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“Use of MSC.Dytran in Developing Blast-Resistant Building Columns”

Emma K. Goodson¹ and Abolhassan Astaneh-Asl²

Abstract:

The focus of the project summarized in this paper is to study steel building columns subjected to car bombs and to develop protection measures to prevent collapse of the columns. In some buildings, collapse of even one column can result in progressive and catastrophic collapse of a large portion of the building. The methodology used in this project was first to establish the structural response of bare steel columns to a blast explosion nearby. Second, after determining the structural response of bare steel columns, to develop protective measures, such as the addition of pre-cast concrete elements around the steel column, such that the column can survive the explosion albeit with damage, and can continue carrying its gravity load.

In this analytical study, a pin-ended wide flange steel W14 x 145 section was used as the bare steel column. The behavior of the column under a blast was considered with two levels of axial loading. Light axial load was established as 30% of the column axial capacity, while heavy axial load was determined to be 60% of the axial capacity. The axial load was applied statically using MSC.Nastran. The results for the pre-stressed column were then imported into MSC.Dytran where the blast simulation was carried out. The column was built using 2D Lagrangian shell elements. Both the steel and the concrete protective elements were defined by bi-linear material models with a pre-defined fracture strain. An Eulerian region of air was built to surround the column. When the blast was initiated, the blast energy propagated through the ambient air and hit the column. In addition, the bomb was also constructed out of Eulerian elements containing compressed gas that were released at the onset of the simulation. It was determined that the primary cause of failure in the steel column was the folding of the flange, which then resulted in the formation of a plastic hinge at mid-height of the column leading to fracture of the column and loss of axial capacity. Once concrete was added to the column, the folding of the steel flange was prevented creating a more stable system, possibly preventing failure of the steel column and possibly preventing catastrophic progressive collapse.

¹ Graduate Student, Department of Civil and Environmental Engineering, University of California, Berkeley.

² Professor, Department of Civil and Env. Engineering, 781 Davis Hall, University of California, Berkeley, CA, 94720-1710, USA, E-mail: Astaneh@ce.berkeley.edu.

1. INTRODUCTION

As a result of increased terrorist activities, such as the bombing of US embassies abroad, the Oklahoma City Federal Building, and the World Trade Center bombing during 1990's, the vulnerability of buildings and their individual structural components to blast attacks has been revealed. The vital need for the development of structural systems that can survive the extreme events such as a terrorist bomb attack is greater now more than ever. The field of blast resistance as applied to civilian facilities is only in its initial stages. The scientific community has only just begun to start identifying areas of potential research. It is clear that in order to begin hardening of structural elements against blast attacks, the global and local behavior of these elements under extreme loading conditions must first be determined. After understanding such behavior, appropriate hardening measures can be developed to prevent catastrophic collapse of buildings and massive loss of lives.

1.1 Objectives

The primary objective of this study is to establish the structural response of steel wide flange columns to a blast explosion. Having determined structural response, considerations into improving the overall performance through the addition of concrete is being examined. This paper is intended to serve as a progress report for the research done to date and provide interim results.

1.2 Case Study Parameters

A large variety of testing parameters could have been explored in this case study. However, in the interest of the time and resources given to complete the study, the most important parameters were chosen to be examined. First, the column was analyzed under two levels of light and heavy axial load. Here, light axial load was established as 30% of the column axial capacity, while heavy axial load was 60% of the column axial capacity. Next, the column was given pin-connections on both of its ends. This allowed for the "the worst case scenario" boundary conditions in terms of maximum displacement and P- Δ effects.

Table 1. Parameters of Study

Pin-Ended	<i>Steel</i>	lightly loaded 30%(AgxFy)
		heavily loaded 60%(AgxFy)
	<i>Composite</i>	lightly loaded 30%(AgxFy)
		heavily loaded 60%(AgxFy)

Trial and error was used in order to determine the size of explosion that would fail the column. The column was considered failed at the point at which it became unstable and could no longer support the applied axial load. The last parameter that was varied was steel versus composite section. Composite section represented the case of hardened steel column by adding pre-cast (or cast-in-place) concrete cover. Table 1 shows the parameters of the study. The details concerning how the model was built and how these parameters were established will be discussed in a later section.

1.3 Column Size

Ground floor columns in buildings are typically most critical due to the high axial loads they are often designed to carry and their high probability of being exposed to a nearby explosion due to a terrorist attack. The column section selected for the case study was designed as if it were a ground floor column in a ten-storey office building. A ten-storey building was chosen because it produced sufficient axial loads so that the column could be heavily loaded, in addition to being a representative of typical urban office and residential buildings. The building was chosen to have a floor foot print of 90 feet by 180 feet. In addition, all bays were chosen to be 30 feet long.

A finite element analysis of a ten storey office building was conducted using SAP (CSI, 2004), in order to determine a suitable size for the ground floor column. Gravity loads entered into the SAP model were in accordance with the 1997 Uniform Building Code (UBC, 1997) specifications for a typical office building. It should be noted, that only gravity loads were considered in the analysis because it was felt that since blast load is an extreme event by itself, there is almost negligible probability of having a terrorist attack during the earthquake thus no need to combine the gravity and blast effects with other loads. The SAP analysis indicated that an axial load of 1,464 kips was produced in the ground floor column from the 1.2 DL + 1.6 L load combination.

The column design was carried out in accordance with the AISC Specification (AISC, 1999). It can be seen from the above calculations that under the axial load given by the SAP analysis, the demand capacity ratio of a W14x145 steel column is 0.92. This is within an acceptable range for typical structural design. The size of steel column chosen to be used in the case study was based upon the following typical design practices for a “standard” office building ground floor column.

2. DYNAMIC ANALYSES OF COLUMNS SUBJECTED TO BLAST LOAD

2.1 General Background

The programs used to run the analyses were provided by MSC.Software Corporation. For the purpose of modeling explosions, the software used must be able to handle many variables. This includes large deformations and non-linear material behavior. The materials should contain the ability to deform plastically and eventually to fracture under a realistic criterion. Finally, interaction between the exploding gas and the solid column must be allowed. The models for this case study were built using

MSC.Patran. Here the geometry was defined and the mesh created. Then the boundary conditions and the loading were specified. In addition, the time step and duration of the analysis was defined. The models were then run using a dynamic finite element program called MSC.Dytran. MSC.Dytran is an explicit code that produced time histories of the desired output. The data collected included grid point accelerations, velocities, displacements, and forces, in addition to element strains, stresses, and pressures.

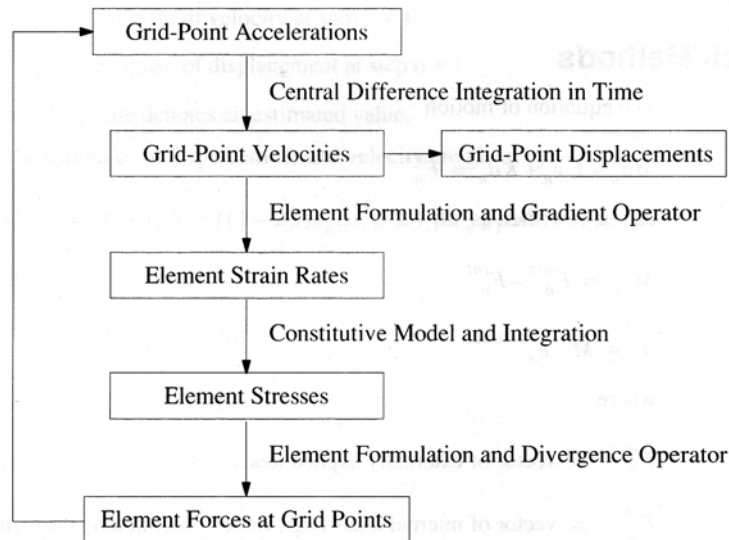


Figure 1. MSC.Dytran Formulation

The above chart outlines the general process used the finite element solver to determine the element results. The details of each step will be described in further detail in the below sections.

2.2 Explicit Methods

Explicit methods have a number of advantages over implicit methods when considering short duration events, such as explosions. They avoid having to invert a large stiffness matrix at each time step to obtain the solution and therefore can be fast and cost effective. In addition, the models can undergo large displacements and rotations. Contact or interaction with a number of meshed bodies is allowed. As previously mentioned, MSC/Dytran (2004) can also handle a variety of material models, including those relating to plasticity and failure. Finally, explicit codes are intended for short duration events, such as those experienced in an explosion (MSC/Dytran, 2004). There are a number of explicit time integration methods; MSC.Dytran uses the central difference method as its numerical integration scheme in time. The following data outlines the equations of motion used by MSC.Dytran to formulate the solution, and then describes the central difference method.

Equations of Motion:

$$M \cdot a_i + C \cdot v_i + K \cdot d_i = F_i^{\text{external}}$$

$$M \cdot a_i = F_i^{\text{external}} - C \cdot v_i - K \cdot d_i$$

$$M \cdot a_i = F_i^{\text{external}} - F_i^{\text{internal}} = F_i^{\text{residual}}$$

F: force vector M: mass matrix

C: damping matrix K: stiffness matrix

if M is diagonal, then: $a_i = M^{-1} \cdot F_i^{\text{residual}} = M^{-1} \cdot (F_i - C \cdot v_i - K \cdot d_i)$

$$a_i = \frac{d(i+1) - 2 \cdot d(i) + d(i-1)}{\Delta t^2}$$

$$v_i = \frac{d(i+1) - d(i-1)}{2 \cdot (\Delta t)}$$

$$d(i+1) = 2 \cdot d(i) - d(i-1) + a(i) \cdot \Delta t^2$$

a: grid point acceleration

v: grid point velocity

d: grid point displacement

Central Difference Method:

$$M \cdot a_i + C \cdot v_i + K \cdot d_i = F_i^{\text{external}}$$

$$M \cdot d(i+1) = M \cdot (2 \cdot d(i) - d(i-1) + a(i) \cdot \Delta t^2)$$

$$M \cdot d(i+1) = M \cdot \left[2 \cdot d(i) - d(i-1) + M^{-1} \cdot (F(i) - C \cdot v(i) - K \cdot d(i) \cdot \Delta t^2) \right]$$

$$M \cdot d(i+1) = \Delta t^2 \cdot F(i) + (2 \cdot M - \Delta t^2 \cdot K) \cdot d(i) - C \cdot v(i) \cdot \Delta t^2 - M \cdot d(i-1)$$

$$d(i-1) = d_i - \Delta t \cdot v(i) + \frac{\Delta t^2}{2} \cdot a(i)$$

The stability of explicit methods is determined by the time step. In general, the time step used in an explicit code is 10 to 1000 times smaller than those used by implicit codes. In order to maintain stability, the time step in MSC.Dytran must be “smaller than the smallest natural period of the mesh” (MSC/Dytran, 2004). The time step is related to the mesh dimension in the following way:

$$\Delta t = \frac{L}{c}$$

L: smallest element mesh

c: speed of sound through the material

Δt : time step

2.3 Element Formulation

Shell elements were used to create the column that was placed under blast loading. Shell elements have four nodes, being similar to a four-node quadrilateral. Each node has two degrees of freedom. In addition, the shells contain one integration point at the center of the element. There are eight modes of deformation including: two translational rigid body modes, one rotational rigid body mode, two normal stress modes, one shear stress mode, and two hour-glass or zero energy modes. In addition, the shell elements contain three integration points along the thickness of the element. The shell elements were

chosen because they generally perform well when the structure thickness is small compared to the structure length. In this case, the column flange was approximately one inch thick as compared to its length of 168 inches.

3. CONSTRUCTING THE COLUMN MODELS

The model of column subjected to explosives can essentially be divided into two sections: Lagrangian elements and Euler elements. Lagrangian elements pertain to those elements which are solid in nature, while Euler elements refer to fluids and gases. The Lagrangian elements are used to define those elements inside a mesh whose grid points deform and move as the structure undergoes loading. These elements have constant mass that is lumped onto the grid points. In this model, those materials that can be physically thought of as solid were created from Lagrangian elements. This includes the steel, concrete, and boundary plates.

Euler elements are those in which the grid points remain fixed in space and material is allowed to flow through the mesh. The Eulerian elements maintain constant volume while allowing mass, energy, and momentum to travel from element to element (*MSC.Dytran Theory Manual*). In this model, the materials that can physically be thought of as fluids or gases were created using Eulerian elements. This includes the air around the column, in addition to the explosive gas that propagates through the air. The following section describes the process which was taken to develop the finite element models.

3.1 Lagrangian Elements: Column

3.1.1 Geometry

The column was built using three surfaces that were later meshed into the shell elements. Two of the surfaces acted as the column flanges, while the third was the column web. The surface thicknesses were dictated by the chosen W14x145 section; the flanges being 1.09 inches thick and the web being 0.68 inches thick. Boundary plates were then added to “cap” the column. These plates were given a thickness of six inches in order to make the plates essentially rigid elements so that the applied axial load could be evenly applied to the wide flange section.

3.1.2 Elements and Boundary Conditions

The surfaces of the column and boundary plates were then meshed using QUAD4 shell elements. Once meshed, the column was “equivalenced.” This procedure eliminates nodes that are shared between adjacent elements.

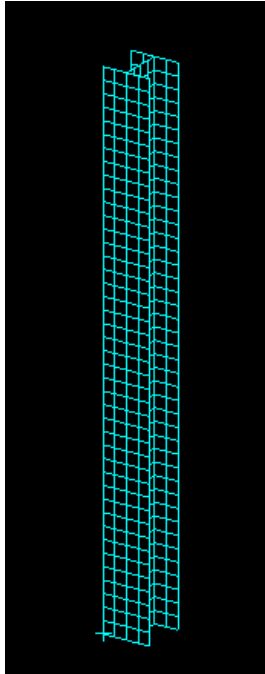


Figure 2. Wide Flange Column

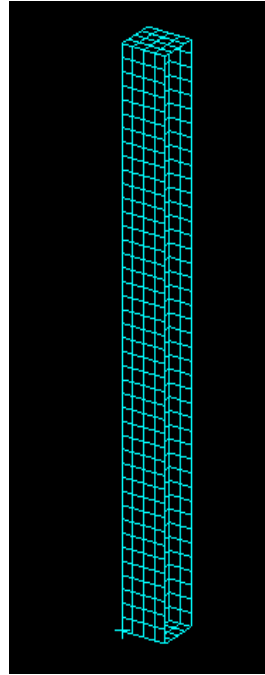


Figure 3. Wide Flange with Boundary Plates

Next, the boundary conditions were applied on the column. The column is pin-ended, to allow rotations but to limit translations. A trial and error procedure was carried out to test the best way to define the pins. It was decided that the center node of the column boundary plates would be constrained. This allows the plate to rotate about this center point. The bottom of the column was prohibited from translations in the x , y , and z -direction. However, since the top of the column has applied axial load, it was prohibited from translation in the x and y , but not the z -direction.

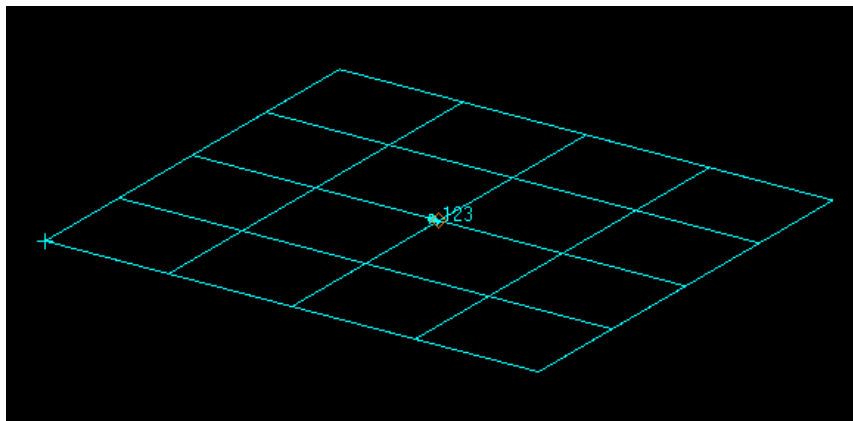


Figure 4. Boundary Plate with Pin Constraint

As previously discussed, the axial load was applied as a static load using MSC.Nastran. In order to avoid creating a singularity in the matrix by applying a large load at a single node, the axial load was applied as a pressure over the top boundary plate. It was necessary to use thick, rigid boundary plates because it was seen during the initial analysis that thin plates failed prematurely, thus causing the termination of the analysis. Since the boundary plates are essentially not the primary point of investigation for this case study, the boundary plates were “reinforced” so that they would not be the governing factor in the analysis. This ensured that the analysis of the column under the blast load could run to its full duration.

3.1.3 Material Models

The materials in both the steel and composite models were specified using a DYMAT24 definition in MSC.Patran. This material model is used for isotropic, elastoplastic materials where a piecewise linear stress-strain curve can be defined (*MSC Theory Manual*). The column was assumed to be Grade 50 steel. The stress-strain relation was defined as a bilinear relationship with a failure of strain of 0.12 as shown in Figure 5..

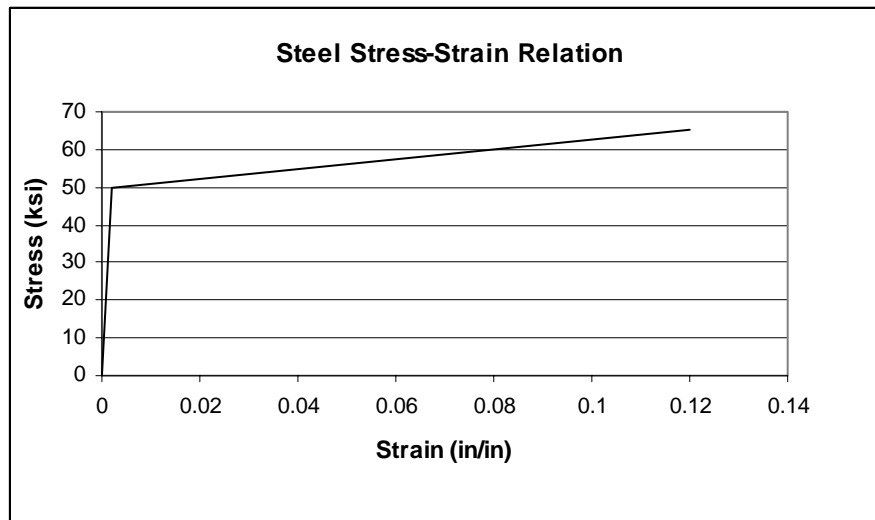


Figure 5. Stress-Strain Curve for Steel

The elastic modulus is $E = 29,000$ ksi, while the hardening modulus is $E_h = 127$ ksi. During the analysis, the elements fail if the strain exceeds a value of 0.12, at this time the element is considered unable to carry load and is removed from the analysis.

Similarly, the concrete used in the composite models was defined using a piecewise linear stress-strain relation. Here, the longitudinal steel reinforcement in the column allowed the concrete to strain harden and to have the same properties in both tension and compression as shown in Figure 6.

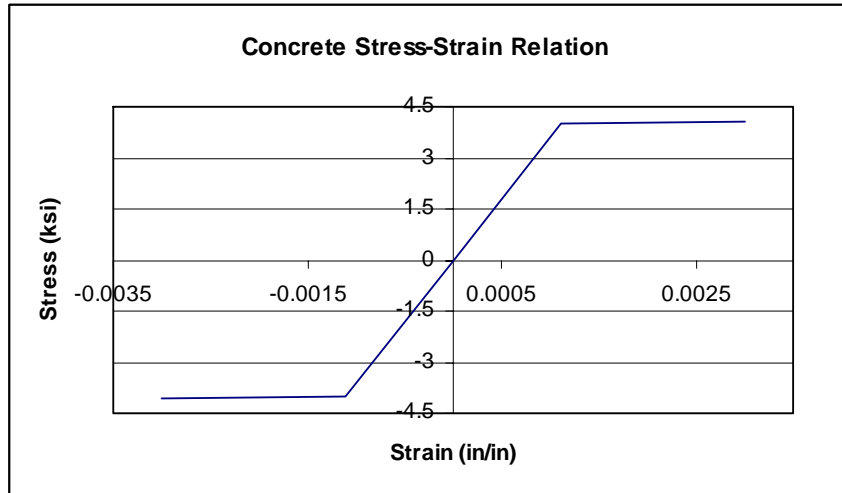


Figure 6. Stress-Strain Curve for Concrete

The steel column is enclosed using a six inch shell of concrete, Figure 7. Here additional surfaces were created in the model and then meshed. For the purposes of the composite material, the concrete and steel are layered together. In the model, they are assumed to have perfect adhesion to one another, whereas in reality, the concrete would most likely be joined to the steel using shear studs. The material properties of the composite shell are computed by MSC.Dytran using Classical Lamination Theory. Essentially, the properties for steel and concrete are “melded” together and a new laminated surface is created.

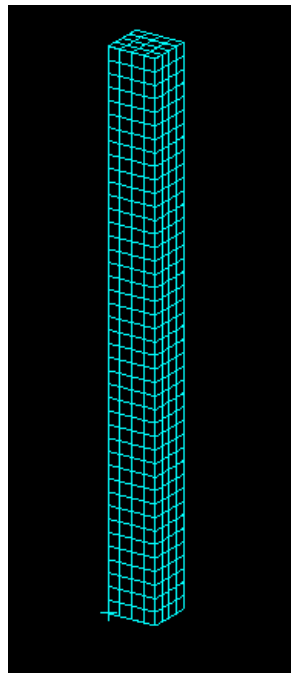


Figure 7. Composite Column

3.2 Eulerian Elements: Explosives and Air

A region of air is created around the outside of the column. It contains “air at rest” which is defined by its density and specific energy. This region of air creates the ambient air pressure that is considered in the explosive formulations.

The explosive was modeled as a sphere of compressed air located at a distance of 10 feet from the column. The mass of the explosive can be altered by either changing the density of the air or the volume of the sphere. In order to model a 10 kilogram mass, the density was set to be $1.54 \times 10^{-5} \text{ lbf-s}^2/\text{in}^4$ and the sphere radius was 9.6 inches.

The resting air definition was given a flow boundary condition at its surfaces. As the explosion propagates, it displaces the resting air. The flow definition allows the air mass and energy to leave or enter the defined region. This is vital because had the air not been allowed to leave, the blast waves would simply bounce off the boundaries of the air region as if the column were enclosed in a box.

Here, the air inside the sphere was given a specific energy so that it is essentially equivalent to TNT. At time zero, the energy of the explosive was released and the blast wave propagates through the air until it hits the column.

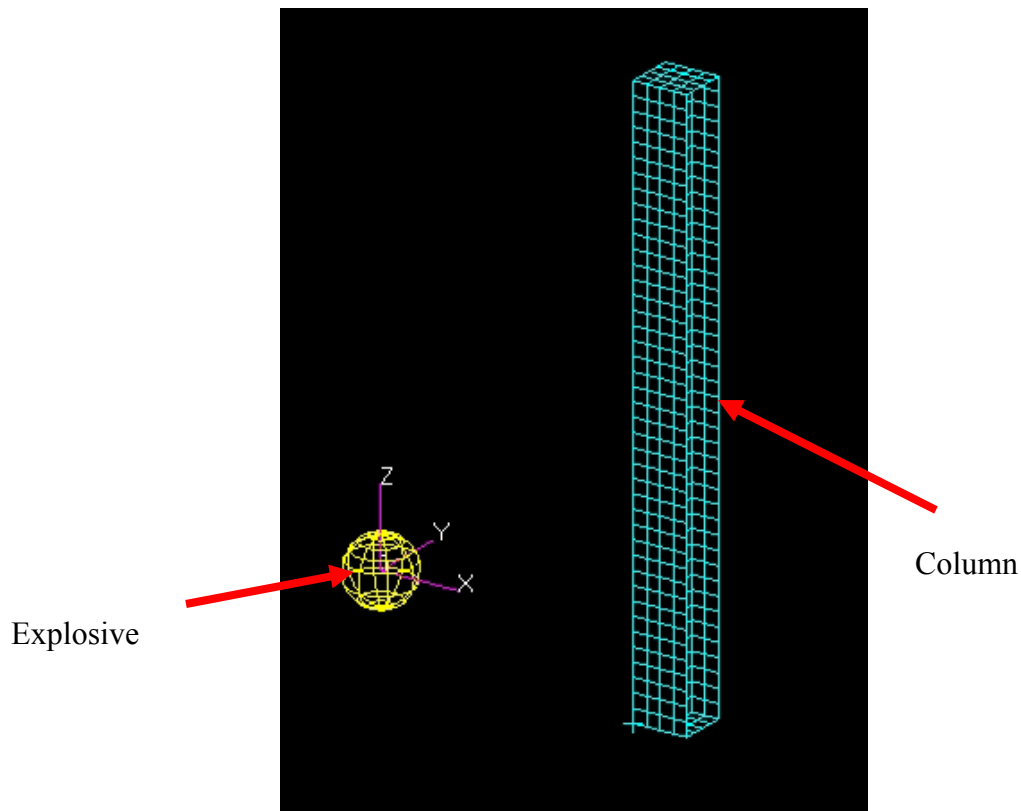


Figure 8. Column with Explosive

4. PRELIMINARY RESULTS

4.1 Steel Column

As previously mentioned, the primary objective of this case study is to determine the overall behavior of the steel wide flange section under blast loading. Once this behavior has been established, the methods of improving the section through the use of concrete will be determined.

In order to gain a preliminary perspective of the column behavior, the models were first analyzed using a steel wide flange section with no applied axial load.

The explosive material was placed at the mid-height of the column and at a distance of 10 feet. In addition, the column is positioned so that strong axis bending will take place. As the explosive material propagates and comes in contact with the column, the column begins to bend in its first mode. As global bending ensues, the stresses at the center of the column increase into the inelastic range. Due to the high pressures placed upon the front flange, the flange begins to fold backwards. At this point, the column has become greatly weakened in its center. A local plastic hinge forms in the column middle. As the flange continues to fold backward, the column continues to bend globally. However, due to the plastic hinge formation, the column essentially begins to fold over on itself until fracture. Finally, after significant deformation, the back flange is pulled apart in what appears to be a tension failure. The following pictures show the sequence of the column behavior. These stages are shown in Figures 9, 10 and 11.

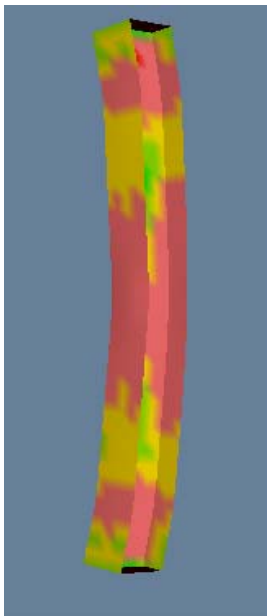


Figure 9. Global Bending

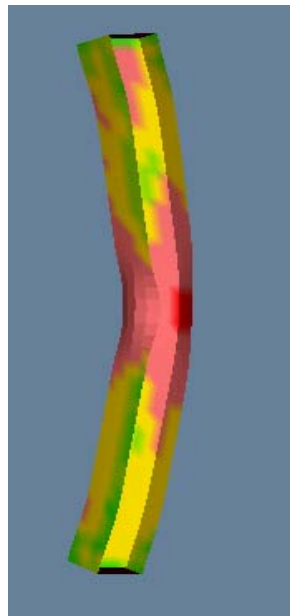


Figure 10. Flange Folding

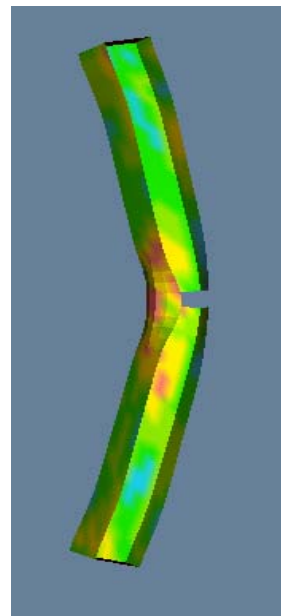


Figure 11. Flange Fracture

It is interesting to note that the back flange does not fold backwards in a similar way to the front flange. It was initially thought that the high pressures would cause both flanges to fold simultaneously. However, because the column begins to bend globally before the flanges start to fold, the back flange is unable to bend backwards. It was also observed that the larger the explosive, the larger the area of the flange that began to fold.

As seen above, the folding of the flange causes results in the formation of a plastic hinge which results in a localized fracture of the back flange. It was determined that if the flange could be prevented from folding, then perhaps the localized failure may be prevented.

4.2 Composite Column

Concrete shells were added to the perimeter of the wide flange section in order to prevent the flange from folding. The shells are six inches thick, constructed from four ksi normal weight concrete. The shells are intended to be a method of retrofitting existing steel wide flange sections. The retrofitted scheme is shown below.

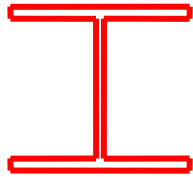


Figure 12. Steel Section

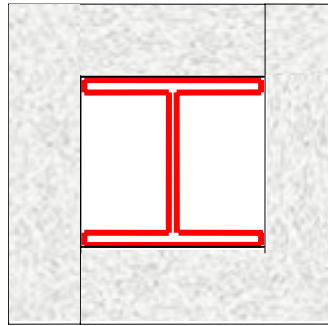


Figure 13. Composite Section

It should be noted, that encasing the steel in concrete will most likely be a very effective way to prevent the steel flange from folding. However, due to difficulties in modeling an encased section it became unfeasible to complete the encased study in the allotted time.

The following pictures show the composite section undergoing blast loading. As the blast waves initially contact the column, the column begins to bend globally in a similar manner to the wide flange section. Again, stresses increase in the column center and a plastic hinge forms. The concrete that is bracing the steel flanges begins to crack and fail. Finally, the back flange fails. It should be noted that the explosive mass used for the below diagrams was scaled so that the composite section would fail. This was done in order to determine the most likely failure mode. It is important to note that the concrete did in fact prevent the flange from folding as was hoped.

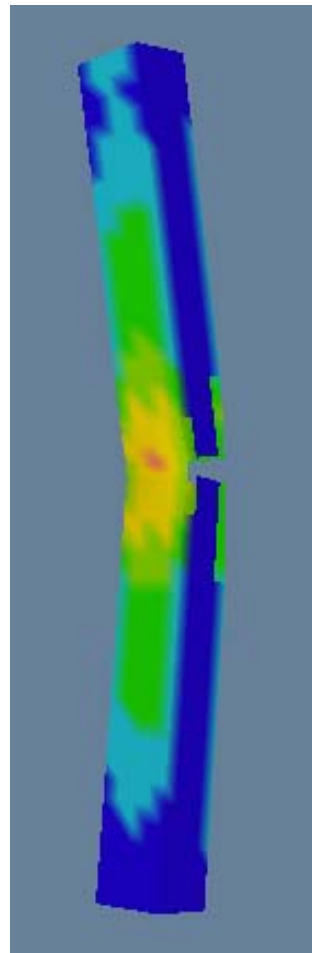
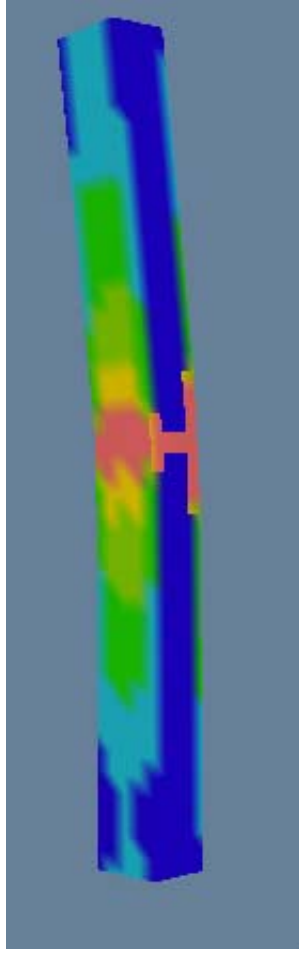
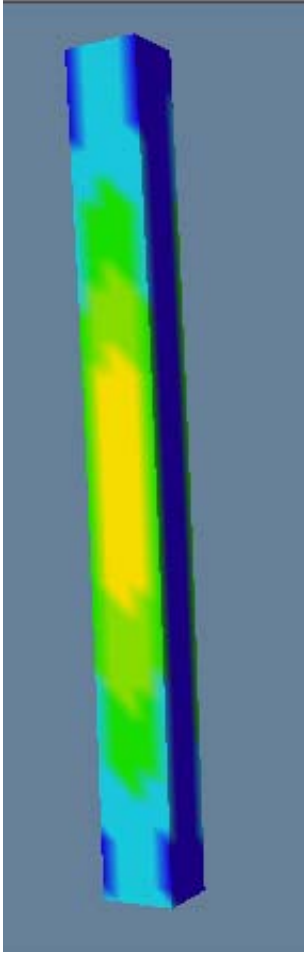


Figure 14. Initial Loading Figure 15. Concrete Cracking Figure 16: Flange Failing

5. CONTINUED RESEARCH

As the above sections demonstrated, we have been able to confirm that the folding of the flange is the primary behavior of a steel wide flange section under blast loading. In addition, concrete shells surrounding the steel can prevent the folding of the flange. Currently, further data is being collected concerning the stability of the steel and composite sections while axially loaded.

6. ACKNOWLEDGMENTS

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The second author wishes to dedicate this paper to the Honorable Vernon J. Ehlers, Congressman from Michigan and a member of the Committee on Science of the U.S. House of Representative for a lifetime of dedication to support scientific research and development of technology. The concept of using pre-cast concrete jackets to protect steel columns, used in this research, was first suggested in 2002 to the second author, Professor Astaneh, by the Honorable Ehlers while being presented some of the results of the earlier work of the second author at a meeting held in Congressman's office in Washington D.C. As discussed in the paper, the studies showed the efficiency of such solution in protecting steel columns from collapse under explosive loads. The

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