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On the effect of steel columns cross sectional properties on the behaviours when subjected to blast loading

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Abstract. For buildings subjected to blast loading, structural failure can be categorized into local failure (direct blast effects) and progressive collapse (consequential effects). In direct blast effects, the intensive blast pressures create localized failure of structural elements such as exterior columns and walls. Columns, and their behaviour, play a key role in these situations. Therefore investigating the behaviour of columns under blast loading is very important to estimate the strength, safety and reliability of the whole structure. When a building is subjected to blast loading, it experiences huge loading pressures and undergoes great displacement and plastic behaviour. In order to study the behaviour of an element under blast loading, in addition to elastic properties of materials, plastic and elastic-plastic properties of materials and sections are needed. In this paper, using analytical studies and nonlinear time-history analysis by Ansys software, the effects of shape of column sections and boundary conditions, on behaviour and local failure of steel columns under blast load are studied. This study identifies the importance of elastic-plastic properties of sections and proposes criteria for choosing the best section and boundary conditions for columns to resist blast loading.

Keywords: steel column; blast load; local failure; nonlinear analysis; section shape

1. Introduction

When an explosion occurs, a loud sound, heat and a wave known as a shock wave will be created in the surrounding environment. This wave is made of compressed air that moves out spherically with the speed of sound and generates an enormous load on obstacles such as buildings in its path. The destruction of a federal building in Oklahoma City, USA, in 1995, which was the result of an 1814 kg TNT bomb at 4.75 meters distance (Longinow 1996, FEMA-277 1996) led to special attention being given to terrorist attacks and the effects of explosions on buildings (FEMA-426 2003, FEMA-427 2003).

The explosion and its load on buildings was studied extensively and a number of papers were produced (Remennikov 2003, Ngo *et al.* 2007, Subramaniam 2009). During the destruction of a structure under blast load, two steps will occur: in the first step and under direct effects of blast

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load, those elements of the structure nearest to the point of explosion will fail. In the next step, due to loss of some basic elements, some of the load paths disappear. If the remaining load paths do not have enough strength, a process known as progressive collapse begins in which the entire structure collapses. Alternate load paths should have been predicted and performed to carry building loads in such situations. Alternate load path method is considered to be influenced by column spacing, size, and end fixing (McConnell and Brown 2011).

Generally blast-resistant design is carried out by simplifying the models and conducting static analysis, single degree-of-freedom dynamic analysis, or rigid-plastic analysis (Kang and Liew 2006). However the variety of blast loading types and the complexity of response mechanisms of elements and their assemblages led to development of the design practice involving complicated numerical methods. This is in addition to empirical and analytical methods which have been required in this field (Marchand and Alfawakhiri 2005).

In blast-resistant design, understanding local damage of structural elements by direct blast loading is vital, and this has been studied many times for steel columns (Godinho *et al*. 2007) and concrete columns (Ngo *et al.* 2003). Lee *et al*. (2009) studied steel columns subjected to blast loading, and showed that the size of column section has a direct effect on its behaviour, but their study was limited to W-shaped steel columns. Other shapes of steel columns (section shape) also need to be investigated. Different shapes of steel columns have not been studied yet, and many questions exist in relation to section shape and behaviour of columns. For instance it is still questionable which cross section provides superior blast resistance in steel columns for design of protective structures.

The purpose of this paper is to study the behaviour of steel columns with different common section shapes, subjected to blast loading. This study is part of extensive research which is being advanced by the authors to understand behaviour of steel frame structures when exposed to blast loading. In this study, as well as blast load estimation, by using finite element analysis software (Ansys 2012), the effects of section shape and properties, such as section area, moment of inertia, elastic and plastic section modulus, and column boundary conditions (fixed or pinned ends) on behaviour and failure of steel columns were studied.

2. Effects of explosion on structure

After all explosions, a huge amount of energy is released. Part of this energy is coupled with air in the form of a wave known as a shock wave. This shock wave hits any obstacle in its path and produces massive pressure on it. Fig. 1 shows a schematic time history of a blast load.

As shown, blast load has two parts: positive and negative phase. In positive phase (which is more important in structural design) the structure encounters great over pressure but in negative phase, it encounters a negative pressure (i.e., suction).

Loading duration in blast loading is very short: fewer than one thousandth of a second for positive phase and one tenth of a second for negative phase. By increasing distance, pick over pressure decreases but load duration increases. Blast over pressure disappears quickly, therefore the effects of blast on front view of building is more important than others. One of the most important things in blast loading is the direction of loading; this can be different from what various elements have been designed for, such as upward pressure on floors.

In studying blast load and its effects on structures, the following factors must be controlled: (Bangash and Bangash 2006)

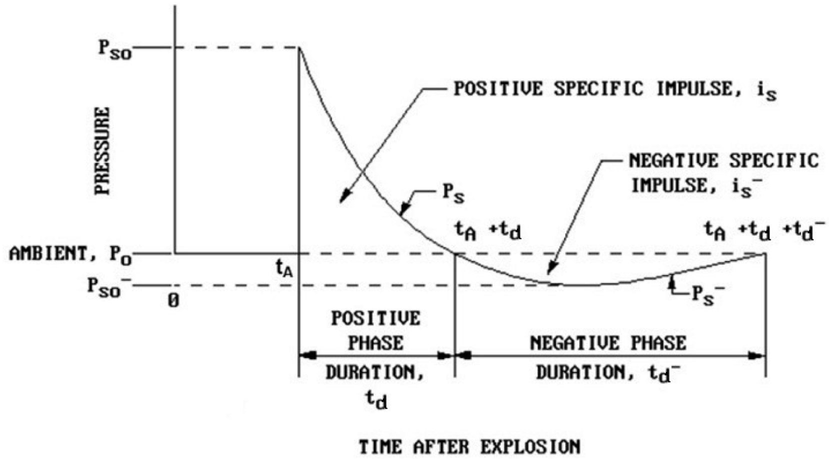


Fig. 1 Schematic time history of a blast load (TM5-1300 1990)

a) Greatness of explosion in scale of kilograms of TNT.
b) Standoff distance.
c) Geometry of building and system of structure.
d) Angle of building with the direction of wave movement.

Soroushian and Choi (1987) showed that in blast loading, because of the very short duration of loading, materials experience a great rate of strain. Blast loading typically produces very high strain rates in the range of 10^2 to 10^4 s^{-1} (Soroushian and Choi 1987). This high straining (loading) rate can alter the dynamic mechanical properties of target structures. Fig. 2 shows the approximate ranges of the expected strain rates for different loading conditions.

In comparison with normal loading, in fast loading, a phenomenon is observed in which materials show more strength but behave as though more brittle. As shown in Fig. 3, by changing the strain rate, the stress-strain curve of material will change. This stress-strain curve was used in this study.

Because of this behaviour of materials under very fast loading, a factor is defined as dynamic increase factor (DIF) which is the ratio of strain rate to the strength (ratio of dynamic yield stress to static yield stress). Blast loading is one of the fastest load patterns, therefore finding and using DIF is one of the key steps in design. Eq. (1) can be used for calculating DIF (Cowper and Symonds 1957)

$$DIF = \frac{f_y'}{f_y} = 1 + \left(\frac{\varepsilon'}{c}\right)^{1/q} \tag{1}$$

In Eq. (1) f_y' is dynamic yield stress, f_y is static yield stress, ε' is strain rate and C and q are

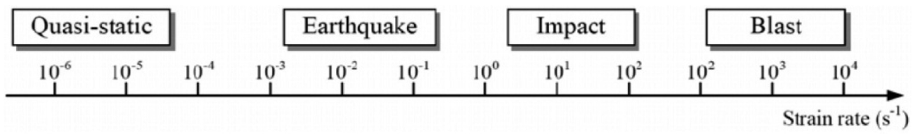


Fig. 2 Different strain rates related with types of loadings (Soroushian and Choi 1987)

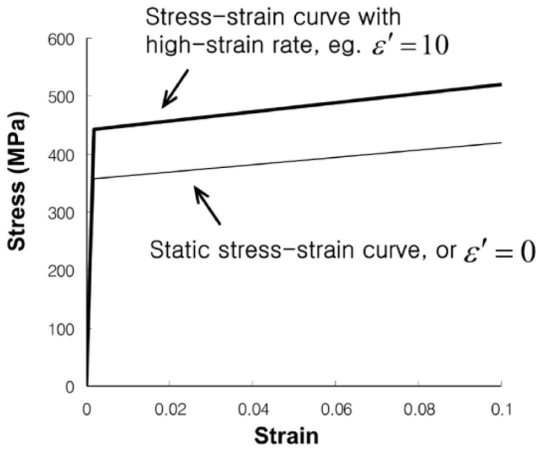


Fig. 3 Stress strain curves with strain rate effect (Soroushian and Choi 1987)

material constants. According to TM5-1300, C = 12800 and q = 5 are suggested (TM5-1300 1990).

The first step in blast related analysis is to predict blast loads on the structure. To achieve this, many field experiments have been conducted and results published in selected references (TM5-855-1 1986, TM5-1300 1990). Using experimental results, a few software packages have been developed in recent years which can estimate characteristics of blast load. ConWep developed by US Army (TM5-855-1 1986) and A.T.-Blast (ARA 2012) funded by US General Services Administration are two examples of these softwares.

All characteristics of blast load depend on the weight of explosive charge which is usually converted to TNT equivalent weight and standoff distance. These two independent parameters are used in scaled distance parameter Z that is defined as Eq. (2) (Brode 1955, TM5-1300 1990)

$$Z = \frac{R}{W^{1/3}} \tag{2}$$

In Eq. (2), R is standoff distance and W is TNT equivalent weight. All formulas that are presented in the article to calculate maximum over pressure (P_{so}) use Z inverted (Ngo *et al.* 2003).

To calculate P_{so}, Eq. (3) has been presented by Brode (1955)

$$P_{so} = \frac{97.5}{Z} + \frac{145.5}{Z^2} + \frac{585}{Z^3} - 1.9 \text{ kPa} \quad (10 \text{ kPa} < P_{so} < 1000 \text{ kPa})$$

$$P_{so} = \frac{670}{Z^3} + 100 \text{ kPa} \quad (P_{so} > 10 \text{ bar}) \tag{3}$$

For calculating load duration (t_d) the Z parameter itself is used (Mays and Smith 1995, Lam *et al.* 2004, Izadifard and Mahrei 2008). Eq. (4) shows the formulation, presented by Izadifard and Mahrei to calculate t_d

$$\log_{10}\left(\frac{t_d}{W^{1/3}}\right) \approx 0.28 + 0.31\log_{10}\left(\frac{R}{W^{1/3}}\right) \quad (Z \geq 1/0)$$

$$\log_{10}\left(\frac{t_d}{w^{1/3}}\right) \approx 0.28 + 2.5\log_{10}\left(\frac{R}{w^{1/3}}\right) \quad (Z \le 1/0) \tag{4}$$

Time history of loading (load curve) as shown in Fig. 1 can be identified by the Friedlander formula that is shown in Eq. (5) (Baker 1973).

$$P_s(t) = P_{so}\left(1 - \frac{t-t_a}{t_d}\right)\exp\left(-b\frac{t-t_a}{t_d}\right) \tag{5}$$

Where $P_s(t)$ is blast pressure at time t, P_{so} is peak incident over pressure, t_d is positive phase duration, t_a is arrival time, and b is a decay coefficient. When a shock wave clashes with obstacles in its path, it will be reflected. Peak reflected over pressure (P_r) is calculated by using Eq. (6) (Ngo *et al.* 2003).

$$P_r = 200P_{so}\left[\frac{7+4P_{so}}{7+P_{so}}\right] \text{kPa} \tag{6}$$

3. Simulation and modeling

In this paper, just like Lee *et al.* (2009), for simulation of blast load on structure a 500 kg TNT bomb with 3 meter standoff distance was modelled (a terrorist attack in which a van with a TNT bomb inside is parked beside a structure). A.T.-Blast program was used to calculate characteristics of blast load such as P_{so}, t_d and P_r. Then the Friedlander formula was used to find the load curve. Columns must be subjected to P_r. Incident pressure load curve is shown in Fig. 4.

Clearly for columns, axial forces are crucial. Therefore all analyses were performed in the presence of axial load. The axial load of the column is considered as 600 kN in the structural analysis. This axial load (consisting of dead and live loads) is estimated based on tributary area of the column in an ordinary 5-storey building.

Columns were made of structural steel with density of 7850 kg/m^3. As shown in Fig. 3 for modeling the material nonlinearity, bilinear elastic-plastic behaviour for steel was considered with yield stress of 345 MPa, elastic modulus of 205 GPa and hardening modulus (tangent modulus) of

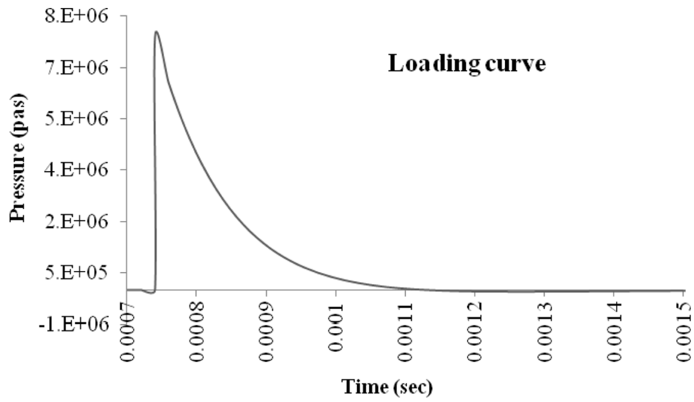


Fig. 4 Loading curve

650 MPa. Also the unloading path of the stress-strain curve is linear with slope (unloading stiffness) equal to the initial slope (initial stiffness) of loading path of the stress- strain curve. In addition, structural damping ratio was defined as 0.05. Columns were assumed to have a height of 3.6 m and to be loaded in the strong-axis direction and all section properties were calculated in this direction. For modeling the columns parts (web and flange plates) the solid elements were used. Columns were modeled in ANSYS workbench, and analyzed by Ls-Dyna solver, in which models can be analyzed using explicit dynamic analysis (Ls-Dyna 1998, 2005).

To observe the behaviour of columns with different sections subjected to blast loading, four sections were supposed: IPB section, double IPE section, cross shape section and box section. The size of cross sections was selected based on the primary design of a 5-storey building against earthquake according to Iranian earthquake code (BHRC 2005). Iran is in the high seismic zone and design of buildings against earthquake in the high seismic zones is almost the same. Because the design of columns under blast load is not together earthquake load then the columns in high seismic zones that designed for bigger earthquake loads, have higher resistance against blast and progressive collapse (Hadianfard and Wassegh 2012). Then IPB 300 (which is a typical column section for 5-storey buildings,) was chosen as the basic section and other sections were made in the way that they may have one characteristic in common with IPB 300. Common characteristics of sections chosen were: area of section, moment of inertia and elastic section modulus. Ten different auxiliary sections were made and named by different auxiliary section ID's that are shown in Table 1.

In Table 1, A is area of section (cross sectional area), I is moment of inertia, S is elastic section modulus, r is radius of gyration, Z is plastic section modulus, K is shape factor (plastic section modulus divided by elastic section modulus as shown in Eq. (7) below), λ_{pinned} is slenderness ratio of column (i.e., effective length divided by radius of gyration) with pinned end and λ_{fixed} is slenderness ratio of column with fixed ends, as shown in Eq. (8)

$$K = \frac{Z}{S} \tag{7}$$

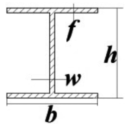
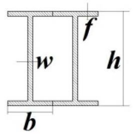
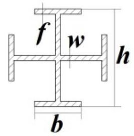
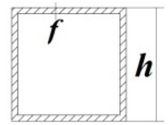
$$\lambda = \frac{kl}{r}, \quad \begin{cases} k_{pinneed} = 1 \\ k_{fixed} = 0.5 \end{cases} \tag{8}$$

In Eq. (8) l is length of column and k is effective length factor (Davison and Owens 2003).

In reality complete fixed or pinned ends for elements cannot be achieved. In this study columns with fixed end and pinned end were investigated.

Because blast is a short time loading, to identify variation of this load, the time steps should be small then in this study the size of time step was chosen as Δt = 0.0005 sec. For the reason that, the computational effort and cost in explicit dynamic methods are low with respect to implicit methods, then these methods are suitable for blast loading with short time step analysis. In the explicit method, the new response values are calculated in each step based only on quantities obtained in the preceding step, then the analysis progresses directly from one step to the next. But in the implicit method, the expressions producing the new values for a given step include one or more values relating to that same step (Clough and Penzien 1995). The central difference and forward Euler methods are examples of explicit time integration.

Table 1 Characteristics of different sections, modelled in this paper

Section Shape										
Section ID	IPB 300	2IPE 340	2IPE 360 II	2IPE 360 III	Cross IPE 360 I	Cross IPE 410	Cross IPE 460	Box 34.5x1	Box 37x1	Box 38x1
h (mm)	300	340	360	360	360	410	460	345	370	380
b (mm)	300	170	190	170	190	185	210	-	-	-
f (mm)	20	11.5	12.5	12.2	12.7	13.5	14.6	10	10	10
w (mm)	11	7.8	8	8	8	8.6	9.4	-	-	-
A (mm^2)	14900	12800	14860	13700	14940	16570	20350	13400	14400	14800
I (mm^4)	2.52E+08	2.52E+08	3.38E+08	3.02E+08	1.86E+08	2.52E+08	3.87E+08	2.52E+08	3.11E+08	3.38E+08
S (mm^4/mm)	1.68E+06	1.48E+06	1.88E+06	1.68E+06	1.03E+06	1.23E+06	1.68E+06	1.46E+06	1.68E+06	1.78E+06
r (mm)	130.049	140.312	150.817	148.472	111.579	123.322	137.903	137.135	146.960	151.122
Z (mm^4/mm)	1.87E+06	1.68E+06	2.10E+06	1.90E+06	1.52E+06	1.78E+06	2.46E+06	1.87E+06	2.16E+06	2.29E+06
K	1.114	1.134	1.118	1.131	1.475	1.449	1.464	1.283	1.287	1.285
λ_{pinned}	27.682	25.657	23.870	24.247	32.264	29.192	26.105	26.252	24.496	23.822
λ_{fixed}	13.841	12.829	11.935	12.124	16.132	14.596	13.053	13.126	12.248	11.911

4. Results and discussion

In this paper commonly used steel column sections were exposed to blast loading. The behaviour of the columns was studied by controlling their maximum displacement and plastic strain which are the most important factors of constructional elements. Fig. 5 and Fig. 6 show the deformed shape of fixed and pinned end columns. Units for all numbers (amounts of deformations) in legends are in metres.

As seen in Fig. 5 and Fig. 6, deformations in pinned end columns are greater than fixed end columns. Therefore the pinned end columns are more critical. These results were expected, because of increasing indeterminacy of structure in the fixed end columns. In blast loading, columns behave as beam-column elements. But as transverse loading is greater than axial loading, their beam behaviour is more prominent than column behaviour.

In fixed end columns, as shown in Fig. 6, at the end of columns (just before connections) especially in cross shape sections, crippling is the most critical problem, principally in flanges. A better view of this phenomenon is demonstrated in Fig. 7.

In Fig. 8, a time history of displacement of midpoint of columns is shown. Left diagrams have fixed end and right diagrams have pinned end conditions.

As expected, in all columns, by changing conditions at the end of columns and increasing indeterminacy of structure, maximum displacement was decreased. For sections with equal area size and pinned ends, increase of section modulus results in displacement increases (Fig. 8(b) and Table 1). However this is not always the case for fixed end conditions. Because the selected column sections have some common characteristics, it is reasonable that some responses in Fig. 8 are close. For example, as shown in Fig. 8(b), for sections with equal area and pinned ends, according to Table 1, section modulus of Box section and IPB section are almost the same, and similarly, the responses of these sections are close. But the section modulus of Cross IPE section and 2IPE section are very different and their responses differ likewise.

In addition, for sections with equal moment of inertia with pinned ends, increase of cross section area leads to decrease of displacement (Fig. 8(d)). In this case according to Table 1 Cross IPE section has the largest cross section area and subsequently it has the smallest displacement; but the areas of the other sections are similar, and consequently their displacements are close. But in columns with fixed end, section modulus is more dominant (Fig. 8(c)). In columns with equal section modulus and pinned ends, increase of section area results in a decrease of displacement unlike the fixed end conditions (Figs. 8(f) and 8(e)).

Material behaviour exits the elastic region and enters elastic-plastic region when the structure is subjected to blast loading. Therefore the elastic-plastic properties of sections should be used, as elastic properties of sections may not interpret behaviour of structural elements correctly. Plastic section modulus and shape factor represent elastic-plastic properties of a section.

As shown in Fig. 8, especially in pinned connections, maximum displacement of columns have an obvious inverse relationship the with shape factor of sections. According to Table 1, the shape factor of the Cross IPE sections is about 1.5 and it is the biggest shape factor among all sections (for example it is 1.34 times the shape factor of IPB sections). Then the columns with a cross shape section have the smallest maximum displacement among all columns. For instance the maximum displacements of columns with IPB section and pinned connection are about 2 to 7 times the displacements of columns with Cross IPE sections. In the fixed ends columns the ratios of displacements are about 2.2 to 3.7. Also shown is that maximum displacement of sections with

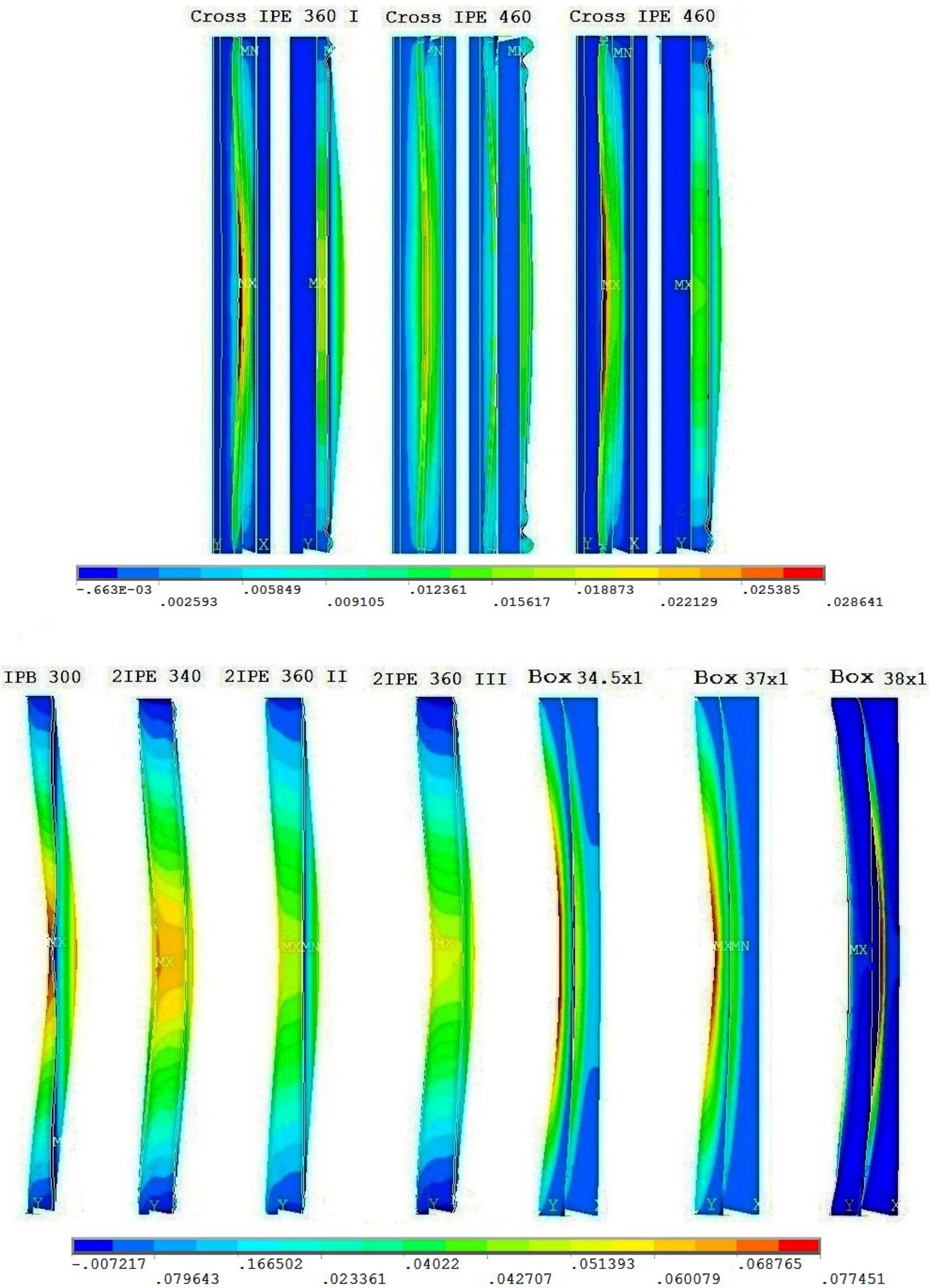


Fig. 5 Deformed shapes of fixed end columns (displacement; in metres)

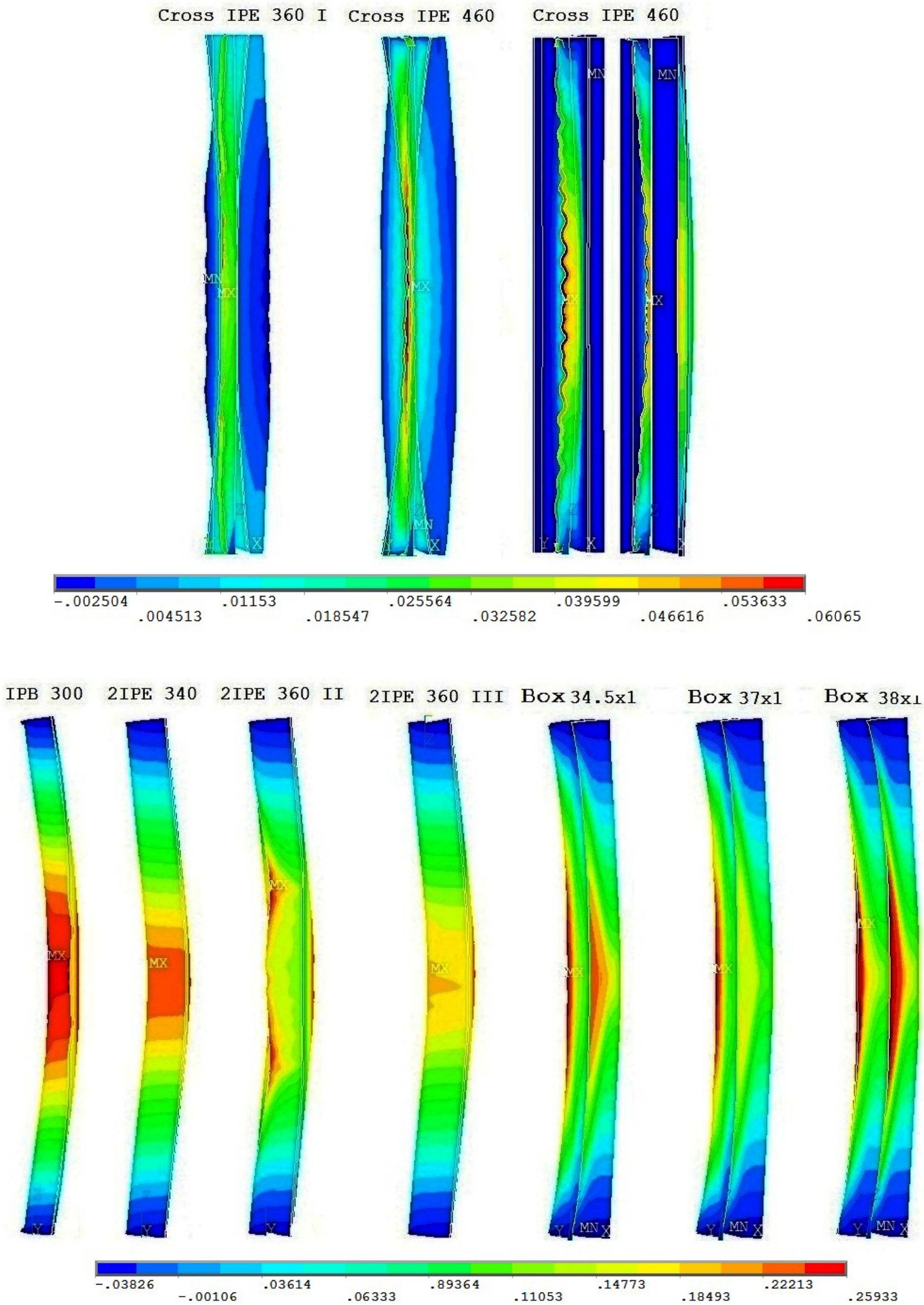


Fig. 6 Deformed shapes of pinned end columns (displacement; in metres)

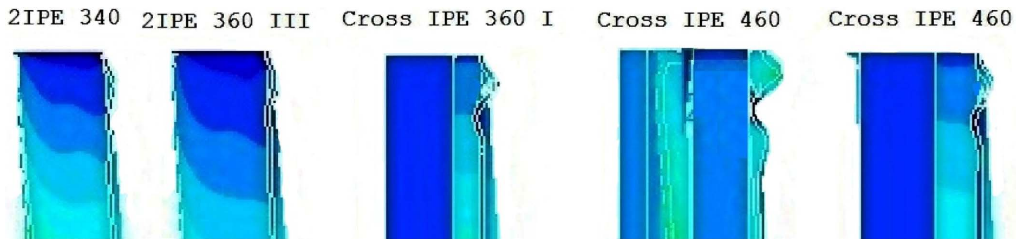


Fig. 7 Deformed shape of column ends (crippling) for fixed support

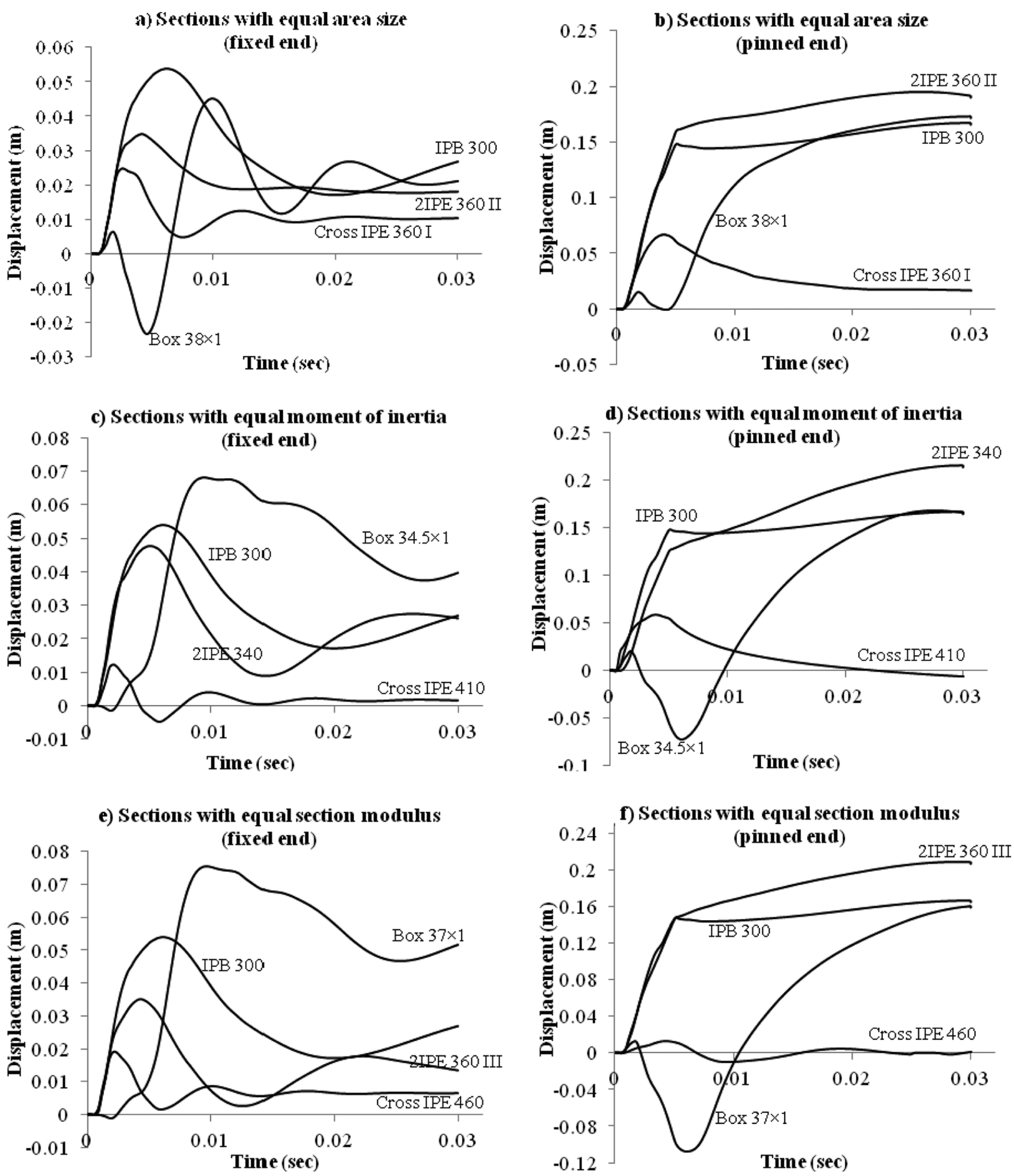


Fig. 8 Time history of displacement of columns

similar shape factors occurs primarily in pinned end columns. Furthermore it is shown that their time-history of displacement is similar with exception of Box sections. From Fig. 8 it can be seen that the best section is the cross shape section, with a shape factor greater than the rest, and where its behaviour is the best when comparing maximum displacement.

Fig. 9 shows time history of effective plastic strain of columns. These diagrams are plastic strain of midpoint of columns, in which maximum displacement took place.

Effective plastic strain is a monotonically increasing scalar value which is calculated incrementally as a function of the plastic component of the rate of deformation tensor. Effective plastic strain grows whenever the material is actively yielding, that is, whenever the state of stress is

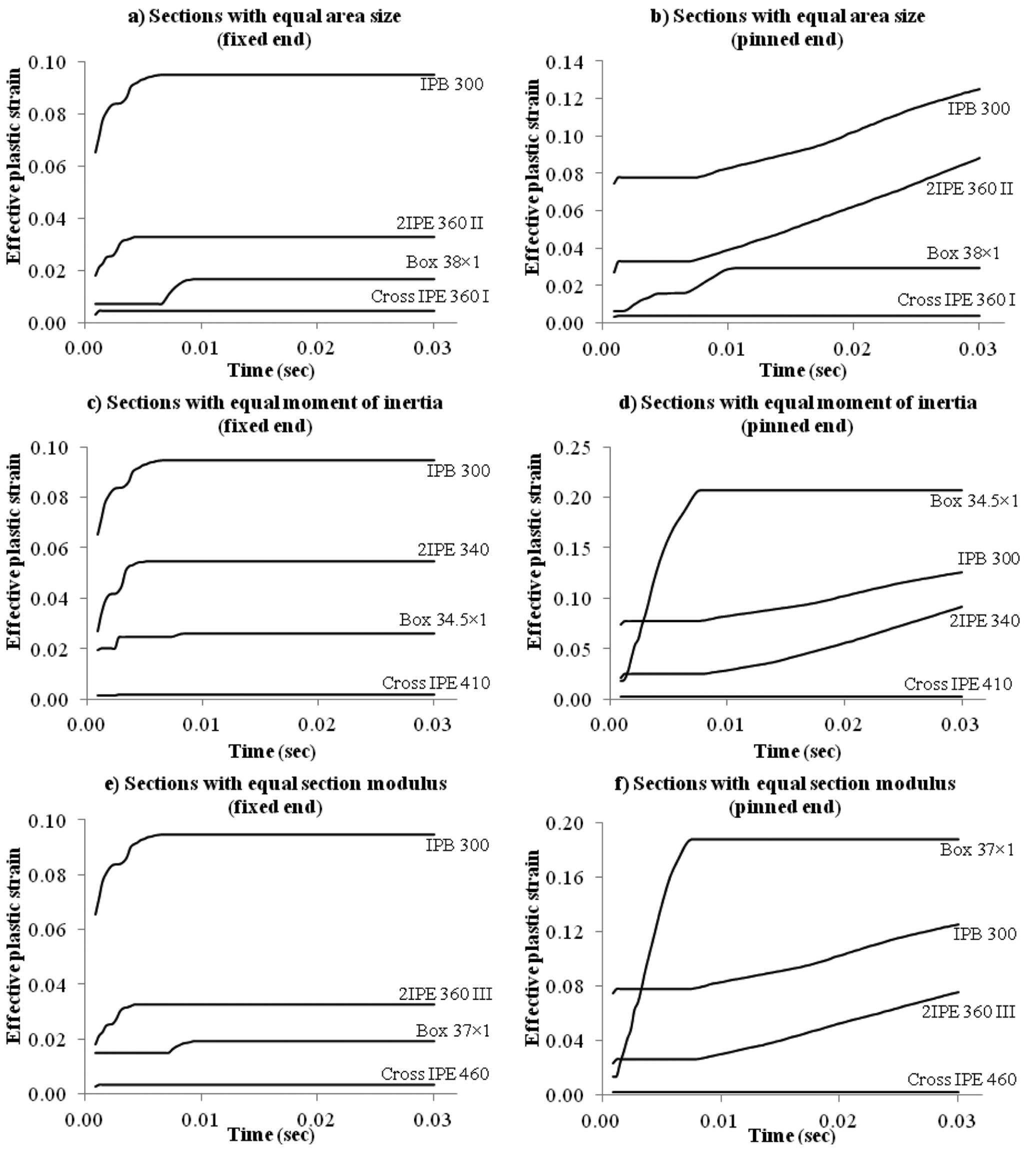


Fig. 9 Time history of effective plastic strain of columns

on the yield surface.

In all columns increase of structural indeterminacy results in a decrease of effective plastic strain of column (which is imposed onto the structure). Results in Figs. 9(a) and 9(b) show for equal area size columns, there is no link between effective plastic strain and the section properties. As demonstrated in Fig. 9(d), in sections with equal moment of inertia and pinned end support, effective plastic strain decreases when section area increases. But in columns with fixed end, section modulus is more dominant (Fig. 9(c)). In sections with equal section modulus and pinned end support, increase of area size results in a decrease of plastic strain (Fig. 9(f)). But in the condition of fixed end support (Fig. 9(e)), it is obvious that increasing moment of inertia has a direct effect on increase of effective plastic strain.

Shape factor is defined as the ratio of plastic modulus to elastic modulus of a section. Shape factor shows moment capacity of a section after it passing its yielding moment and until creation of plastic hinge which in turn leads to element failure. As shown in Fig. 9, especially in pinned end columns, effective strain has an inverse relationship with shape factor. As shape factor increases, effective strain decreases. Columns with cross shape section have the smallest effective strain in all columns and these sections have the largest shape factor among all.

Taking into consideration all the diagrams (Fig. 9), it can be said of the pinned end column, the best sections are: cross shape sections, box sections, IPB section and double IPE sections respectively. Regarding fixed end columns, the best sections respectively are: cross shape sections, double IPE sections, IPB section and box sections.

Again it can be observed that in the case of plastic strain, cross shape sections have the best behaviour. This may be because of their greater capacity in undergoing plastic moment and absorbing loading energy.

Today, improve the resistance of buildings against terrorist attacks is very important, and capacity of Columns against blast loads, plays a key role in these situations. Thus practical implementation of this study is to select the best column section for increasing capacity of the column against local failure under blast loads due to terrorist attacks. Based on this research the cross shape sections are the best section for this purpose.

5. Conclusions

In the design process selecting the cross section which responds effectively to the loading condition is very important. In this paper, the behaviour and local failure of different steel column sections was studied under a blast loading situation equal to 500 kg TNT at 3 m distance (a terrorist attack in which a van with a TNT bomb inside is parked beside a structure). The size of column cross sections was chosen based on primary design of a 5-storey building against earthquake (high seismic zone) according to Iranian earthquake code, and IPB 300 which is a usual column section for 5-storey buildings, was selected as the basic section. Other sections were made in a way that they could have one characteristic (area, moment of inertia and section modulus) in common with IPB 300. Four sections were modelled in ten cases and two different boundary conditions were considered (pinned and fixed ends). Elastic-plastic behaviour of material and dynamic increase factor was considered in the study. Responses of columns were interpreted by using both elastic and elastic-plastic properties of sections. The results of this study are summarised below:

1) By fixing the end of columns, and increasing indeterminacy of structure, maximum

displacement and effective plastic strain of column decreases.
2) In columns with a fixed end, one of the most important things to be considered is bearing stress (crippling) near supports (ends of column).
3) Increasing the area of sections can be the right choice to control behaviour of a section by decreasing displacement and strain, especially in columns with pinned ends. But it is not suggested for all cases.
4) Increasing section modulus has different results on the behaviour of columns. When area is kept constant, increasing section modulus increases displacement and strain, but when moment of inertia is kept constant it decreases displacement and strain.
5) Increasing moment of inertia of a section has a direct result on behaviour of columns, especially in plastic strain.
6) In plastic properties of sections, plastic section modulus was checked and similar effects to elastic section modulus were shown.
7) Controlling elastic-plastic properties of sections seemed to be the right way to interpret and predict the behaviour of elements. It was demonstrated that increasing shape factor decreases maximum displacement and effective strain. Therefore using sections with greater shape factor (up to 1.5) is advised for designing a protective structure.
8) By investigating the behaviour of different sections, the conclusion is that the best section for columns under blast loading is the cross shape section. Its shape factor is greater than other sections and by using that, displacement and plastic strain are more controllable.

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