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The Best Location of Belt Truss System in Tall Buildings Using Multiple Criteria Subjected to Blast Loading

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Abstract

The main goal of this paper is to investigate the effect of blast phenomenon on structures to determine the best location of belt truss system in tall buildings. For this purpose, one of the exterior frames of a tall steel building, in which the belt truss is located, is considered. The steel frame model is subjected to two different charges of equivalent weight which are applied in two different standoff distances. In this research, the best location of the belt truss system is determined using OpenSees software based on the nonlinear dynamic analysis. The best location of the belt truss system for different types of loading is investigated both with and without considering the post-buckling effect for all members of the belt truss system. The results show that when blast charges are located in a 5-meter range from the building (R=5), post buckling effect of truss elements are more obvious than the case in which blast charges are located in a 10-meter range (R=10); this, in turn, causes the amount of base moment to be completely different when the belt truss is located in the first storey in comparison to the cases where the belt truss is located in any other stories. In addition, if the explosion occurs near the building when the base moment is considered as a criterion, the post buckling effect has a significant role.

Keywords: Blast Loading; Nonlinear Dynamic Analysis; Tall Building; Belt Truss System; OpenSees.

1. Introduction

In past decades, blast issues and earthquakes have received considerable emphasis. In comparison to blast loading, problems related to earthquake are older and this is because the former has been paid attention to only in the past 60 years. Generally, conventional structures are not designed for blast load due to complexity in analyzing the dynamic response of blast-loaded structures; this complexity might be due to issues such as the effect of high strain rates, nonlinear inelastic material behavior, uncertainties of blast load calculations, time-dependent deformations or high costs of design and construction. On the other hand, terrorist attacks on facility structures are increasing more and more. These factors reveal the importance of blast phenomena and examination of its effects on structures. Therefore blast issue and its effects have been studied and investigated from many different point of views and many researchers have investigated different parameters and problems in this domain such as progressive collapse issue, effects of adjacent structures on blast load, response of structure's member due to blast loading, etc. [1-6]. In 1959, Department of the Army of America published a manual titled "structures to resist the effects of accidental explosions" [7], which is the best known source in the literature for designing structures. The revised version is widely used by both military forces and civilian organizations to provide protection for the personnel and valuable equipment. Ngo et al. [8] presented an overview on the analysis and design of structures subjected to the blast load for understanding the nature of explosions and the

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mechanism of blast waves and dynamic response of various structural elements.

In the same line of research, Remennikov [9] studied methods of predicting bomb blast effects on buildings. He used simplified analytical techniques for obtaining conservative estimates of the blast effects on a building subjected to blast loading, produced by detonation of high explosive devices. Additionally, Liew [10] studied the effects of blast loading and fire attack on survivability of steel frame structures. He proposed a numerical method for modeling large-scale frameworks and generated fire–blast interaction diagrams to determine the fire resistance of columns, considering the initial damage caused by blast loads. Song et al. [11] proposed a method for nonlinear analysis of steel frame subjected to fire and explosion loading conditions. Their paper describes the component of beam-column formulations and discusses their incorporation within an adaptive analysis framework, which is largely responsible for considerable efficiency of the proposed method.

Since terrorist attacks on landmark structures such as tall buildings are more probable these days, special attention is paid to understanding blast phenomena and dynamic response of various structural elements. When the height of a building is more than a specific limit, rigidity and stability criteria are of greater importance than strength criterion, so determining the best structural system to resist lateral loadings, in this case, must be taken as the first priority. One of the effective systems to resist lateral loading is a belt truss on a braced core with exterior columns which is called belt braced system. This system assists a building to restrain the outriggers and bend the shear core by engaging the exterior columns and, consequently, decreasing lateral deformation as well as bending moment at base of the structure [12-17].

In tall structures with outrigger and belt truss system, one of the most important challenges is to determine the optimum location of belt truss system in order to decrease values of displacement of the roof, bending moment at the base of the building and the base shear. A Study on the stiff beam as an outrigger was initially carried out by Taranath [18]. He calculated the displacement at the top of the structure and the restraining moment at outrigger's place. This was done using structural analysis and mechanics of materials to determine the optimum outrigger location subjected to uniform loading. Additionally, Rahgozar and Sharifi [19] extended a mathematical model for a system consisting of framed tube, shear core, outrigger and belt truss system. They aimed to determine the optimum location of belt truss. Also, Lee et al. [20] adopted a continuum approach to idealize the wall-frame structure with outrigger as a shear-flexural cantilever beam with rotating springs and, in this way, they formulated the governing equation of the whole structure.

In another study, regular and irregular buildings with and without outrigger, with centrally rigid shear wall and steel bracings as outrigger, were modeled using equivalent static and response spectrum method. Responses of the structures were obtained and compared [21]. Mistry and Dhyani [22] investigated the behavior of 40–storey three-dimensional models of outrigger and belt truss systems subjected to wind and earthquake load with the objective to determine the lateral displacement reduction related to the outrigger and belt truss system location. In their study, the maximum reduction in displacement and shear force is obtained when the first outrigger is placed at 20th storey. However, the second outrigger is located at 10^{th} storey and the third outrigger is placed at 30th storey. Patil and Sangle [23] study high rise 2-D steel building models to find the optimum location of outrigger. They investigated the seismic behavior of different outrigger braced high rise steel buildings with different stories using nonlinear static pushover analysis. Results indicated that the position of outriggers in high rise building influenced the seismic performance significantly, which were considered in parameters like base shear, storey displacement, inter-storey drift ratio and performance point.

Kamgar and Rahgozar [24] assessed the optimum location of an outrigger-belt truss system based on maximizing the belt truss system's strain energy. Another study was conducted by Kamgar and Rahgozar [25] to determine the optimum location of a flexible outrigger-belt truss system based on maximizing the strain energy of system. In their study, the combined system of framed tube, shear core, belt truss and outrigger system was modeled using a continuum approach. The effect of outrigger and shear core system was considered as a rotational spring and was placed at the location of belt truss and outrigger system. Three types of lateral loading, i.e. uniformly, triangularly distributed loads along the structure's height and concentrated load at the top of the structure, were applied and the optimum location for outrigger and belt truss system was calculated. Lee and Tovar [26] used hybrid finite element types for a practical tall building simulation and solved the outrigger placement problem using topology optimization.

On the other hand, some studies have also investigated the blast effect on tall buildings. Kulkarni and Sambireddy [27] studied the dynamic response of a high rise building subjected to the blast loading. The blast loads were determined based on the methods of TM5-1300 and a nonlinear analysis by SAP2000, was used for evaluating the behavior of buildings from a general perspective to determine the total drift and the inter-storey drift. In this regard, Li et al. [28] carried out a study to determine the structural responses of a tall building subjected to close-in detonation in Singapore. The ABAQUS was used for modeling a 2D frame subjected to a charge of the equivalent weight of 1 ton of TNT which was located at two different distances. The effects of large deformations of beams and columns corresponding to the short time loading duration depicted by the explosions were analyzed from a local perspective. Fu [29] proposed a method to model direct simulation of blast load to examine the real behavior of a 20 storey tall building under blast load. The robustness of the building under the blast load was assessed by considering the duration of the blast load affecting the structure; a comparison was made between the proposed method and the APM (alternative path method).

In this paper, however, the best location of the belt truss system in a high rise building subjected to the blast loading is determined by considering some important parameters, such as bending moment at the base of the building, base shear, maximum displacement of the roof and the amount of strain energy. For this purpose, a 30 storey tall building strengthened by a belt truss system is considered here where one of the exterior frames with the belt truss system is modeled. The nonlinear dynamic analysis, which is performed by OpenSees software, is used for determining the optimum location of belt truss system. The best location of the belt truss system is determined in the frame building subjected to different amounts of blast loading caused by varying amounts of charge weight and different standoff distances of charge detonation. It should be mentioned that, in all different types of blast loading, the optimum locations are found for the building with and without considering post-buckling effect for the members of the belt truss system.

2. Blast Phenomenon

2.1. Blast Definition

Blast is a pressure disturbance caused by sudden release of energy. Loads resulting from a blast are created by a rapid expansion of the energetic material, creating a pressure disturbance or blast wave radiating away from the explosion source, as shown in Figure 1. Also, Shock waves are high-pressure blast waves that travel through air at a velocity faster than the speed of sound. As a blast wave travels away from the source, the pressure amplitude decreases and the duration of the blast load increases. Overexpansion at the center of the blast creates a vacuum in the source region and a reversal of gas motion. As a result, this negative pressure region expands outward, causing a negative pressure, which tails the positive phase. The negative phase pressure is generally lower in magnitude but longer in duration than the positive phase [30].

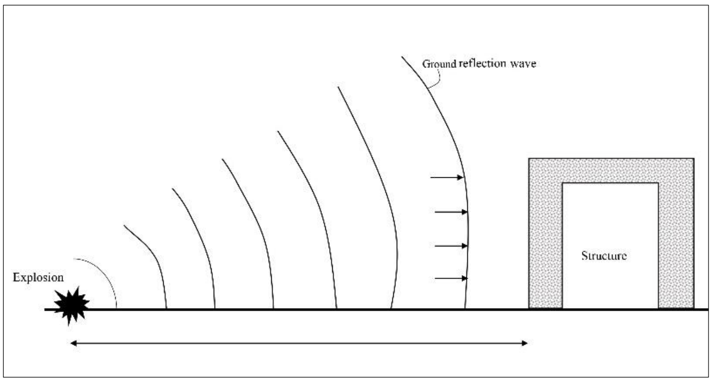


Figure 1. Propagating blast wave

2.2. Blast Parameters

Figure 2 shows a typical blast pressure profile. At the arrival time (t_A) following the explosion, pressure increases to a peak value of overpressure (P_{so}) over the ambient pressure(P_o). The pressure then decays to ambient level at time (t_d) which then decays further to an under pressure (P_{so}–) (creating a partial vacuum) before eventually returning to ambient conditions at time ($t_d + t_d$–). Here, the quantity (P_{so}) is usually referred to as the peak side-on overpressure, incident peak overpressure or merely peak overpressure [7].

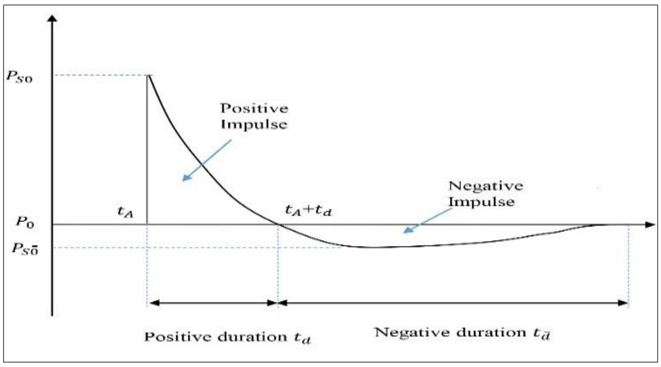


Figure 2. Shock wave from detonation

The most commonly used approach to present blast wave relationship for high explosive is the Hopkinson-Cranz or cube root scaling method which was introduced by Hopkinson and then was formulated by Cranz [30] . The cube root term results from geometric scaling laws in which charge diameter varies in proportion to all distances, and thus the charge weight is proportional to the cube of the charge diameter. The scaled distance parameter used for calculating blast parameters is determined according to following Equation:

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

Where R is the standoff distance from the blast source and W is the explosive equivalent TNT weight. There are different equations for predicting the blast load. One of them which has been introduced by Brode [31] is for estimating the peak overpressure due to spherical blast based on the scaled distance. This equation is as follows:

$$P_{SO} = \frac{6.7}{Z^3} + 1 \qquad (P_{so} > 10\ bar)$$

$$P_{SO} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \qquad (0.1 < P_{S0} < 10) \tag{2}$$

In order to calculate the maximum blast overpressure caused by a high explosive charge detonates at the ground surface, a relationship is introduced by Newmark and Hansen [32], too:

$$P_{SO} = 6784\frac{W}{R^3} + 93\left(\frac{W}{R^3}\right)^{1/2} \tag{3}$$

Also, Mills [33] introduced another expression to predict peak overpressure in KPa as follows:

$$P_{SO} = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \tag{4}$$

In this paper, Mills formulation is used to estimate the peak value of the overpressure due to explosion.

2.3. Different Modes of Blast Loading

There are three different blast loading situations in terms of the size of a structure and its dimension. The first is related to a blast wave interaction with a rectangular structure of finite size. The second situation is a blast wave interacting with a relatively small structure such as a vehicle that is effectively engulfed with blast pressure acting on all sides of the structure at once. Finally, the third situation is for a blast pressure acting on a relatively large structure such as a tall building, where the magnitude of the blast wave varies significantly across the surface of the structure. Some surfaces of these structures may see less if any external blast loading [34]. Since the blast effects on a tall building are studied in this paper, among the above mentioned condition, the third condition of the blast mode is effective for calculating the blast loads.

2.4. Blast Distribution

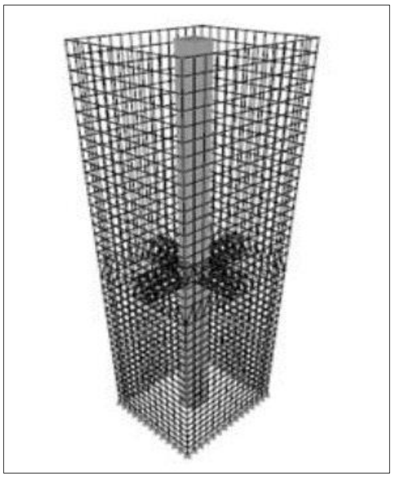
As mentioned in the previous sections, blast load parameters depend on scaled distance; so distribution of pressure and impulse over the facade of the building should be taken into account duo to unequal scaled distance of different heights on the façade. When the blast source is far away enough from the building, the distribution is approximately uniform. Also, it is significantly unequal at close range. For example, if the building is 70 m high and the range from the surface burst to the base of the building is 10 m, the range from the surface which is burst to the top of the building is about 70.7 m. The different ranges (scaled distances) result in different pressure, impulse, different arrival time t_A of the blast pressure and different positive phase duration (t_d). In this paper, as described in the following sections, the blast explosion occurred near a tall building, the range (R) and scaled distances (z) between the blast source and every point on the facade are calculated and the blast parameters are determined by considering angle of incidence (α). At last, blast load curves are calculated for different heights of the building.

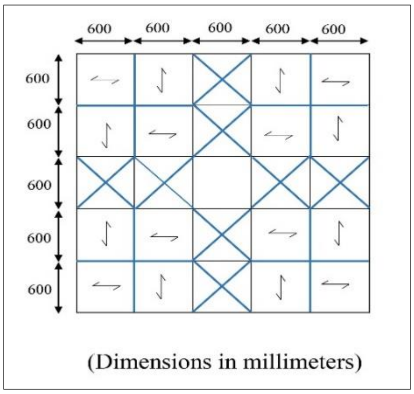
3. Modelling and Analysis

3.1. Modelling of Tall Building

In the present paper, a 30-storey tall building with outrigger and belt truss system is considered as shown in Figure 3. Then only one of the exterior frames as a two dimensional moment resisting frame is modelled specifically for dynamic analysis of blast load which is depicted in Figure 4; the reason for this choice is the placement of belt truss in exterior frames which causes them to resist lateral load and some part of gravity loads as well. In 3D model, the plane dimension of building is considered to be 30×30 meters. The building is analyzed and designed for static and earthquake loading using SAP 2000 program and LRFD method based on AISC 360-10. The dead and live loads are taken 500 and 300

(N/m^2), respectively. The height of each storey is 3.2 meter. The core stiffness is the same all over the building's height. All beam-column, connections are considered rigid and hinge connection is considered for all the outrigger-belt truss connections. In 2D frame which is modelled in OpenSees for dynamic analysis of blast load the dimensions of columns are considered as shown in Figure 4. All belt truss members have the same cross sectional area of 304(cm^2). For all beams of the first storey and stories twenty-sixth to thirtieth, W14× 22 is used and W21× 57 is the beam section of other stories. The first three natural frequencies of the building are 2.067, 5.928 and 9.817 (rad/sec), respectively. In addition, young modulus of elasticity for the used materials is 2×10^{11} (N/m^2) while the value of the yield stress is 248×10^6(N/m^2). The numerical model which is subjected to blast loading is shown in Table 1.





a) **b)**

Figure 3. a) Modeling of tall building with outrigger and belt truss system, b) Plane of building

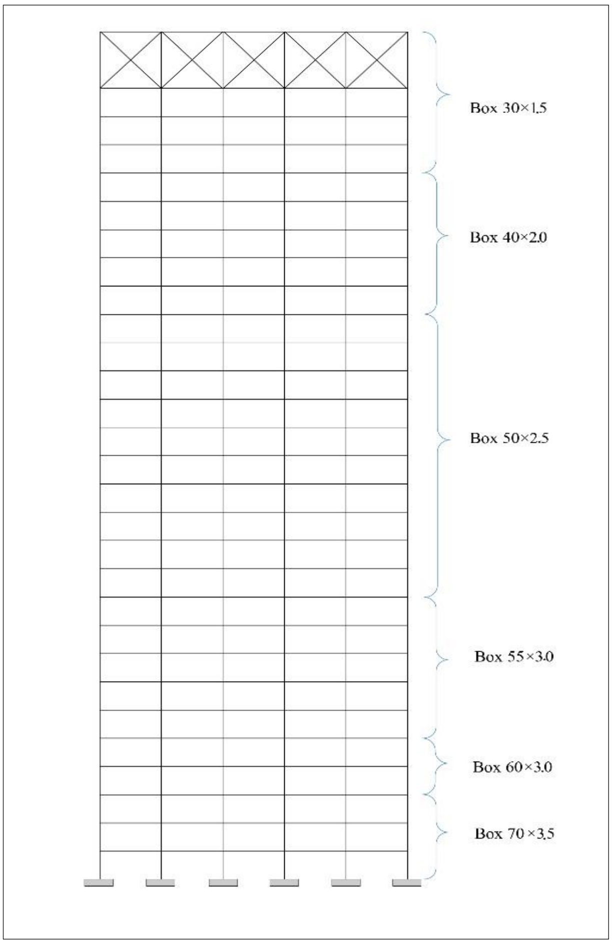


Figure 4. An exterior frame of tall building and the size of columns (dimensions in cm)

Table 1. Numerical model properties

Type of model	stories	Column section (cm)	Beam section (cm)	Structural properties
2D external frame in which the belt truss is located	1	Box 70*3.5	W14*22	Structure properties:
	2-3	Box 70*3.5	W21*57	Story height= 3.2 m with a bay of 6 *m*; Area of
	4-5	Box 60*3.0	W21*57	cross section of belt truss members=304(cm^2).
	6-10	Box 55*3.0	W21*57	Material properties:
	11-20	Box 50*2.5	W21*57	Fy=248 $\times 10^6$ (*N/m*^{2}); Fu=400 $\times 10^6$ (*N/m*^{2});
	21-25	Box 40*2.0	W21*57	Mass density=7698 (*kg/m*^{3}); Poisson's ratio=0.3;
	26-30	Box 30*1.5	W14*22	Modulus of elasticity= 2×10^{11}(*N/m*^{2})

3.2. Blast-Building Interaction

For studying the blast effects and dynamic response of the structure, four different levels of blast loading are considered. Two different standoff distances of 5 and 10 meters are considered and, for each range, the model frame is subjected to two different charges of the equivalent weight of 1 ton and 0.5 ton of TNT.

As mentioned in the previous section, the distribution of blast load significantly differs along buildings height; as distance to blast load is different for every single storey. For developing blast load time histories over building's height, a theoretical and empirical based approach is used. This simplified approach is consistent and compatible with the simplified numerical model selected for the structure, and its results are repeatable and easily reproducible [35].

Different stages used for determining the blast wave parameters for a surface blast are as follows. For all the equations, units of m, kg, kPa, and seconds are used for length, mass, pressure and time, respectively. First the weight of charge, W, in its TNT equivalent must be determined. In this paper 0.5 ton and 1 ton are considered as two different weight of charges. Then, for the point of interest (middle height of each floor), the standoff distance R_h can be calculated according to Equation (5) and Figure 5; where h is the height of each floor and R_G is the distance from the base of the building to the detonation location.

$$R_h = \left({R_G}^2 + h^2\right)^{1/2} \quad (5)$$

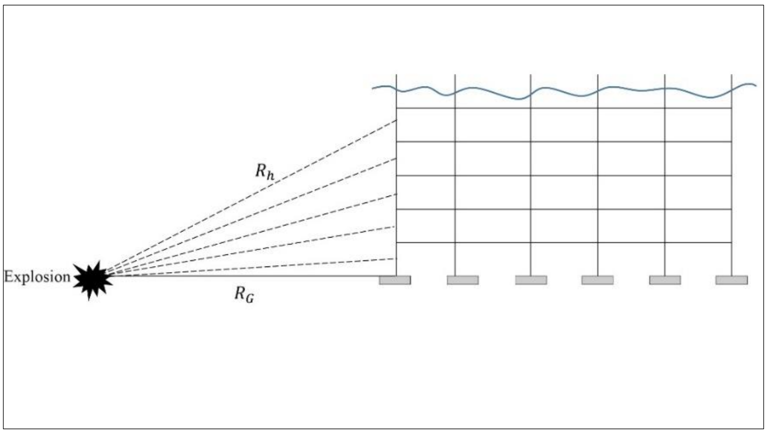


Figure 5. Geometry of building frame for calculating R_h

Then the scaled standoff distance (Z_h) is calculated using Equation (1) and all blast parameters are calculated based on determined Z_h as follows:

The peak value of the reflected overpressure (P_{so}) is calculated by an equation proposed by Mills, as described in the previous section. The positive time duration can be determined using Equation (6) proposed by Lam et al. [36].

$$t_0 = w^{1/3} 10^{[-2.75+0.27\log(Z_h)]} \quad (6)$$

The explosive wave front velocity U is defined by Rankine [37]:

$$P_{SO} = a_0 \sqrt{\frac{6P_{SO} + 7P_0}{7P_0}} \quad (7)$$

Where P_o is ambient air pressure (101 kPa typically) and a_0 is the speed of sound in the air (335 m/s).

The arrival time of blast wave for each point of interest is determined by Equation (8) as follows:

$$t_A = \frac{R_h}{U} \tag{8}$$

Coefficient Cr is calculated by Equation (9) which is given by Lam et al. [36] as:

$$C_r = 3\sqrt[4]{\frac{P_S}{101}} \tag{9}$$

Then the value of reflected overpressure is determined by:

$$P_r = C_r \times P_{so} \tag{10}$$

Finally, time history of blast pressure for each storey is determined based on the calculated parameters in the previous steps. Friedlander's equation is used for developing time history of the explosion pressure wave, which is usually described as an exponential function:

$$P(t) = P_o + P_r\left(1 - {}^{t}/_{t_o}\right) \exp^{-\gamma t/t_o} \tag{11}$$

In which γ is a parameter to control the rate of wave amplitude decay, defined as:

$$\gamma = Z_h{}^2 - 3.7Z_h + 4.2 \tag{12}$$

By multiplying the effective area of each storey by time history of blast pressure for that storey, the blast loading on each storey is determined. As an example blast loading for the first four stories of the frame building in our different explosion types are shown in Figure 6. As shown in Figure 6 in closer distance of blast detonation, the distribution of blast load on different levels are more unequal and the value of the blast loading, for the closer distance, is higher.

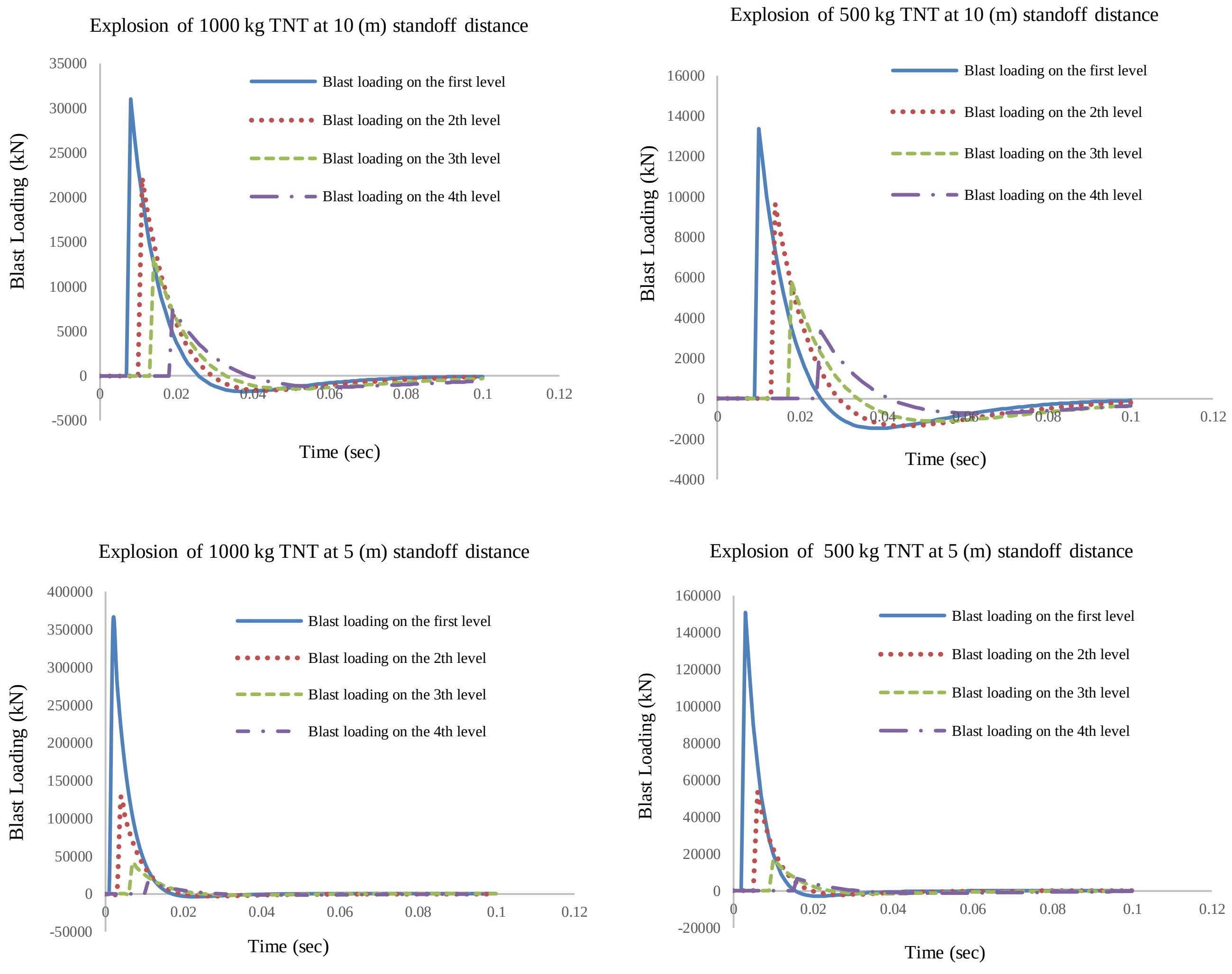


Figure 6. Blast loads of 500 and 1000 kg TNT at two different distances on the building

3.3. Dynamic Analysis

OpenSees software is one of the most powerful tools for nonlinear dynamic analysis of structures which is particularly popular in recent years. It is an open- source finite element software which is publically free to all. The software uses a very fast and powerful engine for analysis of different structures; these properties are the main reasons OpenSees is dependable and proper choice for academic research. In this paper OpenSees is used for time history analysis of frame building subjected to blast loading. For modelling and analysis of structure in OpenSees; property of materials and type of elements should be defined. Nonlinear beam column element is utilized for modelling all beams and columns due to its property in prediction of highly nonlinear inelastic material behavior .As one of the blast loading effects is high strain rate which causes enhancement of dynamic mechanical properties of target structures, the steel dynamic increase factor (DIF) is considered about 1.24 for yield stress and 1.1 for ultimate stress [7].

The time histories of blast loading determined in previous section are applied to the exterior columns of the frame building as linear loading. Applying blast load as linear loading is more precise relative to nodal loading at column-beam connection especially when the base shear and base moment as dynamic analysis outputs are focused. Since blast loading suddenly increases to a peak value and this sudden increase of blast loading might not be recognized by OpenSees, the value of blast loading should be increased with a steep slope from a few microseconds before the arrival time of blast from zero to the maximum value.

For obtaining the optimum location of belt truss, belt truss location has been moved from first to the top storey and each time blast loading is applied in order to determine the maximum value of base shear, base moment, roof displacement and strain energy. Moreover, optimum location of belt truss is found based on mentioned parameters.

For each amount of blast loading, the dynamic analysis is carried out for two different behaviors of the members of the belt truss system. In the first model, the truss elements with similar behavior in compression and tension are taken into account, while for the second model, the post-buckling effect is considered for the members of the belt truss system. In order to model post-buckling behavior of a truss element, a minor imperfection in the middle of truss element is made as shown in Figure 7 along with consideration of $p - \Delta$ effect.

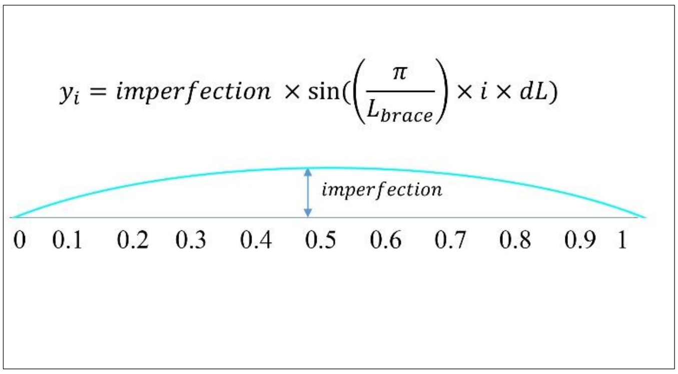


Figure 7. Modelling of truss element for considering post-buckling effect

4. Results

4.1. Base Shear

One of the main objectives of using a lateral load resisting system is to decrease the maximum amount of base shear. In order to compare the maximum value of base shear in different locations of belt truss system and to determine the best location based on this factor, the variation in amount of base shear caused by different placement of belt truss are calculated and depicted in Figure 8.

Each diagram is related to a specific blast loading with a specific amount of charge and a specific standoff distance. In addition, it presents the base shear for two kinds of systems, with and without considering post-buckling effect for the members of the belt truss elements.

As it is illustrated in Figure 8, for all different types of blast loading, a major difference is observed between the value of base shear when the belt truss is located in the first storey and when it is placed in other stories; base shear is greater in the first storey and therefore the first storey could not be an appropriate candidate as the belt truss system location. The changing pattern for the value of the base shear is similar in the two different kinds of systems: with and without consideration of post buckling effect. But only with consideration of post buckling effect, when the belt truss is located in the first storey, the value of base shear is greater than the other system. As the difference in the amount of base shear for other stories is not recognizable, when the first storey is included in the diagram, the optimum location of belt truss system based on these diagrams cannot be determined.

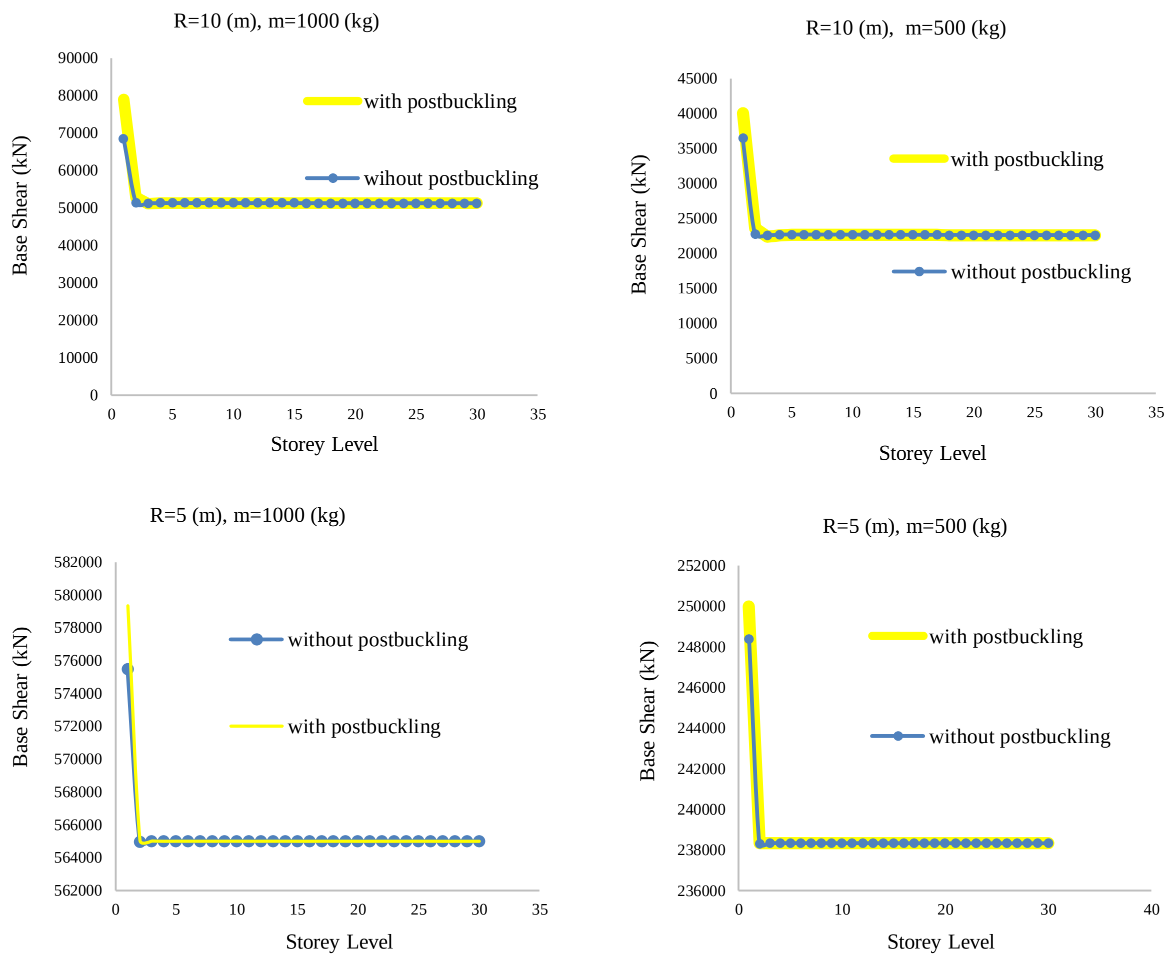
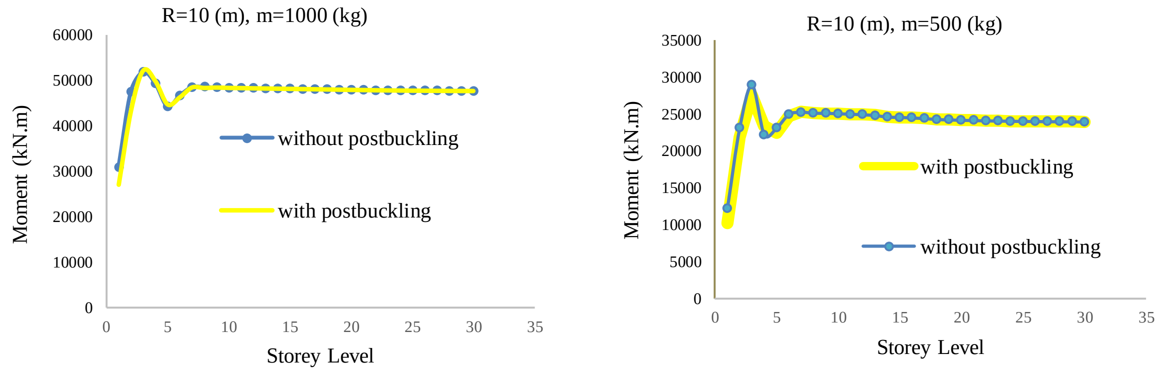


Figure 8. Base shear of the building frame as a function of belt truss location for different types of blast loading

4.2. Base Moment

The bending moment at base of the building is another major criterion which is considered here. Figure 9 shows the maximum value of bending moment as a function of belt truss level. According to Figure 9, when charge detonation distance from building frame is 10 meters long, the minimum amount of base moment is that of the first storey; this continues with a sudden increase for 2nd and 3rd stories and then stops. Therefore the maximum amount of base moment is acquired when the belt truss is located in the 3rd storey and for this reason 3rd storey is not a proper location for belt truss system, if base moment is consider alone; the best location is the first storey in which the minimum amount of base moment occurs. By comparing diagrams in Figure 9 it be concluded that when blast charges are placed in a 5-meter range from building, post buckling effects of trust elements are greater than 10-meter range and this causes a major difference between base moment of the first storey level and other storey levels in this system. Both systems (yellow and blue colour) in 5-meter range have the same changing patterns in base moment in different levels of the belt truss location, but as in the system with post buckling effect (yellow in diagram) the difference between first storey and other stories is much greater than the system without post buckling effect (blue in diagram), this similarity in changing pattern may not be recognizable.



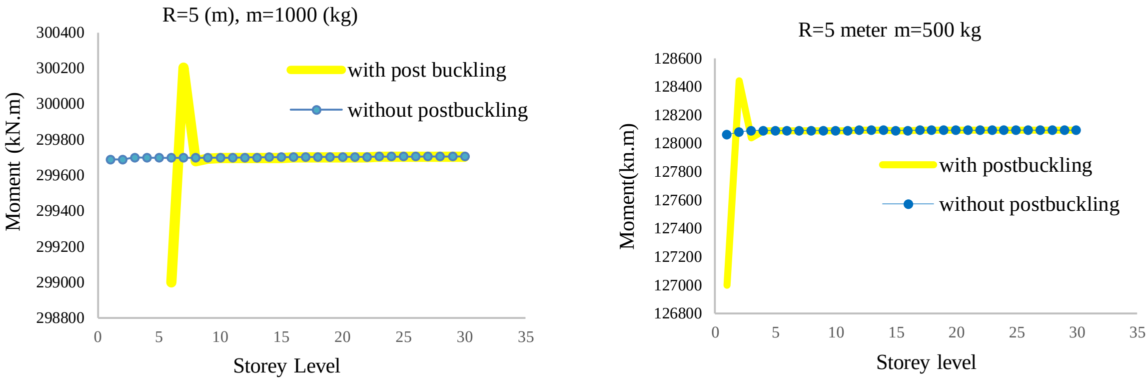


Figure 9. Base moment of the building frame as a function of belt truss location for different types of blast loading

4.3. Roof Displacement

The maximum roof displacements are obtained for different location of belt truss system all over the building and depicted in Figure 10. Since distances of detonation charges of this paper are considered among close range distances, effects of blast load are generally local and blast loading distribution over the building's height are unequal with the greatest amount at the base. Maximum roof displacements may not be considerable. As it can be interpreted from Figure 10, changing pattern of maximum roof displacement for different belt truss locations are similar for both systems in all different loading types and it is obvious that minimum roof displacement happens when the belt truss is located at the first or second storey which makes them idle candidates for belt system according to this criterion.

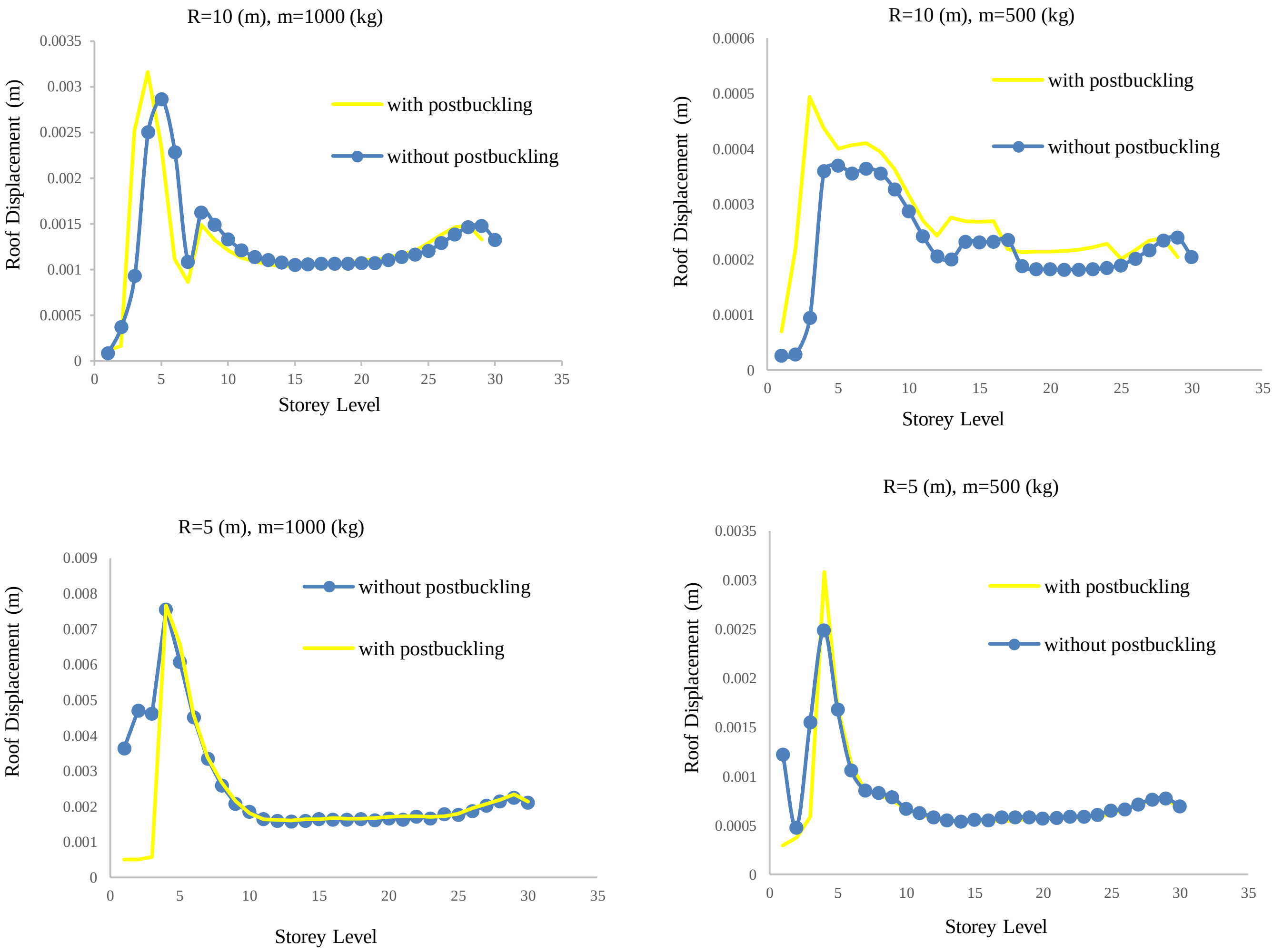
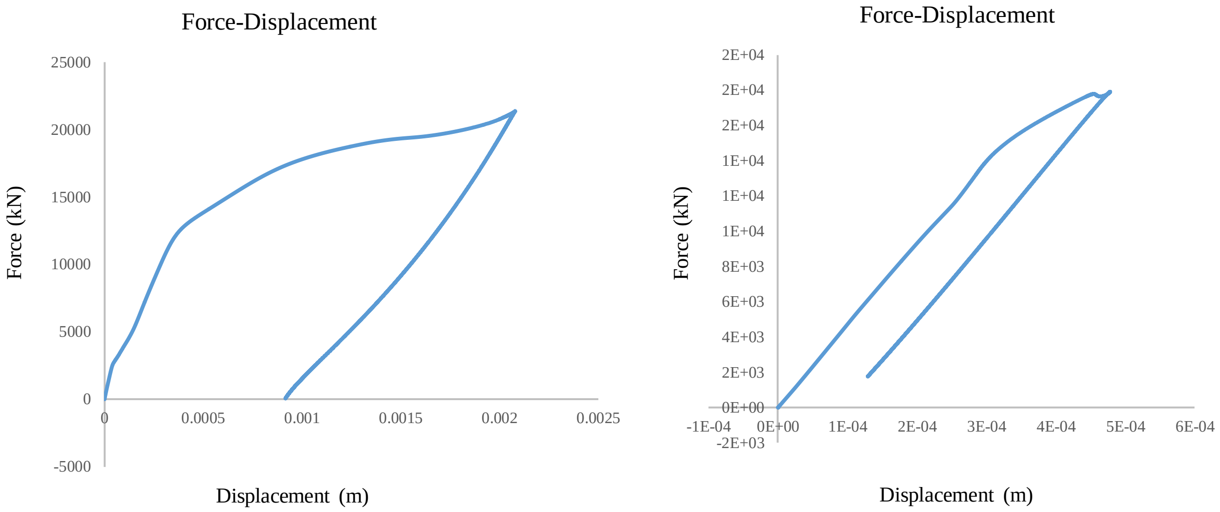


Figure 10. The maximum value of roof displacement as a function of belt truss location for different types of blast loading

4.4. Strain Energy

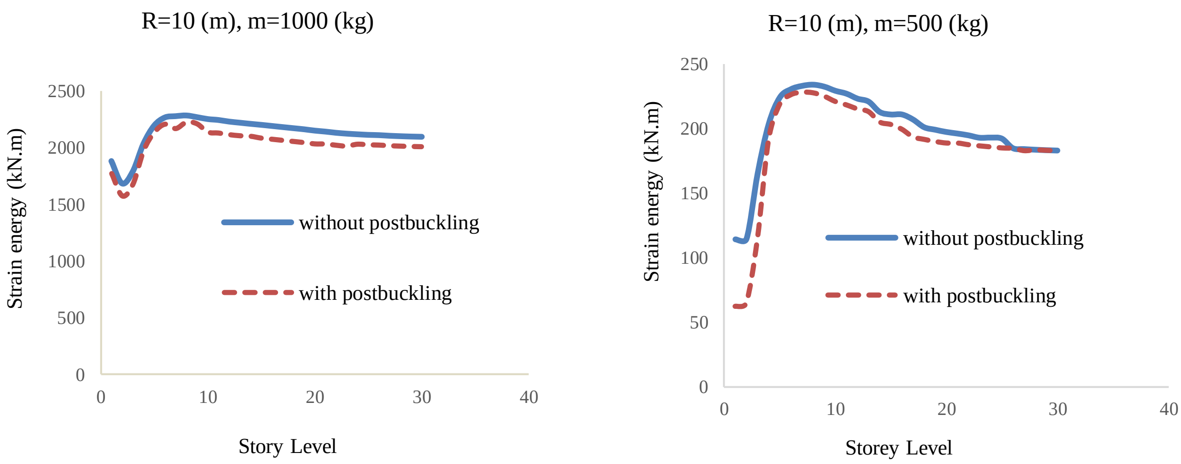
As the last criterion, the ability of the structure to dissipate the input energy is investigated to determine the best location of belt truss system. To this purpose, the displacement-force diagram for each element is obtained and the summation of area under displacement-force diagram of all elements as the whole amount of strain energy of the system is determined. Displacement force diagrams of one element for both systems are depicted in Figure 11 before calculating strain energy of all elements, as it can be seen, post buckling effect of the truss element influences the displacement force diagram and decreases the amount of dissipated energy.

The whole amount of strain energy for the storey level in which the belt truss is located is depicted in Figure 12. As shown in this figure, in all cases, the amount of dissipated energy in the system, in which post buckling effect is not considered (blue in diagram), is greater than the other system. Another point which can be understood from Figure 12 is that the minimum dissipated energy occurs when the belt truss system is located in the first three stories. The maximum amount of dissipated energy when the belt truss is located in one of 6th to 8th stories which can be good candidates for belt truss location with consideration of strain energy as the main criterion.



a) Without considering post-buckling **b) considering post-buckling**

Figure 11. Displacement force- diagram



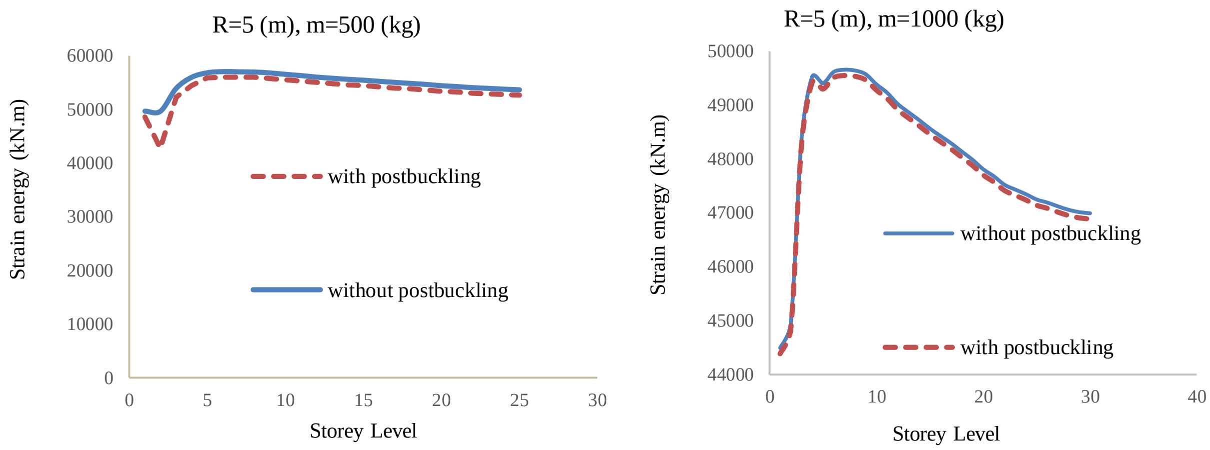


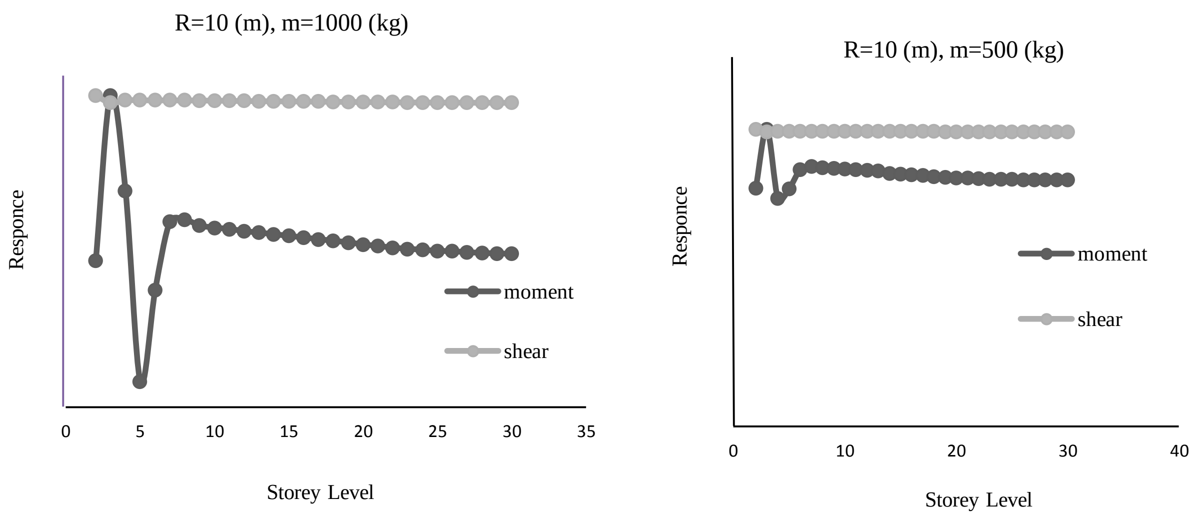
Figure 12. Amount of strain energy as a function of the belt truss location for different types of blast loading

5. Multiple Criteria

To determine the optimum location of belt truss system considering the combined effects of criteria discussed. As maximum roof displacements are not considerable due to close blast distances, this criterion is not combined with others. The three remaining criteria may be combined in three ways for all to determine the optimum location of belt truss system.

5.1. Base Shear and Base Moment

As discussed previously, when the belt truss system is located in the first storey, the base shear has its maximum amount and the base moment has its minimum which makes it a bad candidate for belt truss location based on these criteria. Therefore to determine the optimum location based on these two criteria combined, by removing the first storey from the results and combine the results of other stories for both of these criteria based on the location of belt truss system in a new diagram after normalization. The normalization is necessary to combine the results and divide all data of each criterion by its maximum amount. The results are shown if Figure 13. According to Figure 13 when the belt truss is located in the 2nd or 3rd storey, the values of base shear and base moment are opposite The first interactions of these two diagrams happens between 3rd and 4th stories in such a way that makes the 4th storey a good candidate for the best location of the belt truss system.



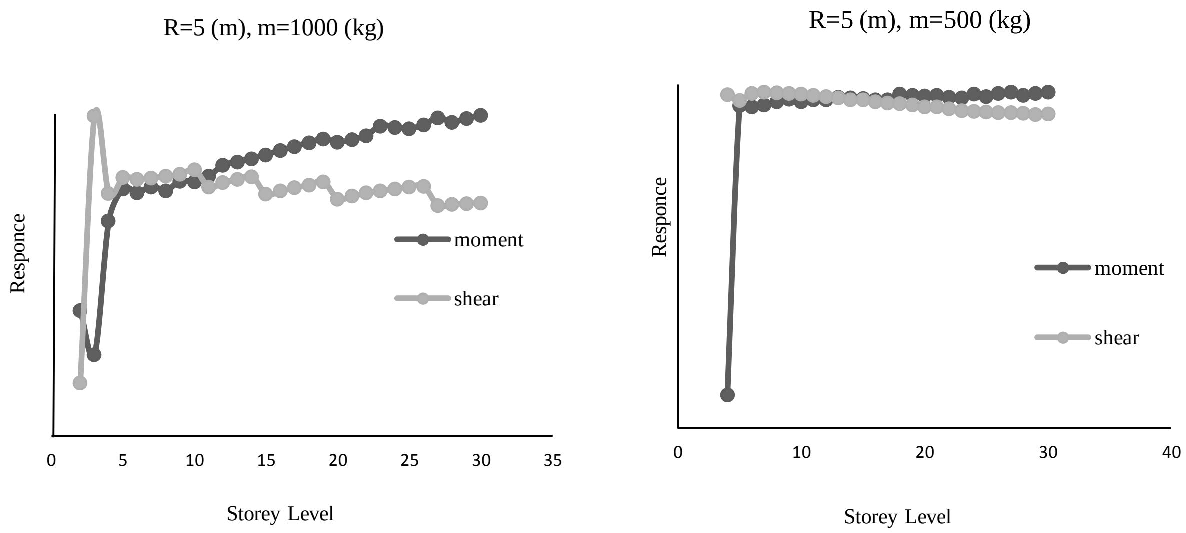


Figure 13. Variation of base moment and base shear based on the storey in which belt truss is located in for different types of blast loading

5.2. Strain Enrergy and Base Moment

From Figure 9 by considering the first storey among the results, the distinctiom of the base moment amount of other stories based on belt truss location would not be eailsy recognisable and readeable. So to determine the optimum location based on these two criteria first by removing the first storey from the diagram and then, by combining the results into a new diagram after data normalization of each criterion. The normalization process is exactly the same as previous section. The optimum location of belt truss system based on the combined results is achieved when the strain energy is at its maximum amount and the base moment is at its minimum. Changes in base moment and strain energy based on the belt truss location is illustrated in Figure 14. As shown in Figure 14, for the case in which R=5, base moment changes from 2nd to last storey is trivial in comparison to strain energy changes; so the optimum location is acquired when belt truss is located in one of the 6th to 8th stories, where the strain energy is at its maximum amount. The case in which R= 10, has minimum base moment in 2nd, 4th and 5th stories where the strain energy is not at its maximum amount. As the final conclusion it can be stated that by placing belt truss in one of 6th to 8th stories, the strain energy reaches its maximum amount in which the amount of base moment is also satisfactory; therefore one of the 6th to 8th stories must be chosen as the belt truss optimum location based on these two criteria.

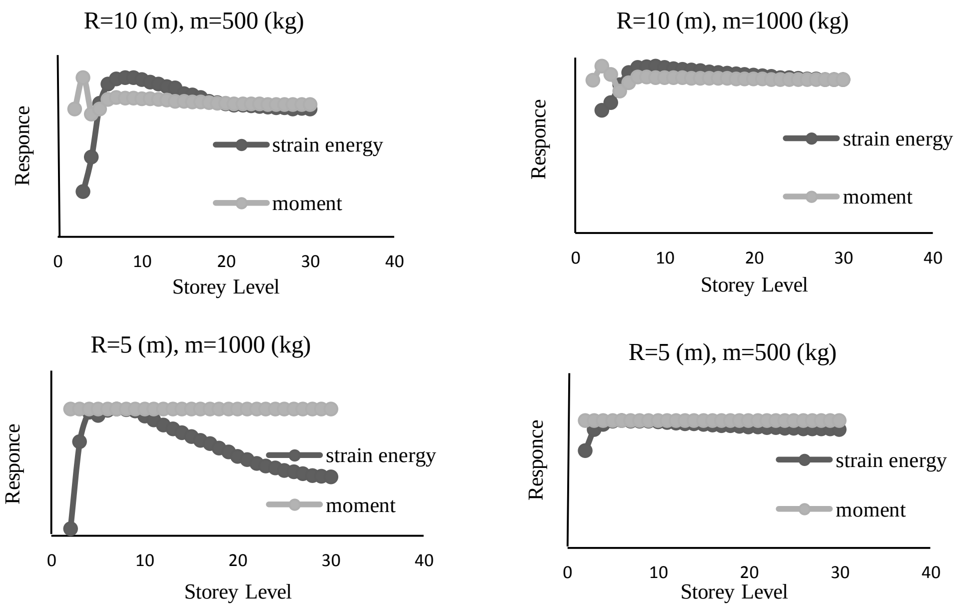


Figure 14. Variation of base moment and strain energy based on the storey in which belt truss is located in for different types of blast loading

5.3. Strain Enrergy and Base Shear

Finally, base shear and strain energy are taken into account simultaneously. First storey is not included in the results for the same reason. Different strain energy and base shear amounts for different belt truss locations are depicted in Figuret 15 for all different types of blast loadings. In all cases, the changes of base shear are not significant so to achieve the best location, one of the stories from 6th to 8th stories is chosen in which the strain energy has its maximum amount.

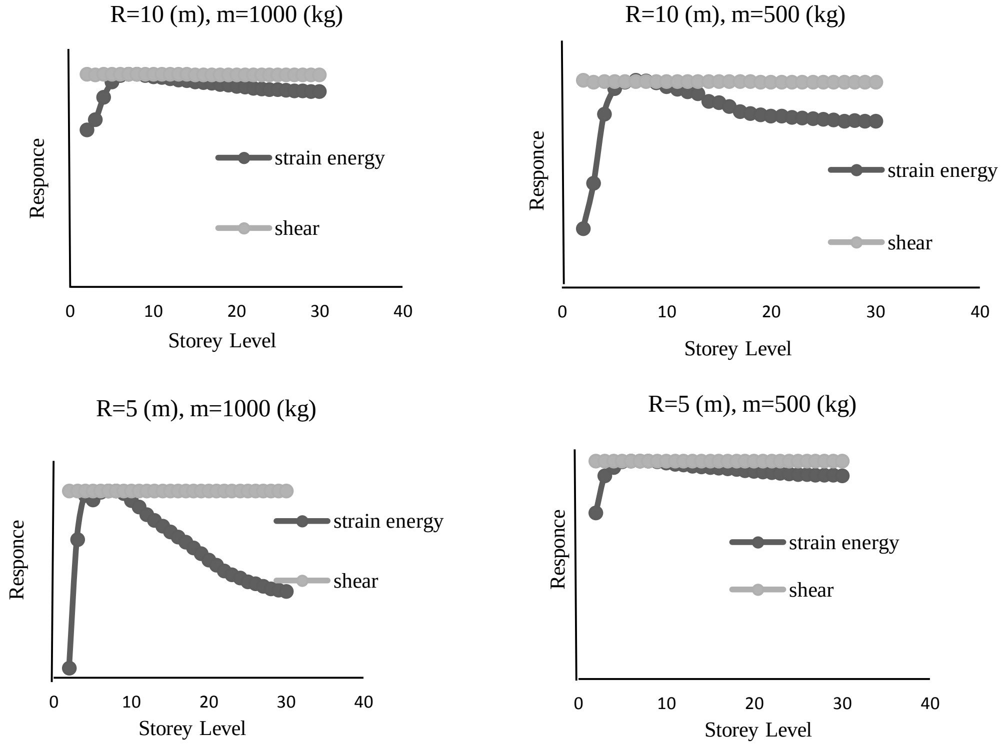


Figure 15. Variation of base shear and strain energy based on the storey in which belt truss is located in for different types of blast loading

6. Conclution

In this paper the optimum location of belt truss system based on a couple of criteria using nonlinear dynamic analysis by OpenSees is determined. The criteria considered in this paper are bending moment at the base of building, base shear, maximum displacement of the roof and strain energy. Four different types of blast loading each time with and without considertation of postbuckling effect are considered. As the final result the optimum belt truss location considering every criterion first alone and then togther. Pounding effect as the top priority, maximum displacement criterion must be chosen to determine the optimum location of belt truss system, in that case the first storey is the optimum location. If damage is the top priority, by decreasing base shear and base moment; and with consideration of these two criteria together, fourth storey is the optimum location of belt truss system. If the amount of dissipated energy is the priority, strain energy is the criterion to consider for specifying the optimum location of belt truss system. This criterion considered alone or alongside any other criterion makes one of the sixth to eighth stories optimum location for belt truss system. Also the results show that when blast charges are located in a 5-meter range from the building (R=5), post buckling effect of truss elements are more obvious than the case in which blast charges are located in a 10-meter range (R=10); this, in turn, causes the amount of base moment to be completely different when the belt truss is located in the first storey in comparison to the cases where the belt truss is located in any other stories.

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