Analysis of Steel Columns for Air-Blast Loads

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Structural vulnerability assessment of mid- to high- rise commercial buildings is a common request of building owners concerned about potential vehicle weapon attacks on nearby streets or within underground parking garages. For these tall buildings, the structural columns carry substantial gravity loads, making it important to include the effect of axial load in the blast analysis. Current design practice often overlooks instability due to axial loading on steel columns when analyzing for air-blast load; instead, conservative performance criteria is set by limiting calculated flexural response to relatively small rotations and ductilities. Additionally, the distribution of air-blast pressure along the height of the column is often approximated as a uniform load by assuming the formation of a plastic hinge at mid-height of the column. This simplification, in addition to neglecting axial load, may result in significant miscalculation of the structural performance for columns with large axial loads.

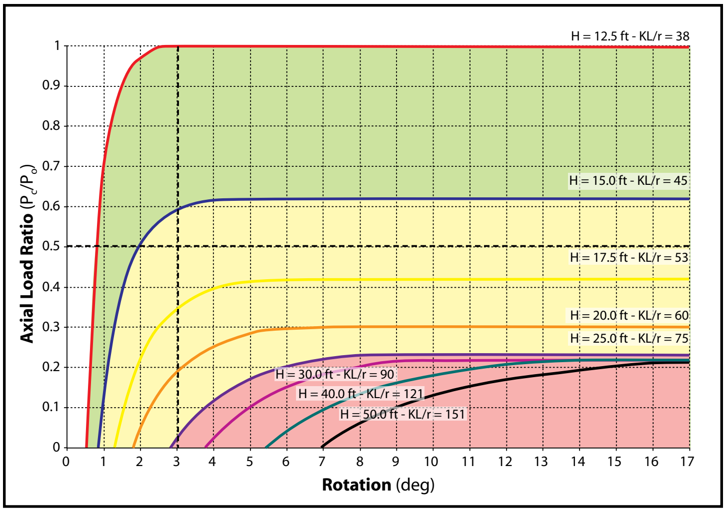

Figure 1a: Axial load ratio vs. rotation for uniform air-blast loading.

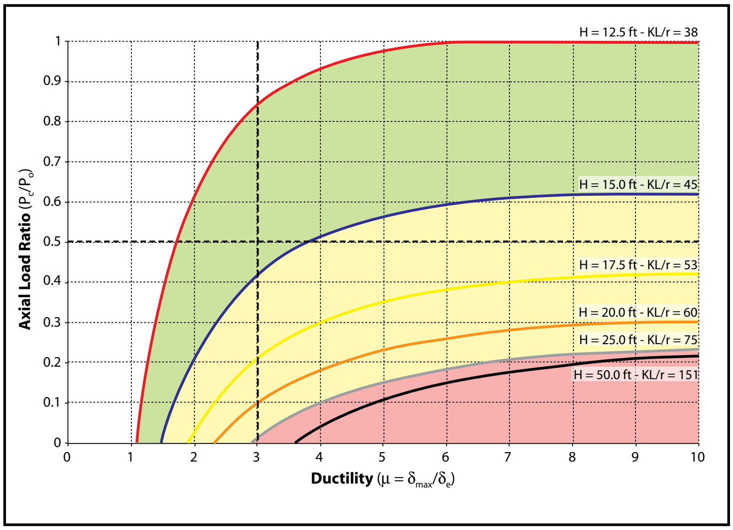

Figure 1b: Axial load ratio vs. ductility for uniform air-blast loading.

Air Blast Effects

An explosion is an extremely rapid release of energy in the form of light, heat, sound, and a shock wave. The shock wave consists of highly compressed air traveling radially outward from the source at supersonic velocities. As the shock wave expands, pressures reduce rapidly with distance, and when it meets a surface in line-of-sight of the explosion, it is reflected and amplified by a factor of up to thirteen. These pressures decay exponentially with time, and their duration is typically measured in milliseconds.

Axial Load Effects

During an explosion, a column directly exposed to air-blast pressures undergoes flexure and corresponding lateral deflection. Explosive pressures are many times greater than conventional loads, therefore it is expected that structural elements will experience large deflections and be loaded beyond their yield strength. Axial forces amplify this lateral deflection and internal moment due to P-δ effects. As the deflection increases, the column will reach its plastic limit, transitioning from a gradual stiffness and strength degradation to a rapid loss of strength due to buckling. This can lead to instability and failure of the column which may have a devastating effect on the overall structural integrity of the building, making it important to consider axial load in air-blast analysis of structural columns.

The extent of axial load effects on a steel beam-column subjected to blast loading is highly dependent on the geometry and support conditions, as represented by the column's slenderness ratio (KL/r). A study using nonlinear dynamic analysis of steel beam-columns of varying lengths and sections for a uniform blast load provides the following results:

- For slenderness smaller than 38, axial effects are negligible.
- Columns with slenderness ratios between 38 and 75 are acceptable according to current standards, as they are below the ductility limit of 3 and rotation limit of 3 degrees when axial load is neglected. However, when axial load is included in the analysis, these columns become unstable.
- Columns with slenderness ratios over 75 exceed the ductility limit of 3 and rotation limit of 3 degrees, even when axial load is ignored. These columns are thus not acceptable under current standards.

These results are represented graphically in *Figures 1a & 1b.*

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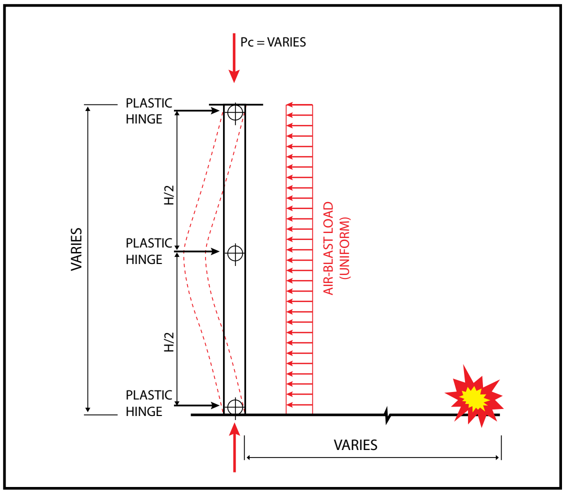

Figure 2: Column subjected to uniform air-blast loading.

Combined Effects of Axial Load and Load-Distribution

In addition to axial load effects, column response can be influenced by the assumed shape of the air-blast loading. Current industry practice often approximates the distribution of air pressure along the height as a uniform load with the formation of a plastic hinge at mid-height of the column, as assumed in the analysis presented above and shown in *Figure 2 (see page 13)*. Although this is appropriate for far-field effects, this simplification is inaccurate for columns located in close proximity to the explosion.

Near-field effects occur when columns are subjected to a close-in explosion causing a non-uniform pressure distribution along the height of the column. This non-uniform distribution of loading typically results in a plastic hinge located below mid-height of the column, as shown in *Figure 3*. Analysis results indicate that shear demand in the column increases as the plastic hinge shifts towards the bottom of the column where the blast load is concentrated; therefore, the assumption of a plastic hinge formation at mid-height may substantially underestimate the shear demand in the column. Under this circumstance, it is likely that the column will be a shear critical element rather than flexural. This effect, in combination with neglecting axial load, can result in inadequately designed columns with large axial loads subjected to close-in explosions, with analysis indicating that ductility may be underestimated by as much as 11% and support rotation by as much as 21%.

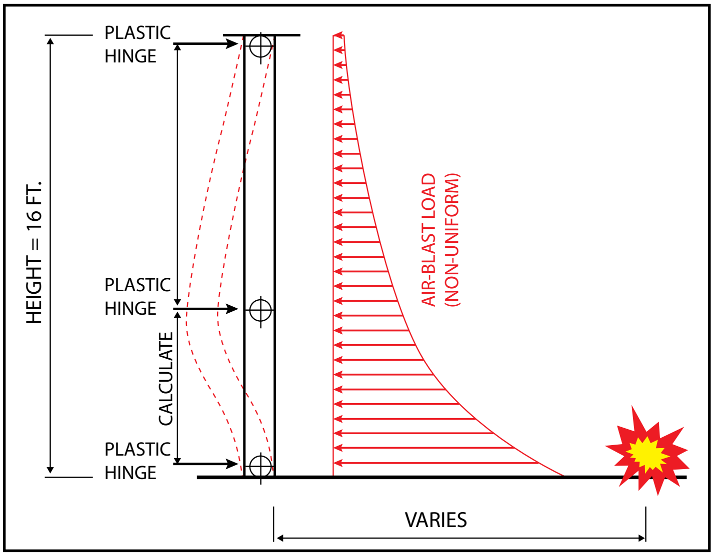

Figure 3: Column subjected to non-uniform air-blast loading.

Combined effects of load distribution and axial load were studied by examining column response to close-in explosions. Column response was determined using a non-uniform load distribution where the expected plastic hinge location was determined by analysis. The following results were found and are represented graphically in *Figures 4a* & *4b*.

- For slenderness smaller than 38, axial effects are negligible.
- For slenderness between 38 and 90, the effects of axial load are significant and should be accounted for in the analysis and design of steel columns due to blast.
- Columns with slenderness ratios over 90 exceed ductility and rotation limits of current standards, even when axial load is ignored. These columns are thus not recommended for use in blast design.

Note that the buckling effects are reduced when assuming a non-uniform load due to the shift of the plastic hinge towards the bottom of the column.

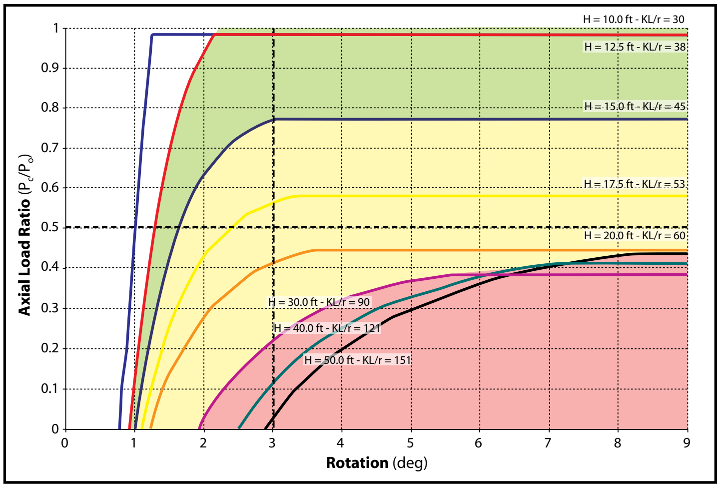

Figure 4a: Axial load ratio vs. rotation for non-uniform air-blast loading.

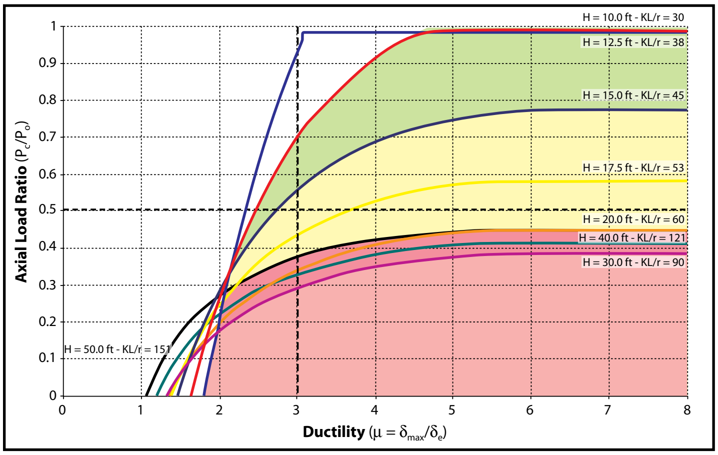

Figure 4b: Axial load ratio vs. ductility for non-uniform air-blast loading

Conclusion

Current design practice often overlooks instability due to axial loading on steel columns when analyzing for air-blast load; instead, what is thought to be conservative performance criteria is set by limiting calculated flexural response to relatively small rotations and ductilities. This approach may result in underestimation of the structural performance for columns with large gravity loads. Modeling of air-blast pressure distribution as a uniform load with plastic hinge at mid-height may also provide inaccurate estimation of column response. This simplification, combined with neglecting axial load, may result in miscalculation of column performance under certain loading conditions, lending to the use of more advanced analysis that incorporates axial load and non-uniform loading effects.▪

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