

Proceedings of the Annual Stability Conference Structural Stability Research Council Atlanta, Georgia, April 21-24, 2020

Stability of steel columns subjected to near-field detonations

Yongwook Kim¹, Jarett Rooney²

Abstract

Blast attacks are no longer uncommon threats to modern society. For steel columns subjected to far-field detonations, several design approaches have been developed by government agencies and organizations. However, there are no design provisions for steel columns subjected to near-field detonations, which do not necessarily cause bending, but often cause breaching of a section instantaneously. The reduced cross-section can be the weakest part of the column, where a premature buckling failure can be precipitated. Recently, provisions were developed for steel bridge towers subjected to near-field detonations. Although bridge towers and building columns are major structural members to support vertical loads similarly, the same approach as bridge towers cannot be applicable to steel columns, due to the differences in geometry and in the order of magnitudes in charge weights and stand-off distances. The purpose of the present study is: first to identify all possible failure modes of standard wide-flange steel columns subjected to near-field detonations, second to evaluate column performance with lost or deformed components, and third to suggest practical mitigation design methods to save columns. Additional protective layers are considered, such as steel plate and reinforced concrete layers around columns, for more efficient and practical mitigation designs. Extensive parametric studies are performed using non-linear explicit finite element analysis for various charge weights, stand-off distances and protective layers. The results are then used to develop simple design approaches that can be used by practicing engineers. The numerical approaches are validated through comparison to experiments by others.

1. Introduction

Steel has been used as one of the most popular materials for structural members for bridges, buildings, and various other types of facilities over one-hundred years. In the United States, ASCE 7 (2016) and International Building Code (ICC 2018) have been the basis for state or local building codes to define potential loadings applied to building structures. On the other hand, AISC Specification (2016) has been used as the primary guide to design steel building structures subjected to the loadings, addressing various types of failure modes, such as buckling, yielding, and rupture.

Blast loadings and associated failure patterns in steel structures have not been addressed directly in these codes or specification, although they have become serious issues recently due to terrorist

¹ Assistant Professor, Manhattan College, <yongwook.kim@manhattan.edu>

² Graduate Research Assistant, Manhattan College, <jrooney01@manhattan.edu>

attacks, causing partial or more extensive collapses of the buildings, such as the World Trade Center bombing in 1983, the Oklahoma City Federal Building bombing in 1995, and the World Trade Center attack in 2001 (AISC 2004). There have been consensuses to develop approaches to mitigating blast effects on structures, resulting in several guiding documentations by various agencies, such as the U.S. Army (1986), ASCE (2010), AISC (2013), and DOD (2014). The approaches in the documents addressed relatively far-field detonations caused by large charge weights.

Recently, however, FEMA 430 (2007) raised concern for near-field detonations with relatively light-weight and portable devices, and a potential progressive collapse resulting from a localized member failure:

"... a hand-carried bomb placed close to the building, can severely ... damage structures."

"The part of the structure closest to the in-ground infrastructure is the most vulnerable. It should be hardened so that any local failure would not initiate progressive collapse in the rest of the building."

Nevertheless, none of the above-referenced documents account for near-field detonations in the blast-mitigation approaches. ASCE 59 (2011) suggests non-linear explicit finite element analysis for near-field detonations, but it does not provide any detailed guidelines regarding the analysis.

Near-field detonations were addressed for long-span steel bridge towers by Davis et al. (2017). In the reference, the failure was identified by early-time transverse shear failure rather than flexural ductile failure. The considered blast loadings were based on a large truck improvised explosive device (IED). Although certain mitigation design schemes were suggested, there were multiple challenges to standardize the designs, such as complexity associated with detonations in multi-cell towers, a variety of geometries, space limitations, and concerns for added mass. The most suggested design option was to shield the three sides of the square tower adjacent to the roadway with a very thick steel plate.

Obviously, the geometry and the ranges of charge weights and stand-off distances that are considered in typical steel columns inside buildings are significantly different from bridge towers. The purpose of this study is to introduce characteristics and failure modes of standard wide-flange steel columns subjected to near-field detonations, suggest a performance evaluation method of a damaged column, and propose practical mitigation design methods with or without protective layers. A series of numerical studies were performed for various key parameters, such as charge weights, stand-off distances, and protective layers, while the results are presented as simple charts. A method to use the charts for mitigation designs by practicing engineers is demonstrated in this paper. Details of non-linear explicit finite element analysis are also presented. The numerical analysis approach is verified through comparison to experiments in literature.

2. Protected versus Unprotected Columns

Wide-flange shapes (or W-shapes) are widely used for building columns in the United States. A W-shape column subjected to near-field detonations can experience the most severe damage when an explosive is placed to face directly the column's web surface, as shown in Fig. 1a. This is because the detonation pressure is trapped in a partially confined space surrounded by the three

elements of the column: two flanges and web. The detonation pressure escalates rapidly, which deforms or damages a localized area of the column adjacent to the detonation center. In certain situations, the damage is large enough to potentially cause a column collapse.

One of the approaches to prevent or attenuate damages from near-field detonations is to increase a stand-off distance (SOD). In the traditional far-field detonation approaches, the conventional SOD was defined as the distance from the center of an explosive to the surface of a structure. However, for near-field detonations, SOD should be defined as the distance from the surface of an explosive to the center of a column, because a small difference of SOD can affect damages significantly and the web element is most vulnerable to the damages subjected to the near-field detonations. The difference between the conventional and proposed SODs is compared in Fig. 1a. The SOD can be maintained by an architectural finish, required for aesthetical and/or fireproofing purposes. The cover strength is not considered for the protection of a steel column subjected to near-field detonations, because the cover is typically made from relatively weak materials, such as gypsum boards or light-gauge metal sheets. For this reason, a column covered solely by the architectural finish is referred to as an "unprotected column" in this study.



Figure 1: A steel W-shape column subjected to near-field detonations when (a) unprotected; (b - d) protected

When maintaining an SOD with an architectural finish is not effective to prevent or attenuate damages to a column, or there are not enough spaces around a column to maintain a required SOD, protective structural layers may be adjoined around the column. The protective layers have been designed in a way to protect the steel column, by sacrificing the layers to dissipate detonation energy as well as hardening the column. Common construction materials, such as steel and concrete, have been preferred for the protective layers due to economic reasons. Similar to the

protected layers suggested by Davis et al (2017) for the steel bridge towers, examples of the protective layers could include; thick welded steel cover plates with concrete fill (Fig. 1b); plain or reinforced concrete encasement (Fig. 1c); thick steel tube filled with plain or reinforced concrete (Fig. 1d). The last three types of blast mitigation schemes are called as "protected columns." In this study, only the last mitigation scheme shown in Fig. 1d is demonstrated, as the other two schemes were found to be ineffective or inefficient. The same SOD definition is used as the unprotected column. The specific range of SOD investigated in this study is not reported to maintain security, but expressed as multiples of undisclosed variable 'X'. The details of steel tube, reinforcement bars, and concrete strength are also unreleased for security reasons.

The charge weight (CW) of an explosive is also one of the most critical variables that can affect the damages to a column. As quoted earlier from FEMA 430 (2007), even a small portable CW can damage a column significantly to cause a collapse, if it is placed in very close proximity. Thus, the range of the CW investigated in this study is limited not to exceed a portable weight that can be carried by a person. The exact range of the CW is not disclosed for security reasons but expressed as multiples of unrevealed variable 'Y'.

3. Numerical Model

The numerical models for near-field detonations were built using Ansys/Autodyn program (2015). The geometric shape of the numerical model consists of a box-shaped Eulerian mesh domain for TNT and air, and Lagrangian meshes for a steel column and optional protective layers, if applicable, as shown in Fig. 2.



Figure 2: Numerical model geometry

The Eulerian and Lagrangian meshes are fully coupled for complete interaction with each other: When the TNT is detonated, the detonation pressure flows through the Eulerian domain. When the flow encounters the steel column or the protective layers, they become a flow boundary. Simultaneously, the flow exerts the detonation pressure on the column and the layers. The flow is not limited in outward directions at the four sides of the Eulerian domain, while it is reflected at the top and bottom of the domain; this is to simulate a typical space around a column in a building. The Eulerian domain was discretized with 640,000 uniform box-shaped elements, but the detailed meshes are turned off for visual clarity in Fig. 2.

The column was discretized with uniform shell elements with rotational degrees of freedom: there are 8 elements across each of the flange width and web depth; and 54 elements along the length, resulting in a total of 1296 elements. The fixed and roller boundary conditions were applied at the base and top of the column, respectively, to imitate the typical building column construction at the in-ground level.

For models with protective layers; a steel tube was modeled with shell elements, concrete fill was modeled with solid elements, and steel reinforcement bars were modeled with beam elements. The mesh sizes of the protective layers are similar to the column.

For steel columns, and steel tubes made from bent plates, the material properties for ASTM A992 and A572 Gr. 50 are used, respectively. These are currently the preferred steel materials (AISC 2017) and their properties are practically the same for analysis purposes. To account for the changes of stress-strain relationship during high strain rate loadings and the temperature effects during detonation, Johnson-Cook (JC) material model (Johnson and Cook 1983) was adopted as expressed in Eq. 1:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^{*m}) \tag{1}$$

where *A*, *B*, *C*, *n*, and *m* are five constants, σ = true stress variable, ε = true plastic strain variable, $\dot{\varepsilon}^*$ = (strain rate variable)/(reference rate), and T^* = homologous temperature variable. The J-C equation is composed of three parts, distinguished by each pair of brackets; strain-hardening, strain rate effect, and temperature effect, respectively. The strain-hardening part of the equation is curvefitted to the uniaxial stress-strain graph in Salmon et al. (2008) to determine the constants within the brackets: *A* = 379 MPa, *B* = 521, *n* = 0.7, while the remaining two constants were determined per Schwer (2007): *C* = 0.17, *m* = 0.917. For steel reinforcement bars, ASTM A615 Gr. 60 steel was used and a similar approach is made to determine the five constants for the J-C equation. Concrete was modeled with the RHT concrete material model (Riedel et al. 2009). JWL equation of state (Lee et al. 1973) was employed for modeling the TNT.

4. Failure Patterns of Steel W-Shape Columns Subjected to Near-Field Detonations

When a typical W-shape column is subjected to near-field detonation at the base as shown in Fig. 2, the intensified detonation pressure within the partially confined space by the components of the column can deform the column significantly; the web is swollen and the flanges become widened adjacent to the detonation center (Fig. 3a). Under this swelling deformation mode, there is a good chance that the column could survive from the detonation because all components of the column are still attached. However, the damage should be repaired, before the reuse of the building. In this

study the levels of damages are defined as Levels 0 through 3 in Table 1, depending on the deformation magnitude.



Figure 3: Failure patterns of W14x342 steel column subjected to various CW at SOD = 4X (a) swelling (Level 3); (b) puncturing (Level 4); (c) cutting-off (Level 5)

Table 1: Damage	level definitions
-----------------	-------------------

Level	Damage Description
5	Steel column flanges and web are mostly cut off or removed, which could result in instantaneous collapse.
4	Steel column web is cracked or perforated, but flanges are considerably deformed, which could eventually cause sudden column collapse.
3	Steel column is not cracked, perforated or removed, but seriously deformed (min. 10% of member width), which may not result in sudden collapse.
2	Steel column is not cracked, perforated or removed, but moderately deformed (min. 4% of member width), which are not likely to result in collapse.
1	Steel column is not cracked, perforated or removed, but mildly deformed (min. 2% of member width), which are not likely to result in collapse.
0	The steel column is not noticeably deformed. (less than 2% of member width).

If a heavier explosive is detonated, a crack could initiate on the web and eventually develop into a large hole (Fig. 3b). Although both flanges remain intact in Fig. 3b, the individual flange elements may buckle before the member buckling. This is because the flanges are no longer supported by the web element adjacent to the punctured hole, and the cross-sectional properties are significantly reduced from a W-shape to two plate elements. The flaring deformations on the flanges could amplify the damages further due to out-of-straightness, which results in a secondary moment as well as premature buckling. Under this condition, the column would not be able to support typical service loads, which is categorized as Level 4 damage in Table 1. If a harsher condition is applied, the entire, or a significant portion of the column cross-section could be cut off (Fig. 3c) and the

column would not be able to support any service loads. The damage shown in Fig. 3c is categorized as Level 5 in Table 1.

5. Verification of Numerical Model

There are few test data available for steel members subjected to near-field detonations. Krishnappa et al (2014) reported experiments for W-shape columns, albeit key parameters were not available for security reasons. Mazurkiewicz et al. (2015) published test results for welded W-shape columns that are loaded in an upright cantilever configuration. Remennikov and Uy (2014) published experimental results for steel square hollow shapes (SHS) with and without concrete fills.

In this study, a numerical model was built to simulate the experiments by Remennikov and Uy (2014) for the concrete-filled steel SHS, which is similar to the protective layer with concrete fill demonstrated in this study. The 2000 mm long SHS 100x5 (100 mm exterior depth and width; and 5 mm thickness) was laid in a horizontal configuration as shown in Fig. 4 for the convenience of the experiments.



Figure 4: Model geometry for experimental simulation of concrete-filled SHS100x5.

The member is simply-supported and subjected to 2.6 kg of TNT in the middle of the member with a 100 mm clear separation between the TNT and the member. The SHS is made of Australian C350 steel. The Eulerian domain was built to simulate the detonation of TNT through the air, where the size is 600 mm by 600 mm by 350 mm. The flow is not limited in outward directions at the four sides and the top of the Eulerian domain, while it is reflected at the bottom of the domain to simulate the actual experimental setup. The remaining parameters required for the experiment simulation were determined in a similar way to the typical numerical models in this study.

The deformed shapes with Von Mises stress distributions are presented in Fig. 5 for both earlier and later stages of the analysis. The column failure seems to be based on the global bending failure of one-point loading in the middle, as shown in Fig. 5c and 5d at 16 ms (milliseconds). However, at an earlier stage of 0.7 ms shown in Fig. 5a and 5b, the middle portion of the column is already damaged significantly; crushed flanges and crippled webs, losing most of the axial load capacity.

Thus, the major source of failure is a localized crushing failure near the detonation center, rather than the bending failure. The detonation pressure, remaining after the localized failure, pushed the column further to result in the final deformed shape in Fig. 5c and 5d.



(a, b) 1,500 cycles (0.7 ms); (c, d) 20,000 cycles (16 ms)

When the final deformed shapes of Fig. 5c and 5d are compared to the photos from the experiment by Remennikov and Uy (2014), they match closely, which validates the numerical model suggested in this study.

6. Results of Numerical Parametric Study

As observed in Fig. 3, the level of damage increases, as the CW increases. This implies that access control in a building to limit the CW size is crucial to protect structural members. In addition, the relationship between the SOD and the level of damage is demonstrated in Fig. 6; the level of damage is inversely proportional to the SOD. The columns can be protected better, if the stand-off distance can be maintained further. This can be attained if the architectural cover radius in Fig. 1a

is increased. Typically, however, there is an upper limit to the cover size for economic reasons, because a building space around the column is occupied by the cover.



(a) puncturing (Level 4); (b) swelling (Level 3); (c) swelling (Level 2)

If there is not enough space to have a proper architectural cover to avoid Level 4 or 5 damages; if the column is potentially exposed to a heavier CW than what is causing Level 3 damage; or both, the protective layers shown in Fig. 1d would be effective to prevent a column collapse. Three different combinations of protective layers were investigated in this mitigation scheme, as shown in Fig. 7; protected by a steel tube only (Fig. 7b), protected by a steel tube and plain concrete fill (Fig. 7c), protected by a steel tube and reinforced concrete fill (Fig. 7d).



Figure 7: Deformed shapes of W14x342 steel column subjected to CW = 6Y at SOD = 4X with varied mitigation schemes; (a) unprotected; (b) protected by steel tube; (c) protected by steel tube & plain concrete; (d) protected by steel tube & reinforced concrete. For pictures (b) - (d), steel columns inside protective layers are shown separately for visual clarity.

When the unprotected column (Fig. 7a) is compared to the counterpart columns inside the protective layers (Fig. 7b - 7d), there are noticeable improvements in damage mitigation. However, the protection using steel tube alone resulted in Level 4 damages (Fig. 7b), which could lead to a column collapse. For the other two schemes, the columns, strengthened either by steel tube and plain concrete fill (Fig. 7c) or by steel tube and reinforced concrete fill (Fig. 7d), were protected properly not likely to cause a column collapse. Although both of the schemes resulted in Level 3 damages, the maximum deformation for the last scheme with reinforcement bars was somewhat less than the third scheme without reinforcement bars. Thus, it can be concluded that the mitigation scheme with a steel tube and reinforced concrete fill functions more efficiently, compared to the other schemes presented in this study.

For a W14x342 column, a numerical parametric study was conducted for a variety of CW (2Y - 6Y) and SOD (4X - 6X) combinations with and without the protective layers. For the models with protective layers, the mitigation scheme with the steel tube and reinforced concrete fill was used. The resulting damage levels are plotted on the two contour plots based on the ranges of CW and SOD in Fig. 8.



Figure 8: Damage level plots of W14x342 steel column subjected to various CW and SOD combinations (a) unprotected column; (b) protected column

The values plotted on the two graphs in Fig. 8 represent damage levels at each of the CW and SOD combinations. For the most ranges of CW and SOD, the unprotected column results in Level 4 or 5 damages, which can constitute a column collapse (Fig. 8a). When the column is protected by the steel tube and reinforced concrete fill, the damage levels are reduced significantly and the column collapse is prevented for the same CW and SOD ranges.

When practical CW and SOD limits are given for a project, corresponding damage levels for unprotected and protected columns can be determined quickly using Fig. 8. This can be used to determine whether or not the protective layers are needed to prevent a column from collapsing. In this research program, the ranges of CW and SOD have been expanded for various column sizes so that a wide variety of blast scenarios can be covered for steel W-shape columns subjected to near-field detonations. This will result in multiple damage level charts, similar to Fig. 8, with a higher resolution. Practicing engineers could use the charts for mitigation designs of steel columns subjected to near-field detonations without performing the high fidelity non-linear explicit finite element analysis. However, the engineers may choose to perform the high fidelity analysis, following the details presented in this study.

7. Conclusion

In this study, blast mitigation design options with and without protective layers are presented for steel W-shape columns subjected to near-field detonations, using non-linear explicit finite element analysis. The details of the numerical approach are presented, which were verified by comparison to experiments in literature. Using the approach, a series of numerical parametric studies were performed. The levels of damages expected on a column subjected to near-field detonations are identified and categorized, depending on the charge weight and stand-off distance combinations. For ranges of charge weights and stand-off distances, damage levels were plotted on each of the two contour plots for protected and unprotected columns. Using the graphs, practicing engineers can perform blast mitigation design without performing the high fidelity numerical analysis.

Acknowledgments

This research is sponsored by Manhattan College. The sponsorship is greatly appreciated.

References

AISC (2004), Facts for Steel Buildings – Blast and Progressive Collapse, American Institute of Steel Construction.

AISC (2013), Design Guide 26 – Design of Blast Resistant Structures, American Institute of Steel Construction.

- AISC (2016), *Specification for Structural Steel Buildings*, ANSI/AISC 360-16, American Institute of Steel Construction, Chicago, Ill.
- AISC (2017), Steel Construction Manual, 15th Ed. American Institute of Steel Construction.
- ANSYS (2015), ANSYS Autodyn User's Manual, Release 16.1, ANSYS.
- ASCE (2010), *Design of Blast-Resistant Buildings in Petrochemical Facilities*, 2nd ed., American Society of Civil Engineers.
- ASCE (2011), Blast Protection of Buildings, ASCE/SEI 59, American Society of Civil Engineers.
- ASCE (2016). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE/SEI 7-16, American Society of Civil Engineers.
- Davis, C., Sammarco, E., Williamson, E. (2017), *Bridge Security Design Manual*, FHWA-HIF-17-032, Federal Highway Administration, US Department of Transportation, Infrastructure Office of Bridges and Structures.
- DOD (2014), Unified Facilities Criteria Structures to Resist the Effects of Accidental Explosions, UFC 3-340-02, Change 2, Department of Defense.
- FEMA (2007), Risk Management Series: Site and Urban Design for Security Guidance Against Potential Terrorist Attacks Providing Protection to People and Buildings, FEMA 430, Federal Emergency Management Agency. International Code Council, ICC (2018), International Building Code (IBC)
- Johnson, G.R., and Cook, W.H. (1983), "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures," *Proceedings of the 7th International Symposium on Ballistics, Hague, Netherlands.*
- Krishnappa, N., Bruneau, M., and Warn, G.P. (2014), "Weak-Axis Behavior of Wide Flange Columns Subjected to Blast," *Journal of Structural Engineering*, ASCE, 140(5).
- Lee, E., Finger, M., and Collins, W. (1973), JWL Equation of State Coefficients for High Explosives. Lawrence Livermore Laboratory.
- Mazurkiewicz, L., Malachowski, J., Baranowski, P. (2015), "Blast loading influence on load carrying capacity of I-column," *Engineering Structures*, Elsevier, 104. p.107–115.
- Remennikov, A.M., and Uy, B. (2014), "Explosive testing and modelling of square tubular steel columns for near-field detonations," *Journal of Constructional Steel Research*, Elsevier, 101. p.290–303.
- Riedel, W., Kawai, N., Kondo, K. (2009), "Numerical assessment for impact strength measurements in concrete materials." *International Journal of Impact Engineering*, Vol. 36, pp. 283-293
- Salmon, C.G., Johnson, J.E., and Malhas, F.A. (2008), Steel Structures: Design and Behavior, 5th ed., Pearson.
- Schwer, L. (2007), "Optional Strain-Rate Forms for the Johnson Cook Constitutive Model and the Role of the Parameter Epsilon_0," *LS-DYNA Anwenderforum*, Frankenthal, Germany.
- U.S. Army (1986), Fundamentals of Protective Design for Conventional Weapons, TM 5-855-1.