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Response of Elasto-Plastic SDOF Structure Under Blast Loading

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Abstract: In spite of the plastic behavior of structure is not often allowed under continuous operating conditions it is quite fit for design when the structure is under loading that only occur a few times during its life. The object of this study is to investigate the response of elasto-plastic SDOF structures subjected to blast loading with different TNT quantities and standoff distances. Numerical analysis by SAP2000 Ver.18 based on bilinear structural resistance function was used in this research. Different structural resistance function values were investigated as a ratio of elastic response resistance function to obtain the degree of economy that satisfied from each case. The result of analysis show, although the maximum displacement of the elasto-plastic system is greater than that of the purely elastic structure, the difference in term of structure capacity is significant. It is concluded that elasto-plastic analysis become entirely feasible, quite appropriate and effective for design of structures subjected to blast load.

Key words: Blast load, elasto-plastic SDOF system, resistance function, dynamic response, TNT, standoff distance

INTRODUCTION

Dynamic structure analysis and design has been important and increasing steadily over the years. Advanced technology with larger and lighter structures led to urgent updating the design phenomena in dynamic field. Flexible structures with longer natural periods are more sensitive to dynamic forces such as suddenly applied loads as blast load.

Literature review: Even considerable efforts have been encouraged to find the structure responses subjected to dynamic loads, few attempts to understand the blast load phenomena and the response of structures under different explosion strength. Due to complexity of blast load problems, the literature in this field at the beginning was depicted on review researches. Remennikov (2003) examined some simple methods for predicting the blast load effect on structures. He used a simplified analytical approaches based on Lagrange numerical solution and other similar solution to predict the response of structure under explosion. While, Ngo *et al*. (2007) was written an overview on blast load and blast influence on structures. This review study essentially focuses on blast concept. Due to the risk from such extreme loading conditions, attempts have been made during the past three decades to develop suitable methods of structural analysis and design to with stand the expected blast load. Their final conclusion was the analysis and design of structures subjected to blast load requires a detailed understanding of blast phenomena and dynamic response of various structural elements. Draganic and Sigmund (2012) described the steps required to find the blast load on buildings. They solved a numerical problem of a typical structure subjected to blast load. Their results were it is possible to simulate the response of a structure under blast loads with SAP Software. Rempling *et al*. (2014) made a review of research on strengthened concrete structures subjected to impulse and blast loading. Their purpose of the review report was to make a summary of ongoing research of strengthening of concrete structures subjected to impact load and its aim was to collect, analyze and summarize existing knowledge.

Many other attempts in the literature studied the response of structures subjected to general dynamic load or blast load in purely elastic range only. Park and Krauthammer (2009) analyzed inelastic two degree of freedom roof frame under blast load. The study done based on development of force equilibrium equations to consider beam-girder interaction and to assess if this model can give a reasonable design approach. Wang *et al*. (2013) proposed a new SDOF method for one-way for reinforced concrete slab under non-uniform blast loading. In this study one way square and rectangular reinforced concrete slab were used. The model was validated with experiment. The test results showed that the model is accurate in predicting the damage level. Aydin (2014) studied the optimal distribution of springs that support cantilever beam. In this study, the optimal size and location of the springs were fixed to reduce the deflection at the tip of cantilever beam. The optimal design recorded from this study was compared with the

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uniform design based on frequency and time responses. While, Lin *et al.* (2016) presented a new mathematical derivation for the elastic solution of the effect of dynamic point load on an isotropic multilayered half-space. The numerical simulation in this study was made on linear algebraic matrix operation.

In the recent year, little attempts in the literature covered a non-linear response of structure subjected to dynamic load especially when the dynamic load is a short duration load. Qureshi and Madhekar (2015) suggested the 3D nonlinear dynamics analyses of typical 45 multi storey building under blast loading. The response of this building was investigated under the influence of different TNT, standoff distance and source height. It had been observed from this study the dynamic response is random and not maximum at top storey. Sabuncu *et al.* (2016) studied the static and dynamic stability of cracked multi storey steel frames. In this study, the influence of storey number, crack depth and crack location in-plane static and dynamic stability of cracked multi-storey frame structures under periodic loading had been investigated numerically.

In this study, the inelastic behavior of structures subjected to blast load with different TNT and standoff distance is investigated. Dynamic design of structures that respond beyond the elastic limit has become practical. However, design of structures subjected to dynamic loads which remain completely elastic resulting uneconomical study. The energy absorption resulting from the structure material plastic deformation leads to a much lighter study than required if all energy had to be absorbed by elastic strain only.

MATERIALS AND METHODS

Blast phenomena: The blast load resulting form an explosion can be defined as a rapid and abrupt release of energy. When the explosive material reacts, huge amount of heat and dense gas with strong explosive pressure wave emitted. So, the explosion is represented in a wave of high-intensity that spread outward from the source to the surrounding air. The strength and speed at this wave decrease as the wave propagates. The main characteristic of any explosion are the TNT (Trinitrotoluene) and standoff distance (R) which is the distance between the explosion center and the target. The TNT is measured based on the specific energy of the charge which is equal 4524 Qx/kJ/kg. Other explosive material is converted to an equivalent mass of TNT (Cormie *et al.*, 2009; Mays and Smith, 1995).

The typical actual, idealized and simplified blast pressure profile is shown in Fig. 1. In the actual pressure profile, the pressure wave is describing as an exponential function Fig. 1a. Whereas the idealized pressure profile is shown in Fig. 1b which is drown based on equivalent impulse principle. Often, the negative pressure phase is remaining for a duration longer than the positive pressure phase and it has a slightly effect on the analysis of structures under blast load comparing to the positive one. For this reason the simplified pressure profile is used in this study for elasto-plastic analysis of SDOF structures as shown in Fig. 1c (Paz, 2004; Chopra, 2007; Needham, 2010).

The blast load main parameters, peak reflected pressure and the equivalent positive phase duration which are provide the basic data for design of structure

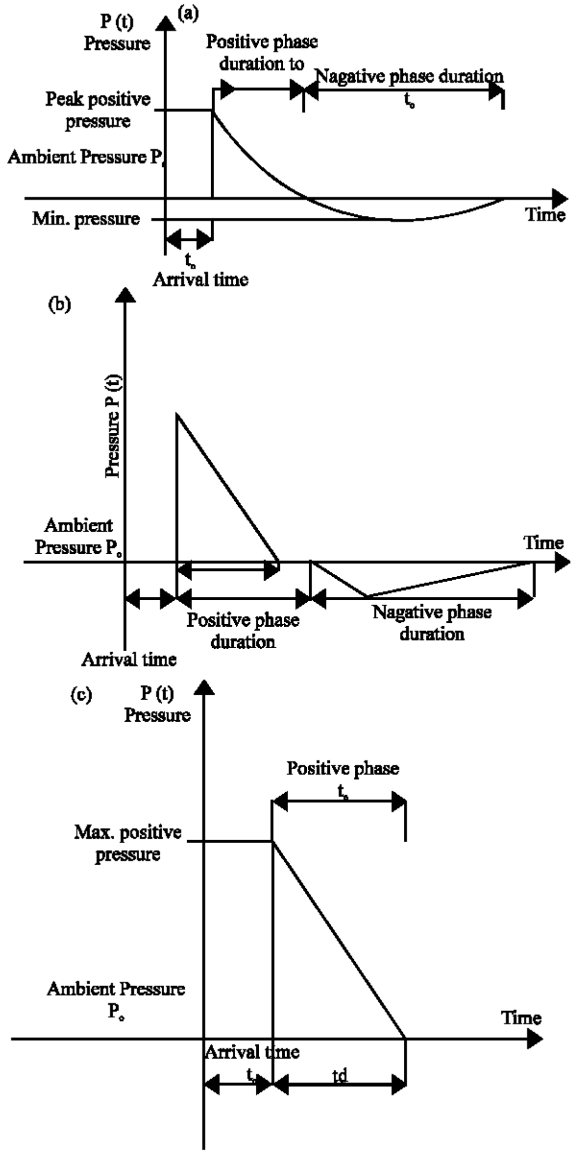


Fig. 1: Different types of pressure profile; a) Actual pressure profile; b) Idealized pressure profilec and c) Simplified pressure profile

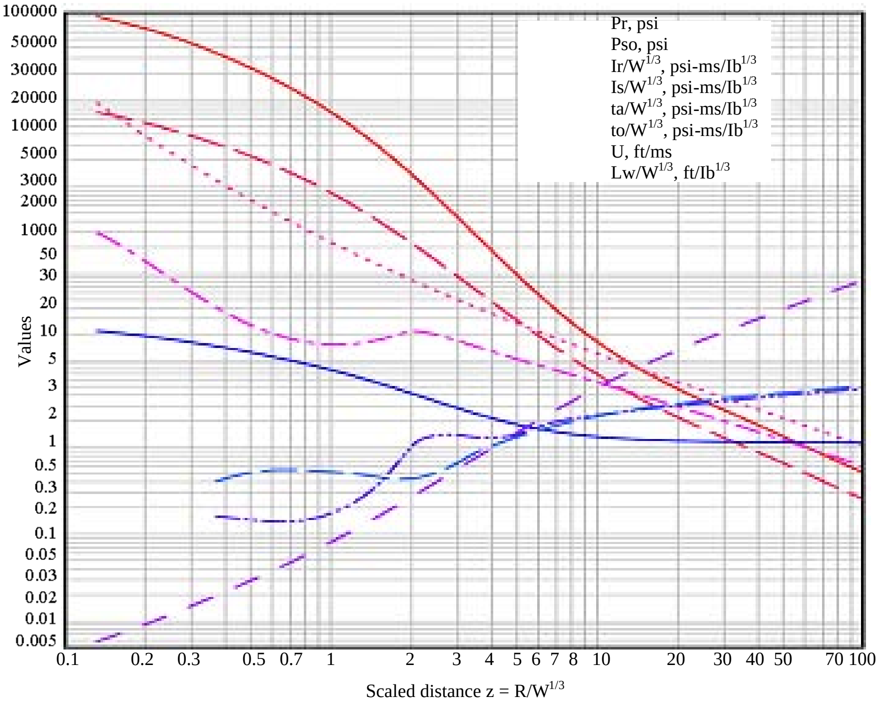


Fig. 2: Parameters of positive phase for spherical wave (on air) (Anonymous, 2008)

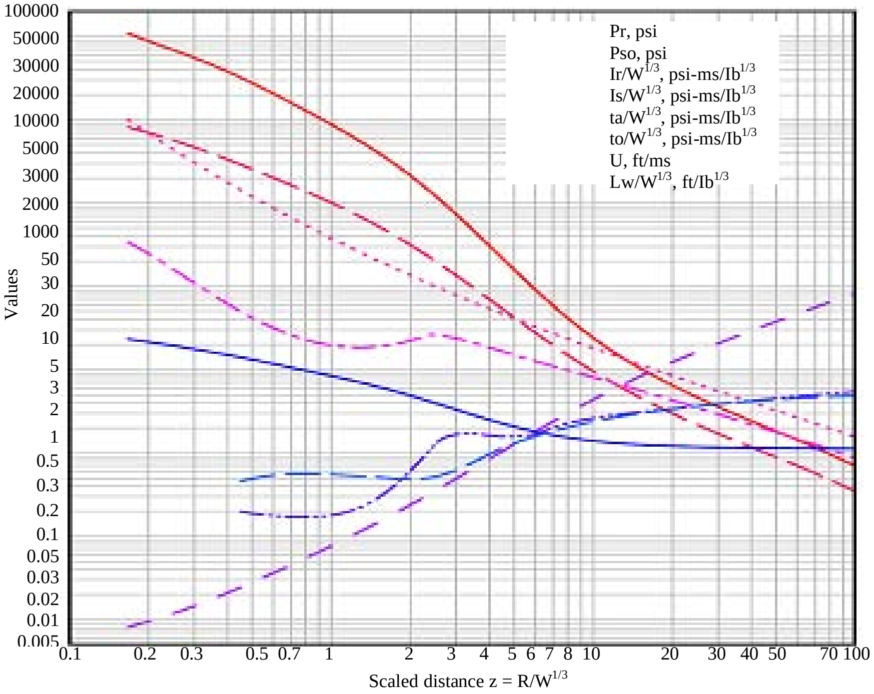


Fig. 3: Parameters of positive phase for hemispherical wave (on ground) (Anonymous, 2008); a) SDOF system; b) Elastic free body diagram and c) Elasto-plastic free body diagram

under explosions are illustrated in diagram based on Unified Facilities criteria (Anonymous, 2008) as in Fig. 2 and 3 for spherical (free-air) and hemispherical (surface) bursts, respectively (Bulson, 2014; Olarewaju, 2013; Anonymous, 2008). Although, there are few information available for bursts at a finite height above the ground, these are rarely necessary for design purposes and the hemispherical surface bursts provides an adequate upper bound. The present study analysis was based on the blast parameters from chart. Evaluate the scaled charge distance $Z = R/W^{1/3}$ which represent the X-axis in the UFC standard diagram of hemispherical surface burst which is generally simulate the real explosion that take place in most terrorist regions. The basic concept of Fig. 2 and 3 is based on empirical method for huge data of explosions with different TNT quantities and standoff distance. For determining the blast load parameters, the following steps are necessary:

- Find the equivalent mass of the charge in term of TNT (W)
- Determine the distance between the explosion centre and the target, standoff distance (R)
- Finally, the explosion parameter can be found easily from the Y-axis of the (Anonymous, 2008) standard diagrams

One-degree elasto-plastic system: If the structure is covered by one type of motion then is termed as a Single Degree of Freedom (SDOF). To formulate the equation of motion for SDOF structure (Clough and Penzin, 2003) the mass is isolated as in Fig. 4a represents the SDOF structures under blast load.

If the structure behavior purely elastic then the structural stiffness is linear as like linear-elastic spring which means that the force in the spring is equal to the spring stiffness multiply by the displacement. For this type of behavior the dynamic equilibrium free body diagram is shown in Fig. 4b and the equation of motion will be as:

$$m\ddot{u}+Ku = F\ (t) \tag{1}$$

Knowing that Eq. 1 can be used only for linear purely elastic SDOF structure. Because the resistance function ($R = Ku$) has been linearly proportion with stiffness (K) of the structure.

The resistance function (R) in linear elastic system does not have an upper limit which is defined the maximum resistance (R_m) allowable by any structure. In reality, the stiffness of the resistance function is not constant. Further more when the structure is unloaded the resistance does not return to zero. Therefore, the resistance function is very important in structural design subjected to blast load because a much greater portion energy-absorbing capacity of the structure is used thereby. The economy of the design by considering elasto-plastic behavior can be significantly increased by employing this concept into account.

In Fig. 4c, the structure behaves as elasto-plastic system and the stiffness of the structure is assumed to have a bilinear resistance function (R) as drawn in Fig. 5. From this figure as the displacement increases from zero, the structural resistance increases linearly with a stiffness (K). The maximum structural resistance value has been reached with linearly progress when the displacement increases and reached to maximum elastic limit (u_{el}). When the displacement increases farther it has been shown from

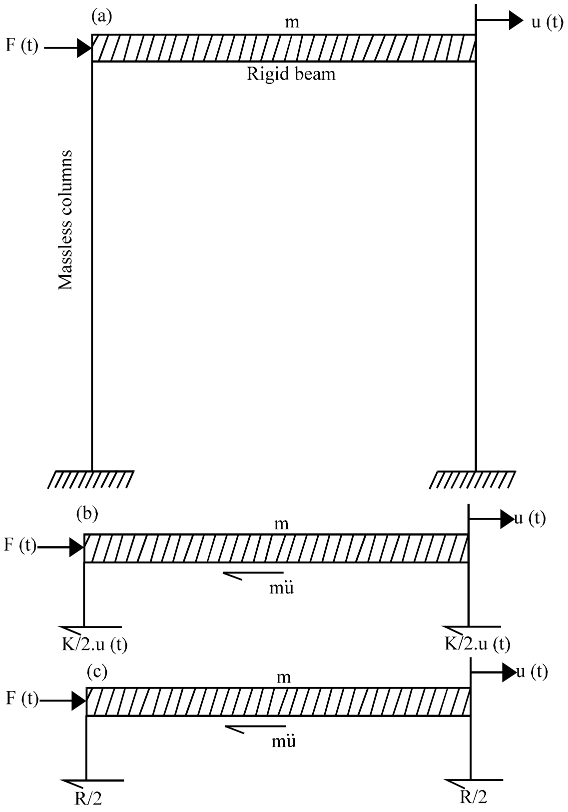


Fig. 4: SDOF structure diagrams

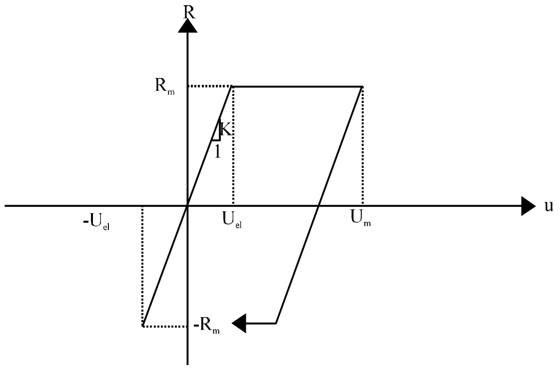


Fig. 5: Idealized resistance function for elasto plastic system

this Fig. 5 the structural resistance is still constant which is called maximum resistance to the structure (R_m). The maximum resistance of the structure is related to the maximum ductility limit of the structure itself. Sometimes, the displacement reaches a maximum elastic limit before the resistance of the structure (R) reaches the maximum allowable resistance (R_m) and then decreases, the structure in this case is said to be "rebound". In rebound range, the resistance is still decreases linearly at the same time of initial elastic slope until the resistance of the structure attained to the maximum structural resistance in the negative sign ($-R_m$). In actual structure, the resistance function is always represented by a curve transition instead of sharp break idealization. In this study, this idealization is assumed adequate for most of civil structures, especially when subjected to blast load (Biggs and Biggs, 1964; Kyei, 2014; Moon, 2009).

For elasto-plastic structure, a dynamic equilibrium of the forces shown in free body diagram of Fig. 2c at any time using D "Alembert's principle can be applied directly. Then the equation of motion of this system can be written as:

$$m\ddot{u}+R = F\ (t) \tag{2}$$

$$m\ddot{u}+Ku = F\ (t)\ \ 0 < u < u_{el} \tag{3}$$

$$m\ddot{u}+R_m\ =\ F\ (t)\ u_{el}<u<um \tag{4}$$

$$m\ddot{u}+R_m\text{-}K\ (u_m\text{-}u)\ =\ F(t) \tag{5}$$

When:

$$(\ u_m\text{-}2\ u_{el})<u<u_m$$

Equation 3 represents the general equation of motion for elasto-plastic SDOF structure. Whereas Eq. 3 and 4 used for both elastic and plastic parts, respectively. While, Eq. 5 used during the elastic behavior after maximum displacement limit (u_m) has been reached.

RESULTS AND DISCUSSION

The SDOF purely elastic and elasto-plastic responses under blast load are investigated using two values of TNT (100 and 200 kg). For each value of TNT, the responses of the purely elastic and elasto-plastic of SDOF structural system with two different standoff distances (30 and 50 m) are recorded. The objective of this study is to compare the purely elastic behavior as a displacement varying with time with the displacement time history based on elasto plastic behavior.

Both purely elastic and elasto-plastic dynamic solutions are done base on numerical analysis by SAP Ver.18. The results of the numerical analysis are plotted in Fig. 6-10 for different value of blast strength. For the sake, of comparison both purely elastic and elasto-plastic solutions for different values of structural capacity or stiffness resistance are shown in same Fig. 5.

In Fig. 6 with 100 kg TNT and 30 m standoff distance, the maximum stiffness resistance was 27.16 kN based on purely elastic solution. This value is compared with different value of structural resistances (6.79, 13.58 and 20.37 kN) based on elasto-plastic solution which represent the one-quarter, one-half and three quarter of the maximum elastic resistance required. One other solution is added when the structural resistance for elasto-plastic behavior equal to the maximum structural resistance required based on purely elastic behavior which is equal to 27.16 kN. Only the SAP nonlinear solution results for this case are shown in Fig.6a while the other cases are not shown as SAP representation due to availability of space. Many interesting notes can be resulted from Fig. 6b. First, the maximum displacement of both purely elastic and elasto-plastic SDOF structure are coincided when the stiffness resistance (which is equal to 27.16 kN) of elasto-plastic solution is equal to the maximum structural resistance (which is also equal to 27.16 kN) of purely elastic one.

Secondly, the maximum displacement of elasto-plastic system, based on stiffness resistance equivalent to one quarter (6.79 kN) of the maximum purely elastic stiffness resistance (27.16 kN) is increased rapidly compared to the elastic solution. Nevertheless it is noticed that, the maximum displacement of the elasto-plastic structure is slightly greater than that of purely elastic structure when only half of the structural resistance (which is equal to 13.58 kN) is available for elasto-plastic solution. On the other hand, the maximum displacement of the elasto plastic system is approach to the purely elastic structure when only three-quarter of the purely elastic structural resistance (which is equal to 20.37 kN) is available for elasto-plastic analysis.

Thirdly, the time at which the maximum displacement of elasto-plastic system occurs is increasingly diverge from the time at which the maximum displacement of purely elastic solution occurs when the structural resistance significantly decreases. While the time of maximum displacement of both purely elastic and elasto plastic solutions approach to equality when the structural resistance used in elasto-plastic system approach to the maximum resistance required by purely elastic solution.

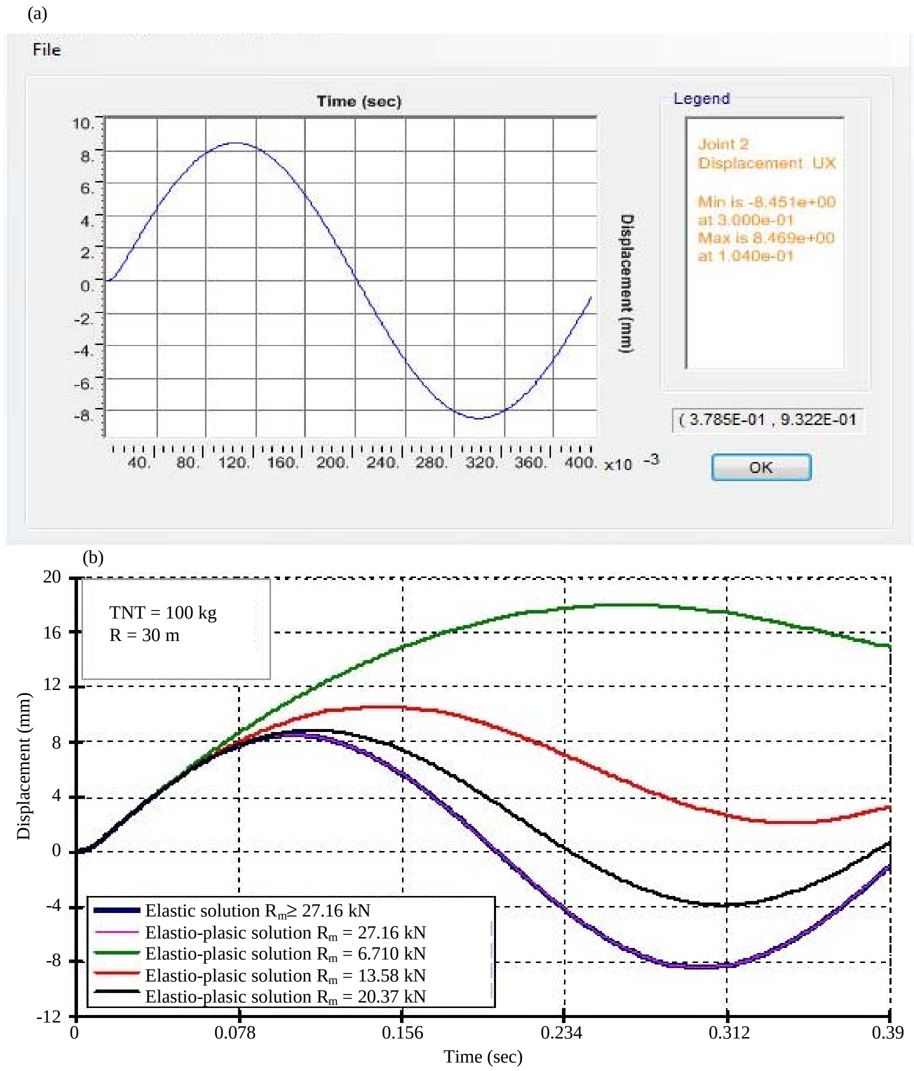
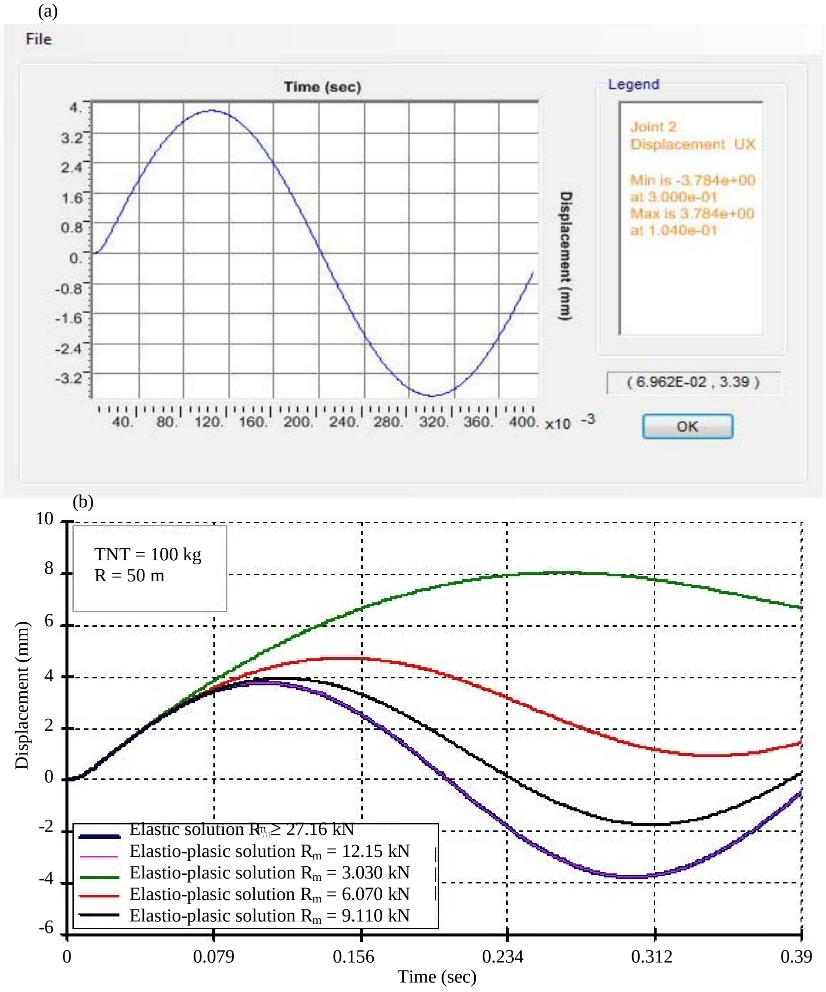


Fig. 6: a) Elasto-plastic solution at R_m = 27.16 kN using SAP (Ver. 18; b) Responses of elasto-plastic structure (R_m = 27.16 kN) and purely elastic structure (R_m = 27.16 kN)

In Fig. 7-9, same behavior is investigated for different TNT and standoff distances. The variation of elasto plastic solution with the changing values of the stiffness resistances are compared with purely elastic displacement time history. The result of comparison behaves in the same trends as in Fig. 6.

In Fig. 7 with 100 kg TNT and 50 m standoff distance, the maximum displacement of elasto-plastic structure as compared to purely elastic system vary in the approximately patterns of Fig. 6. Respect to time also, the time at which the maximum displacement occurs for elasto-plastic SDOF system is coverage and diverge according to the value of the structural resistance used in the analysis. Figure 7a represents the SAP solution with structural resistance equal to 12.15 kN while Fig.7b illustrates the comparison between purely elastic and elasto-plastic structure. In Fig. 8 with 200 kg TNT and 30 m standoff distance and in Fig. 9 with 200 Kg TNT and 50 m standoff distance, similar behavior has been observed in term of maximum displacement and time at which occurs for both purely elastic and elasto-plastic solutions for different structural resistance. Finally, Fig. 10 shows the displacement time history for elastic structure of the four previous cases in one graph to show the effect of TNT and standoff distances variation on the displacement time history.

Figure 10 proves that the solution patterns of SDOF structure subjected to different blast load strength is approximately similar to the solution of free vibration analysis with initial velocity only.

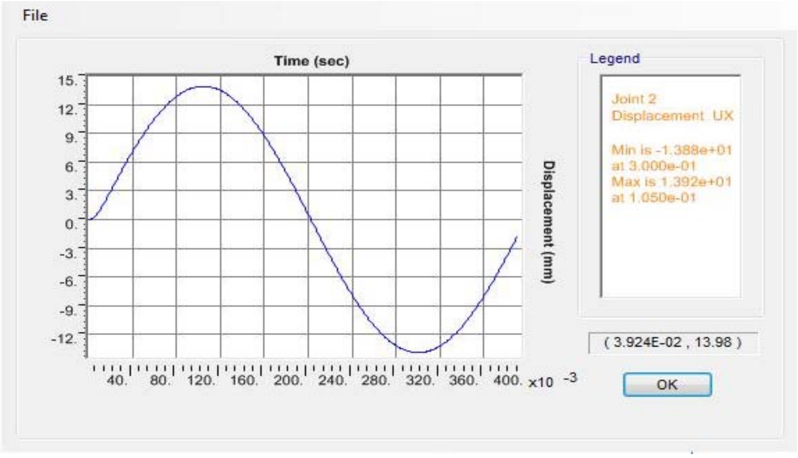


Joint 2
Displacement UX

Min is -3.784e+00
at 3.000e-01
Max is 3.784e+00
at 1.040e-01

(6.962E-02 , 3.39)

Fig. 7: a) Elasto-plastic solution at R_m = 12.15 kN using SAP (Ver.18; b) Responses of elasto-plastic structure (R_m = 12.15 kN) and purely elastic structure (R_m = 12.15 kN)



Joint 2
Displacement UX

Min is -1.388e+01
at 3.000e-01
Max is 1.392e+01
at 1.050e-01

(3.924E-02 , 13.98)

Fig. 8: Continue

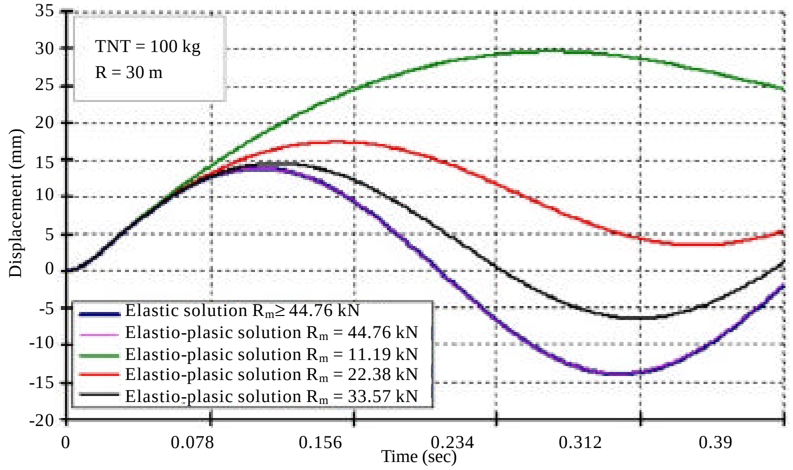
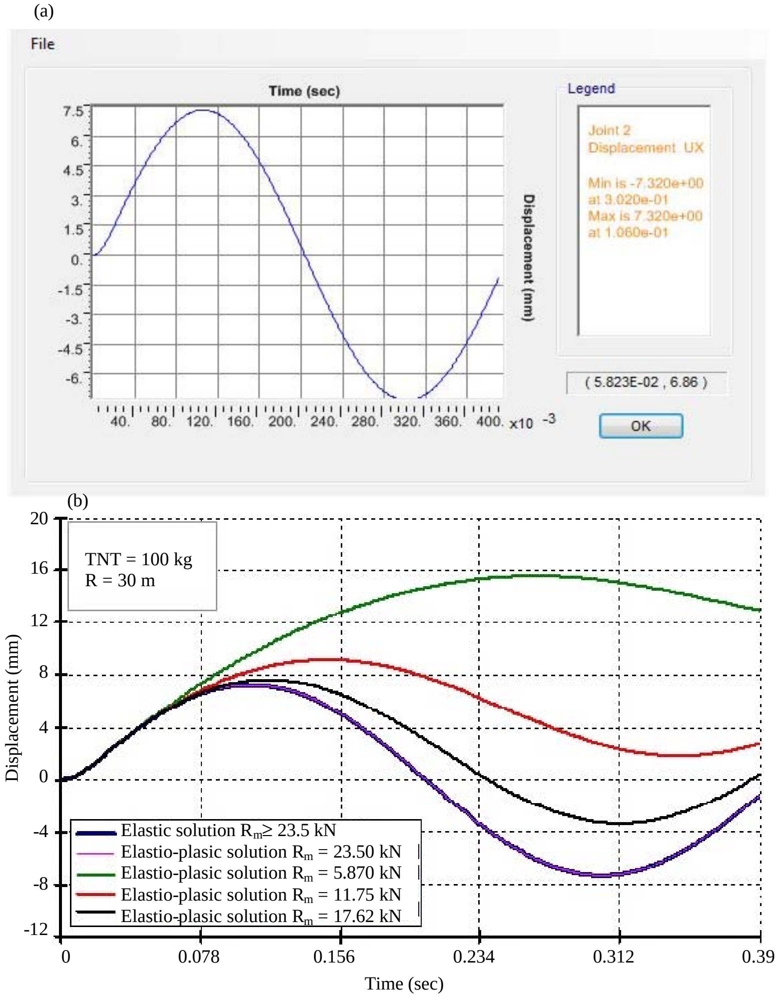


Fig. 8: a) Elasto-plastic solution at R_m = 44.76 kN using SAP (Ver. 18) and b) Responses of elasto-plastic structure (R_m = 44.76 kN) and purely elastic structure (R_m = 44.76 kN)



Joint 2
Displacement UX

Min is -7.320e+00
at 3.020e-01
Max is 7.320e+00
at 1.060e-01

Fig. 9: a) Elasto-plastic solution at R_m = 23.5 kN using SAP (Ver. 18) and b) Responses of elasto-plastic structure (R_m = 23.50 kN) and purely elastic structure (R_m = 23.50 kN)

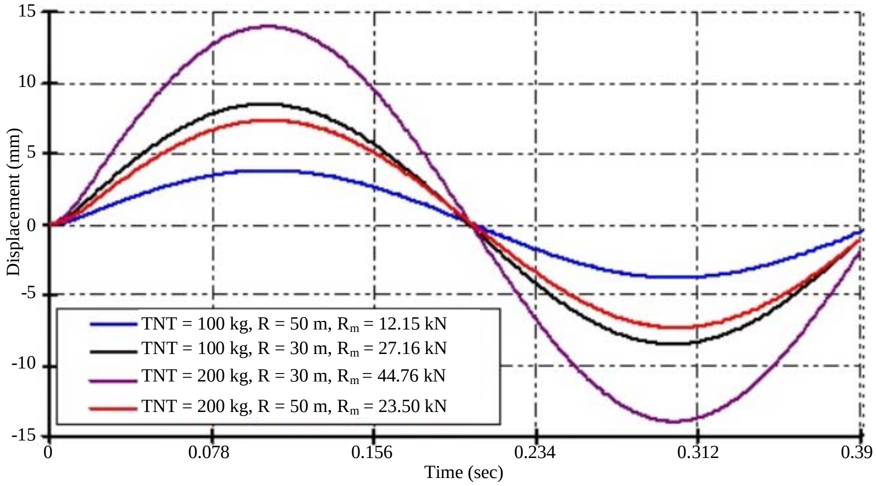


Fig. 10: Purely elastic response for different blast loads

CONCLUSION

The results and discussion for both purely elastic and elasto-plastic structural responses under different values of TNT and standoff distance was carried out to prove the manner in which the elasto-plastic structural systems can be analyzed and also to mark some of the important characteristics of plastic behavior of structure subjected to blast loading. The advantage of the plastic part behavior for the structural systems under different blast load strengths now after this discussion become obvious. If the structural analyst can allow some permanent plastic deformation or distortion in any structure subjected to blast loading, the amount of structural resistance and then the structural materials and cost can be significantly reduced. A reduction in the strength of one-half resulted in an increase in deflection of only about 25%.

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