Journal of Structural Engineering & Applied Mechanics (2022) 5(1):13-21
DOI 10.31462/jseam.2022.01013021

RESEARCH ARTICLE

Structural response of multi-story building subjected to blast load

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Article History

Received 16 September 2021
Accepted 18 February 2022

Keywords

Blast load
Explosion
ANSYS Workbench
AUTODYN
TNT

Abstract

This paper aims to present blasting effects on the structural response of a 5-story building considering its columns, shear walls, beams, slabs, raft foundation, masonry walls, and windows. The building with a geometry of 12×20 m in plan and a height of 15.5 m is considered. The three-dimensional finite element model of the building is constituted using ANSYS Workbench and blasting analysis is explicitly performed in ANSYS AUTODYN. TNT is exploded to give blasting effects on the structure. The duration of the explosion is set to 3-msec. Stresses, displacements, material status, and pressures due to blasting on some gauge points are presented. It is seen from the study that the blast causes local damage to the load-bearing elements.

1. Introduction

In recent years, terrorism has become one of the biggest problems all over the world, so full protection against terrorist attacks awaits a definitive solution. The ignition of the fuse of the explosive affects the environment, structures, and people therein. To date, researchers have conducted numerous studies and, based on experimental results, have increased the protection against explosive loads.. It is necessary to investigate the behavior of explosion effects on structures. As a consequence, some of the studies in the literature have been examined.

Nicholls et al. [1] investigated blast vibrations and their effects on structural behavior. In the study, they stated that if the particle velocity that will occur during the explosion is about 5 cm/s and the air pressure effect on the structure is up to 3.5 kN/m² levels, the structures will remain on the safe side, and damage may occur in the structures for larger values. Gad et al. [2] investigated the effects of the explosion in a single-story building near the mine. For a year, the building was monitored by accelerometers during explosions with a ground particle velocity of 1.5-222 mm / s. The crack conditions before and after an explosion in the building have been examined, and a procedure has been tried to be developed between the particle velocity and the crack formation. Ngo et al. [3] studied the explosion load and its effect on structures and drew attention to the terrorist attacks carried out by trucks loaded with explosives in the city centers and made a general evaluation of this issue. In the study, he examined the nature of the explosion and the propagation mechanism of the explosion waves in the air environment and mentioned different methods related to the structural behavior and estimation of the explosion loads. Nateghi et al. [4] investigated the effect of explosion waves on the concrete of underground structures. In the study, methods to control the explosion waves were developed and the negative effects of the waves were tried to be eliminated. Draganic and Sigmund [5] prepared and analyzed a model in the SAP2000 program to see the behavior of a structure that

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they exposed to the explosion. In the study, they stated that the program was sufficient for the beginning to produce the explosion effect. Tripathy et al. [6] examined the negative effects of the explosions on earth structures. In this context, they investigated the effects of explosions on an 85-year-old masonry dam in India and the concrete poured into the rocky part around it. Syed et al. [7] studied the performance of earthquake-resistant reinforced concrete frame structures subjected to blast load. The vulnerability of these structures was investigated under different realistic blast scenarios obtained by varying scaled distances and explosion charge-weights to study the structural response. Altunışık et al. [8-9] aimed at the effects of design parameters such as concrete strength and openings in infill walls on the blasting responses of reinforced concrete buildings. Kiakojouri et al [10] studied the blast-induced progressive collapse of steel moment-resisting frames. Numerical studies and a framework have been used to create an alternate load path method. Xiao et al. [11] investigated the blast loads on a two-storeyed reinforced concrete (RC) and masonry building with a gable roof through full-scale experiments and numerical simulations. Five full-scale experiments were conducted. Various aspects of the effect of explosions on structures have been eliminated in the literature.

In this study, the effect of explosive load on structural behavior is investigated. Within the scope of the study, 3D fininite element model of the reinforced concrete building is constituted and designed using ANSYS Workbench [12]. The effects of explosions occurring in the structural and non-structural parts of the reinforced concrete building are presented with graphs, tables, and contour diagrams.

2. Theory of blast

With the detonation of the condensed and compressed explosive, the resulting pressure can reach up to 300 kilobars and the temperature can rise to 3000-4000 °C. For a while, the explosion wave can increase suddenly and rise above the atmosphere of the environment. After a short time, the high pressure may fall below the ambient atmospheric pressure. In this negative phase, a partial vacuum is created and the air is sucked out. This situation along with the high vacuum wind, can bring back some of the debris pieces that were removed during the explosion.

When the characteristics of the air explosive waves are observed, it has been noticed that the explosive is affected by its physical properties. A typical burst pressure profile is seen in Fig.1 [13]; with the explosion at the moment of t_A, it is seen that the pressure suddenly reaches the P_{so} peak (P_o: ambient pressure). After t_d, the peak pressure drops to ambient pressure, then P_{so} reaches negative pressure (vacuum). Then it returns to the P_o level. Occurring peak points (P_{so}); during the explosion, if the shock waves encounter a reflective factor (for example, a load-bearing element) it becomes larger. Reflective factors depend on the intensity of the shock wave. In large explosions, reflectors cause an increase in pressure.

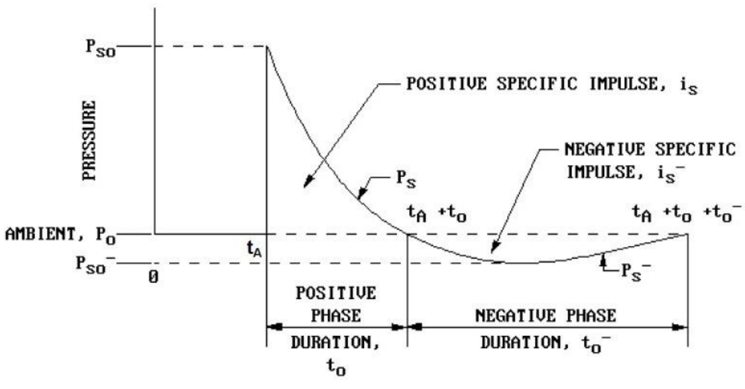


Fig. 1. Pressure–time graph of the blast load [13]

2.1. Cube root scaling law

Calculation of burst load values depends on some basic parameters. These are distance and explosive mass. These basic parameters are combined and transformed into a single parameter, and this theorem is called the "Cube Root Scaling Law" and was proposed by Hopkinson-Cranz [14]. Most of the research has been based on the value (Z) obtained from this theorem.

$$Z = R/W^{1/3} \tag{1}$$

where, Z: Scaled Distance (m/kg$^{1/3}$), R: distance between explosive and structure (m), W: Charge mass of the explosive material (TNT, kg)

TNT is the basic unit for determining the scaled distance, Z. if the explosive type is different from the TNT, the explosive must be converted to the equivalent mass of the TNT and the equivalent weight and the coefficient equivalent factors for other explosives.

3. Multi-story building and finite element model

In this part of the study, a five-story reinforced concrete building was selected and the effects under blasting load were examined. It was investigated that the way structure behaves as a whole, against the large number of explosives placed under the columns on the ground floor of the RC building. 3 D FEM of the building is constitued and desiged using ANSYS Workbench Software. The building model was assumed as a solid and this is represented by the Lagrangian aprroach. The explosive and air were assumed as fluid and these are represented by the Eulerian approach which were considered using ANSYS AUTODYN Software [15].

Concrete reinforcement materials are selected as C35, B420C respectively. The infill walls are chosen as masonry walls and the windows are preffered as float glass. Material properties according to these acceptances are given in Table 1.

RHT Concrete Model is used to represent to nonlinear material properties of the concrete. Similarly, the reinforcement bars are nonlinearly assumed. Dead and live loads were applied to the building considering load combination [16]. The distributed loads of 2.5 kN/m² were applied to each floor as live loads.

Accordingly, in the five-story reinforced concrete building there are totally 24 columns, 8 out of them in the ground story, and they have 60×40 cmdimensions in the corners and inside. The other 16 columns have 40×40 cm dimensions at the sides and inside. The beams have 50×30 cm dimensionas and the height of slabs are selected as 12 cm in size. In addition, there are 3 shear walls with the dimension as 300×30 cm around the perimeter of the stairwell. The exterior of the whole building is covered with a brick wall, and a 120×120 cm window is asseumed in the middle of the walls and a 120×200 cm door at the entrance of the building is considered.

The building is designed with five floors. The story heights are 300 cm, the distance between axles is 400 cm and the foundation of the building is a raft foundation with a thickness of 50 cm. In the middle of the building, there is a stairwell from the foundation to the top floor, the size of this opening is 400×400 cm.

Table 1. The material properties of components used in the FEM

Material	Material type	Elasticity modulus (MPa)	Density (g/cm^3)	Compressive strength (MPa)	Tensile strength (MPa)
Concrete	C35	3.3×10^4	2.45	35	3.5
Reinforcement	B420C	2.1×10^5	7.83	420	420
Wall	Masonry Wall	7.8×10^3	1.00	5	0.5
Window	Float Glass	4.5×10^4	2.20	-	-
Air	Air	-	0.00123	-	-
Explosive	TNT	-	1.63	-	-

Each column has 8Ø18 longitudinal reinforcement bars. Stirrups are considered with Ø8/20 cm intervals for both columns and Ø8/20 cm around the column-beam connection points. The beams have 50×30 cm section. The section has 5Ø16 tension reinforcement bar, and 3Ø12 compression reinforcement bar. The stirrup in the beam is consered with Ø8/20 cm. In slabs; thickness is selected as 12 cm and the reinforcement is designed as Ø12/20 cm (Fig. 2).

The raft foundation has 21×13 m dimensions and has and 0.5 m thickness. The walls are designed as brick walls with a thickness of 20 cm. Windows and doors are incluede as glass and the thickness is taken into account as 1 cm. A stairwell has been created to observe the air diffusion.

The multi-story building has a reinforced concrete carrier system, which has three spans in one direction and five spans in the other direction, and the wall, glass, and shear wall elements have been taken into the system. The three-dimensional finite element model of the building created according to these assumptions and the positioning of the TNT explosives designed in the model are shown in Fig. 3.

3.1. Gauge points

In the study, pressures, stresses, displacements, and damages are obtained on the gauge points of the model. As can be seen in Fig. 4, each column and shear wall on the ground floor are individually numbered. A total of 27 load-bearing element behaviors have been studied.

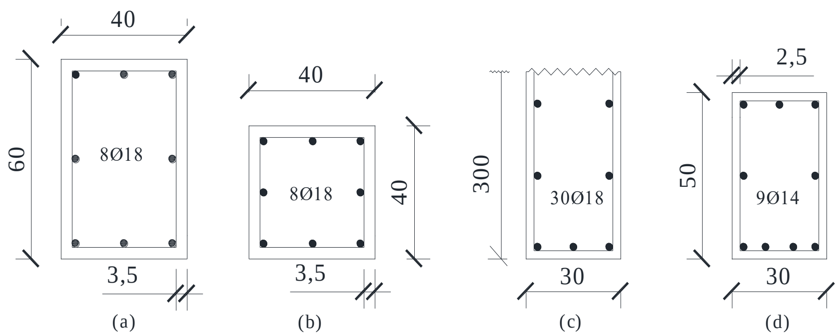


Fig. 2. Section properties of the building used for columns, shear wall, and beam (cm)

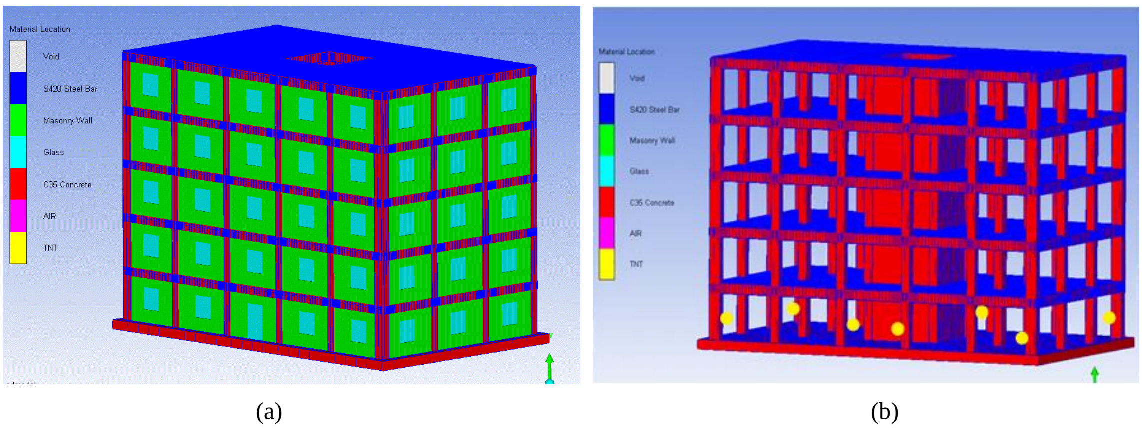


Fig. 3. Multi-story buildings: a) FEM, b) The positioning of TNT explosives

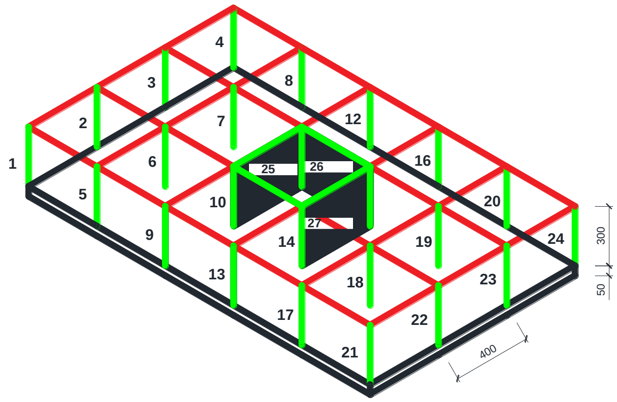


Fig. 4. The positioning of the columns

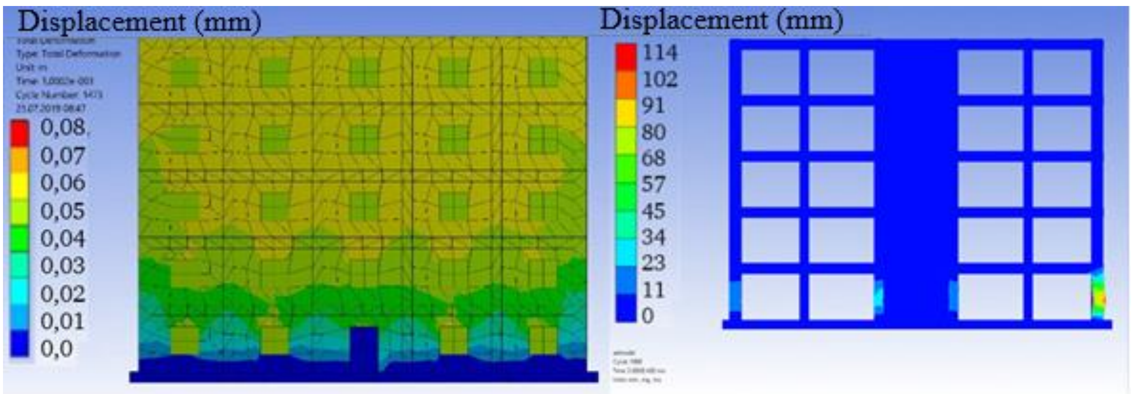
3.2. Blasting model

In the blasting model, 352 kg of TNT explosives were used in total and this explosive was used as 8 pieces (8×44 kg = 352 kg TNT); It is prepared adjacent to columns 1, 4, 9, 12, 13, 16, 21 and 24, i.e., the outer columns on the ground floor. In this study, it was firstly aimed to determine the behavior of the building under dead and live loads as statically, and then a blast analysis was performed to understand structural response under explosive load. Since the building is modeled as five stories, examination of the columns on the ground floor is considered the right approach in terms of providing a safe service life for the building.

3.3. Analysis results

3.3.1. Displacements

The displacement contour diagrams and graphs are respectively presented in Figs. 5-6 obtained for both static and blasting analyses. As inticated form Figs 5 and 6 that the displacements obtained from static analysis change in the order of 0.05-0.02 mm. While the blasting case is close to explosives, it is in the order of 25-30 mm on the columns. This means that the damage may occur in the basement columns and the transfer of the load-carrying capacity to the plastic zone due to this damage may cause great damage to the ground floor, and even collapse when we consider the 4 floors above the foundation floor, and this may cause the collapse of the whole structure.



(a) (b)

Fig. 5. The displacements of the FEM a) Static analysis b) Blasting case

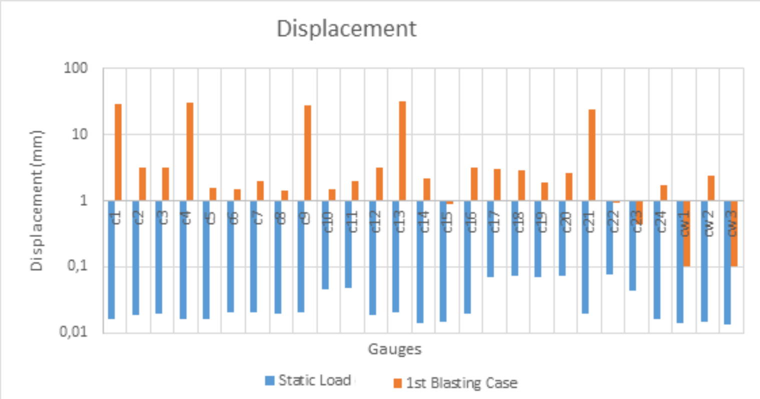


Fig. 6. Displacement values of static analysis and blasting case

3.3.2. Stresses

The stresses (Von-Mises) occured in the load-bearing elements on the mainframe of the building are examined on the contour diagrams (Fig. 7). As seein in Fig. 7 that the stresses are statically occured in the ground floor of structural system, and then the stresses are increased on the upper floor cosidering blast loading depending. Also, the damages are obtained on some elements. It is seen that the stresses occurring in the ground floor columns as a consequence of static loading can reach a maximum of 0.40 MPa.

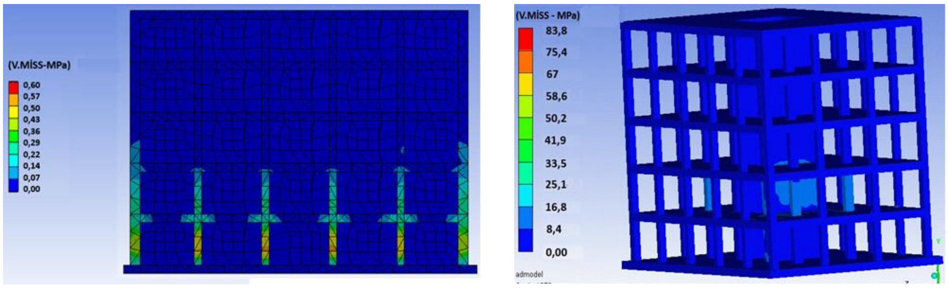
On the other hand, when the applied explosion is examined; it was observed that the stresses in the columns where the explosive was applied reached the highest point and exceeded the critical level (Fig. 8). According to the blasting case; when the outer columns are subjected to explosive effect; it was determined that it reached the level of 70-80 MPa and even exceeded the level of 100 MPa for columns 1 and 4. It is understood that the stresses on the columns and shear walls, where the explosive material TNT is applied, reached well above the critical level, which may mean that these load-bearing elements are broken down, although this is far above the capacity of the carrier system.

3.3.3. Material status

The damages on structural system of the building due to the blasting load is countered in Fig. 9 According to the Fig. 9 the columns are damaged at a rate of 100%, and the beams are damaged between 60% and 70% considering both of static and blasting analyses, and partial breaks are observed in the floors. However, when the elastic-plastic behavior of the structure is examined and the columns are destroyed, the beams are partially disintegrated - the parts that do not break behave like plastic, the shear walls around the stairwell behave partially plastic in the explosion situation case it completely disintegrates and loses its carrying capacity. The columns, which are closer to the explosives, on the outer part of the basement, are completely fragmented while the inner columns still behave elastically.

3.3.4. Pressures

The diagram of the explosion pressure on the system is shown in Fig. 10. It is seen that the pressure load on the outer columns where the explosive effects, the pressure reaches up to 18 MPa. Besides, the compressive load in the -Y direction of 3 MPa only affects the floors and beams, and the pressure in this direction can have a destructive effect on the beam. According to the pressure diagram, the pressure values occurring on gauges are plotted in Fig. 11. The biggest pressures occur on gauges 1, 4, 9, 12, 13, 16, 21, and 24. The other gauges on columns have smaller pressure values which are negligible.



(a) (b)

Fig. 7. Stress diagram of the FEM a) Static analysis, b) Blasting case

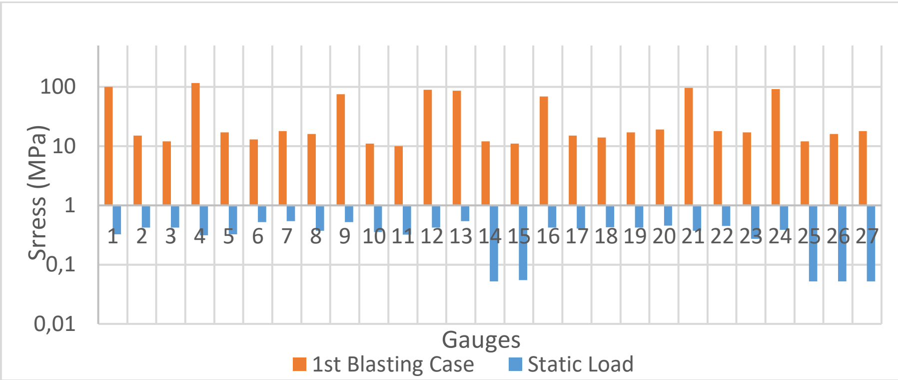


Fig. 8. Comparison of the von mises stress values of static analysis and blasting case

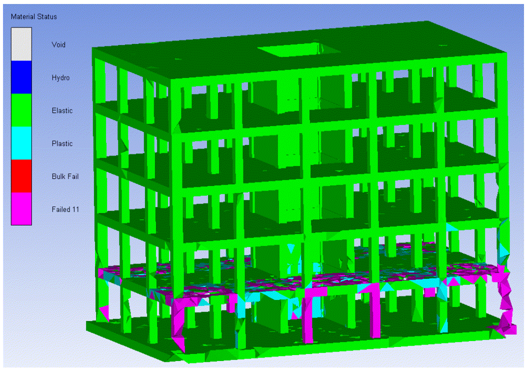


Fig. 9. Material status diagram of the FEM

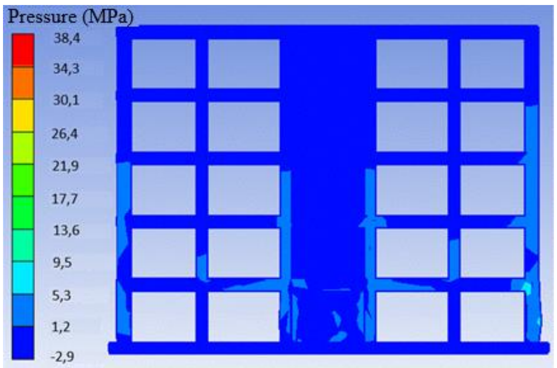


Fig. 10. The pressure diagram of the multi-story building

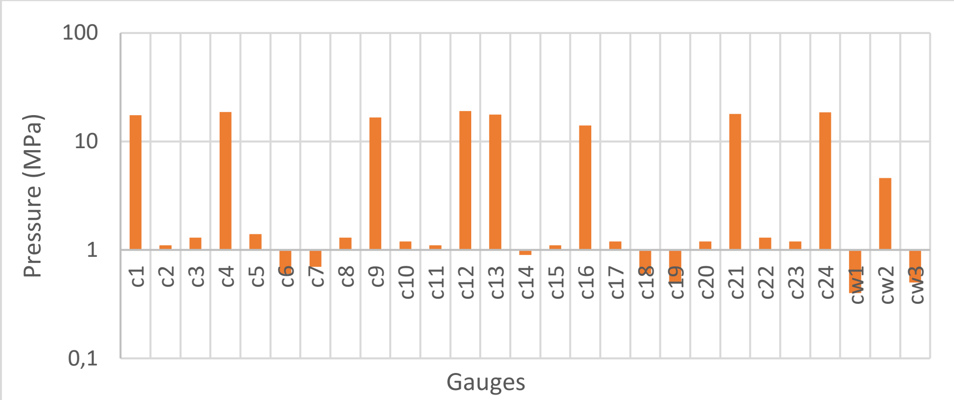


Fig. 11. Distribution of the pressure values measured in the blasting case

4. Results

In this study, blast effects are investigated on a 5 story RC building considering TNT explosive material which is placed in the columns on the ground floor of building. The detonation time is set to 3 milliseconds. In the Explosion Model, 352 kg of TNT explosives are totally used and the explosive is shared into 8 pieces (8×44 kg = 352 kg TNT). It is prepared adjacent to columns 1, 4, 9, 12, 13, 16, 21 and 24, i.e., the outer columns on the ground floor. The finite element model and analyses are performed using ANSYS Workbench and AUTODYN Module. The results obtained from the study are listed as follows:

- It is seen that the displacements in the columns after the explosion case is reached the value of 25-30 mm which can be critical over time.
- The stresses obtained from the blasting case are occurred on the columns at the level of 90-100 MPa. It is observed that the stresses formed on the carrier system on the ground floor increase suddenly. Also, the stresses are increased in the columns on the upper floors.
- When the damage level and material behavior are examined, it is observed that the columns closed to the explosive material are completely disintegrated, and the beams are partially fragmented.
- Brick walls and windows are extremelly destroyed after blasting analysis.
- The exterior columns are highly damaged when the interior colums are not due to TNT explosive positions. On the other hand two of the shear walls surrounding the stairwell. But when considering whole building, the structural system has much damages to be not used under operational conditions.
- The building exposed to blasting load may collapse overtimely under the environmental effects such as dead and live loads or other structural effects.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

This research has been supported by Yıldız Technical University Scientific Research Projects Coordination Department. Project Number: 2015-05-01-DOP02.

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