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Experimental testing and numerical modeling of steel frames under close-in detonations

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Abstract

Even though blast events in inhabited areas are characterized by a low probability of occurrence, they can present a high risk for buildings and their occupants. The means to reduce the vulnerability and prevent the progressive collapse of buildings includes large stand-offs, enhanced local strength of structural elements, and increased redistribution capacity after a local damage. Blasts are extremely complex events, especially when the charge is detonated at a small distance from the building. In such cases, the application of analytical methods may give inaccurate results. The paper presents the results of a combined experimental/numerical program, which focused on the response of steel frames to close-in detonations. Two identical specimens were tested inside a specialized bunker for different charge sizes and stand-off distances. Very similar behaviors and failure modes were observed for the two specimens. The numerical model, calibrated against test data, was able to accurately predict the deformations and failure mode of the specimens. The results of the parametric numerical study indicated that the local failure mechanism and resistance to progressive collapse of steel building frames depend very much on the blast load parameters but also on the level of gravity loads in columns.

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Keywords: Steel frame building, explosive charge, blast wave, scaled distance, strain rate, progressive collapse; column loss

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1. Introduction

Building structural systems should be sufficiently robust to withstand the effects of extreme loadings (e.g. blast, impact) without being damaged to an extent disproportionate to the original cause (EN1991-1-7 [1]). Even if it is very straightforward, the requirement is difficult to apply in practice and poses serious difficulties that are hard to overcome due to the lack of coherent design provisions. Moreover, in case of blast loading, due to the complexity of the blast-structure interaction (dynamic release of pressure, dynamic response of materials and elements, ultimate stresses and strains, propagation of failure, residual capacity), the application of analytical methods may give inaccurate results.

Magallanes et al. [2] performed a full-scale test on a steel wide-flange column subjected to a large explosive force. No local fractures were observed in the column, while some combinations of shear and flexural response (strong-axis direction) or purely flexural response (weak-axis direction) were noticed. F. Fu [3] studied numerically the response of a tall building under a 15 kg package bomb. The results showed that, while a small-scale blast can remove or heavily damage a structural member, it is hard to trigger the collapse of the whole building if the redistribution capacity and alternate load paths are available. Mazurkiewicz et al. [4] used multistage numerical analyses (different types of solvers for different behavior stages) for the load carrying capacity assessment of a blast loaded I-column. Using numerical models calibrated against experimental tests, they found that, apart from the charge mass, shape and the initiation point of detonation can change the level of structure damage. Several studies [5], [6], [7], [8], [9], [10] also investigated the behavior of structures under blast loads, indicating the need for more data in order to improve the efficiency and accuracy of the current design recommendations.

As seen, the capacity of a building to resist progressive collapse following a blast is an issue of high interest worldwide. In this regard, the study deals with the experimental testing and numerical model calibration of steel frames under close-in detonations. Two identical specimens were tested inside a specialized bunker using different charge sizes and stand-off distances until complete failure. No gravity loads were applied to the columns or beams. The test data were used to calibrate numerical models in Extreme Loading for Structures (ELS) [11]. A study was also undertaken to investigate the behavior of the tested models when increased gravity loads are applied to the columns. The study is part of a research project (FRAMEBLAST, 2017-2018) [12], which aims at providing the validation of the response of a full scale building structural frame system under blast loading conditions in laboratory environment. The building will be subjected to blasts (TNT or equivalent) with different charge sizes and locations.

2. Experimental set-up and specimen details

Two identical steel frame specimens were designed and constructed for blast testing inside a bunker (Fig. 1). The specimens were extracted from a typical moment resisting steel frame structure designed for permanent and seismic design situations. The specimens include a column (with the column weak axis oriented in the plane of the frame), two half-span longitudinal beams, rigidly connected to the column using extended end plate bolted connections, and one half-span transversal beam, connected to the column web using a simple clip angle connection, see Fig. 2. Lateral restraints made from tubular profiles were used at the ends of the longitudinal beams. IPE220 sections were used for beams, while columns were made from HEB260, but with flanges reduced to a 160 mm width. The steel material in plates and profiles was S275 J0 and bolts were grade 10.9. Table 1 summarizes the measured material properties of the specimens. The dimensions of elements are identical to those used in other progressive collapse experimental tests within a previous research project ([13], [14], [15], [16]).

The main hazard components of an explosion are blast (overpressure), fragmentation, and thermal effect. In our study, only the first issue was of interest. The peak pressure value depends very much on the distance of the detonation point from the structure of interest. The effect of distance on the characteristics of blast can be taken into account by introducing the scaling laws (DoD, 2014) [17]. These laws have the ability to scale parameters, which were defined through experiments, in order to be used for varying values of distance and charge energy release (Karlos & Solomos, 2013) [18]. The experimental results are, in this way, generalized to include cases that are different from the initial experimental setup. The most common blast scaling law is the one introduced by [19] and [20]. According to the Hopkinson-Cranz law, a dimensional scaled distance is introduced as described by Eq. (1):