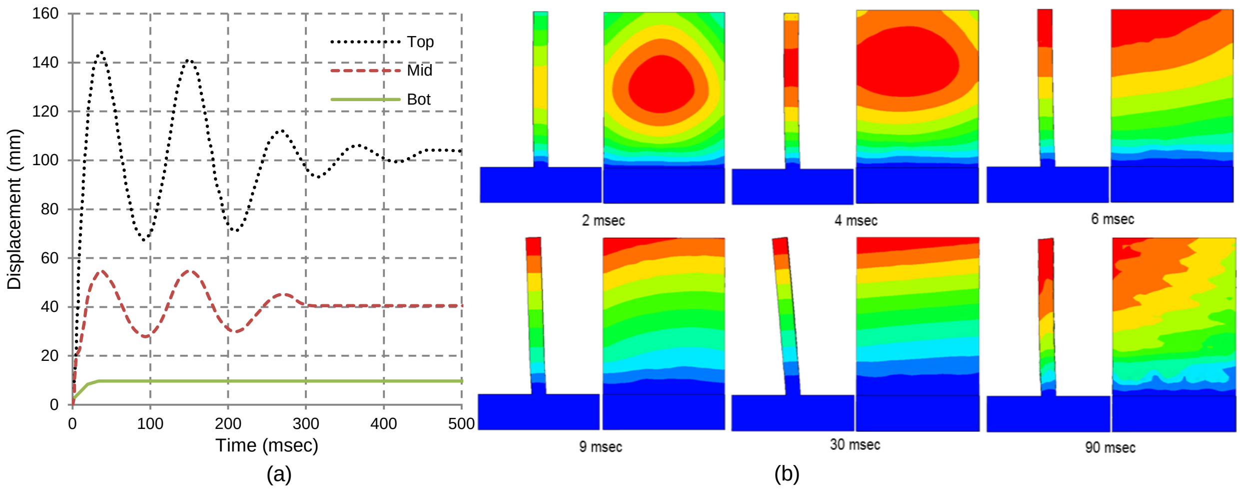

Figure 5: (a) Deflection-time history (b) Deflection propagation

Conclusions

A three-dimensional material model including reinforced concrete wall, explosive and air using nonlinear finite element analysis software Ansys-Autodyn has been employed to predict related parameters of cantilevered reinforced concrete wall with strip footing under blast load. Comparisons of numerical and experimental results in literature show that the present model gives reliable prediction of blast pressure and wall damage. For the cantilevered reinforced concrete wall, it is observed that the permanent deformation of the structure occurred after few cycles of deformation oscillation due blast load and the ductility of RC wall. According to the deformation propagation, the movement on each side is in contrary direction. It is also observed that the highest blast pressure on the wall surface is not at the perpendicular from the centre of the charge weight, but it is at about the bottom of the wall. With further modifications on the element size, erosion criteria and boundary condition, the higher accuracy in the numerical result is expected.

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