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Evaluation of progressive collapse alternate load path analyses in designing for blast resistance of steel columns

Jennifer Righman McConnell [a,*], Houston Brown [b]

[a] University of Delaware, 301 DuPont Hall, Newark, DE 19716, USA

[b] Pennoni Associates, Inc. 62 Rockford Rd, Suite 201, Wilmington, DE 19806, USA

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ABSTRACT

The alternate load path method is a convenient, "threat-independent" method used in progressive collapse analysis and design. Because no actual loadings are considered in this method, the resistance provided by the alternate load path method for specific extreme events is not well quantified. However, such quantification allows for an understanding of what real scenarios can be efficiently represented by alternate load path analyses. As blast loading is one of the abnormal loading events typically motivating an alternate path analysis, this load type is selected for evaluation in the present work. In order to find the blast threat that is representative of the alternate load path method in steel-framed buildings, finite element analyses of steel columns being subjected to blast loads were analyzed in the program LS-Dyna. Prior to this, sensitivity and validation studies were also completed, which are described herein. The results of the column analyses show that failure is governed by a stability-based deflection criterion. Conclusions regarding the charge sizes that the alternate load path method may be considered to be representative of, as well as the influence of column spacing, size, and end fixity on these results are given.
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1. Introduction

The alternate load path analysis method is quite popular because it is easily incorporated into design codes, engineers are familiar with the analysis methods accompanying it, and consideration of the initial loading event is not needed. These features currently make it one of the most efficient options available for performing a progressive collapse analysis and assessing the redundancy of a structure. However, it is not the intent of this method to give a direct indication of the structure's ability to withstand a true abnormal loading.

The primary motivation of this work was to shed light on what real scenarios correspond to the state of damage implicitly assumed in the alternate load path analysis method — failure of one and only one column. Realizing that it is not the intent of this methodology to represent any specific loading, this information is nonetheless useful for two key reasons. First, this information can inform the profession's understanding of the connection between real threats and the assumed state of damage inherent to alternate load path analysis. Second, once realistic scenarios that can be enveloped by the alternate load path analysis method are known, labor-intensive threat dependent analyses for these threats can be minimized if desired. Thus, the goal of this work was to determine a practical range of blast threats that can be accurately and efficiently represented by an alternate load path analysis. In practical terms, this means it is to be established what blast threats will cause the failure of no more than one column. The research also takes column size, spacing, fixity, and service loading into consideration and final conclusions are formed in terms of column spacing and end restraints. The research is limited to considering columns only, however; no other structural or non-structural components are considered in the present study.

The literature on progressive collapse is vast, ranging from initial work on the topic in the 1970's through work spurred by a resurgence in interest in this topic as a result of terrorist activity in the early part of the present century. Of this large body of research, the works most relevant to the present study are research addressing the performance of steel-framed buildings during blast scenarios. Marchand and Alfawakhiri [1] have reviewed the best-practices with respect to both progressive collapse and blasts for steel-framed buildings. Hamburger and Whittaker [2] also review the current practice relating to blast-related progressive collapse for steel-framed buildings, while Krauthammer [3] reviews the background on blast effects and focuses on connection performance in steel-framed buildings. All of these documents emphasize the need for ongoing research. In particular, Marchand and Alfawakhiri state that an understanding of the effectiveness of progressive collapse design methodologies in resisting "real" threats is a key issue to be addressed. This work directly relates to this need.

* Corresponding author.
E-mail addresses: righman@udel.edu (J.R. McConnell), hbrown@pennoni.com (H. Brown).

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Outside of the realm of progressive collapse-related research are several additional studies investigating behavior of steel structures under blast loads. The work of Lawver et al. [4] is the most directly related to the present work and documents steel columns' response to a known blast loading. In contrast, the goal of the present work is to approach the problem of a steel column's response to blast loading from the opposite perspective in that it is desirable to determine the blast loading causing a given response, where the response of interest is the failure of one and only one column. In other words, the response of interest is known and the corresponding loading is unknown.

To determine this, an iterative process is adopted. Specifically, a column's response to a given loading is evaluated to determine whether or not failure occurs. If not, a more severe blast scenario is evaluated and if so, a less severe blast scenario is evaluated to determine if this would also cause failure. Because a blast loading is characterized by a combination of charge size and standoff distance, analyses were completed for two different fixed charge sizes and then the standoff distance was iterated to determine a "failure standoff distance". The resulting combination of charge size and failure standoff distance is used to assess the extent to which an alternate load path analysis is representative of a known blast threat. This is accomplished by comparing the failure standoff distance to typical column spacings to determine the number of columns that are possible to be failed by representative charge sizes. For an assumed threat, designers are then able to determine whether an alternate path analysis is sufficient for their needs or if a more rigorous analysis is warranted.

This approach is used to evaluate three different column cross-sections having two different heights. After determining the columns producing the upper- and lower-bound results in an initial parametric study where boundary conditions and loading type are constant, the influences of end fixity and end moments versus axial loading are investigated for these columns in a second phase of parametric study. The following sections detail the LS-Dyna analysis methods used in these analyses, validation of the modeling methods, a mesh sensitivity analysis, the criteria used to establish column failure, and the analysis results. The results are then synthesized to suggest the range of charge sizes that can be generally represented by an alternate path analysis in qualitative terms.

2. Analysis method

2.1. Modeling details

The program used for the finite element analysis (FEA) was the commercial software LS-Dyna and the commercial program Patran was utilized to create the nodes, elements, and boundary conditions. A typical view of the FE model is shown in Fig. 1, where the web is located on the x–z plane and the flanges are located on the y–z plane. Each column was modeled as a mesh of four-node, reduced-integration quadrilateral shell elements employing Belytscho–Lin–Tsay element formulation, which is the default element formulation in LS-Dyna because it provides accurate results for elements with co-planar nodes and requires a relatively small amount of computation time [5]. The quadrilateral elements also share coincident nodes at the intersection of the flange and the web and are proportioned to have element aspect ratios as close to 1 as possible. Patran also allows the user to view the direction of the element normals and switch them if required, which proved to be a useful feature for applying blast loadings.

Steel members subjected to blast loads will experience high strain rates and the inelastic constitutive response of steel is known to be sensitive to this effect. For example, the plastic strain rate reached a value as high as 180/s in this work, which corresponds to a predicted increase in flow stress of 76 MPa (11 ksi) using the input parameters described below. Thus, the Johnson–Cook constitutive material model [6] was used in this work due to its accepted use in modeling steel under high strain rates. This model contains an empirical relation between stress and strain that considers strain hardening as well as strain rate and temperature effects, which is termed the strength model. This material model also includes a failure strain calculation, which is termed the failure model. In addition to material constants for both the strength and the failure models, the user must specify the density for the material (7850 kg/m^3 = 490 lsbs/ft^3), shear modulus (76000 MPa = 11050 ksi), elastic modulus (200000 MPa = 29000 ksi), and Poisson's ratio (0.30), where the values in parentheses are the specific values used in the analyses described herein.

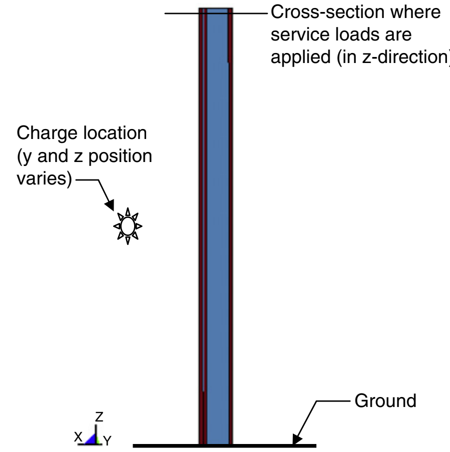

Fig. 1. Orientation of FEA models.

The strength model uses three independent terms to account for strain hardening, strain rate effects, and thermal softening through the three terms in brackets shown in Eq. (1),

$$\sigma_{flow} = \left[A + B\varepsilon_{pl}^{n}\right]\left[1 + C\ln\dot{\varepsilon}^{*}\right]\left[1 - \left(T^{*}\right)^{m}\right], \tag{1}$$

where σ_{flow} is the flow stress, A, B, C, n, and m are material constants, ε_{pl} is the plastic strain, ε^{*} is the dimensionless plastic strain rate, and T^{*} is termed the homologous temperature. While a blast is accompanied by a release of heat, the duration of the elevated temperatures (in the absence of a secondary fire caused by the blast) is negligible. Thus, there are no heat transfer calculations performed in the analysis, resulting in T^{*} equaling zero and the last bracketed term of Eq. (1) dropping out of the equation.

The constant A represents the yield stress of the material. Assuming Grade 345 steel and applying a 10% material overstrength factor (as is typically done in progressive collapse analysis) results in an A value of 379 MPa (55 ksi). There are not well-established values representing typical structural steels for the remaining material constants (B, C, and n). Thus, the strain hardening constants (B and n) were derived by Brown [7] from a large sample of standard tension tests of Grade 50 structural steel completed by Righman [8]. Here it was found that B = 146 MPa (21.165 ksi) and $n = 0.241$ conservatively represent the test data. It is noted that the format of the Johnson–Cook model allows static testing to be used in determining the strain hardening response as this behavior is represented separately from the strain rate effects. The constant C is taken from a study carried out by Kingery and Bulmash [9], in which the authors conclude that a value of 0.0327 for C can be used for mild steel.

The failure model given by Johnson and Cook [6] is shown in Eq. (2),

$$\varepsilon^{f} = \left[D_1 + D_2 e^{D_3\sigma^{*}}\right]\left[1 + D_4\ln\left|\dot{\varepsilon}^{*}\right|\right]\left[1 - D_5 T^{*}\right], \tag{2}$$

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