Journal of Constructional Steel Research 101 (2014) 143–157

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Progressive collapse potential of a typical steel building due to blast attacks

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ARTICLE INFO

Article history:
Received 10 February 2014
Accepted 17 May 2014
Available online 11 June 2014

Keywords:
Progressive collapse
Steel building
Blast load
LS-DYNA
FE analysis

ABSTRACT

The recent terrorist attacks all around the world and the evidence of the threats found especially in the Kingdom of Saudi Arabia have prompted the concerned authorities to address the risks to the critical infrastructure of the Kingdom. Understanding of the progressive collapse mechanism is an essential step to protect buildings against blast attacks. Buildings are very vulnerable to progressive collapse if one or more columns are lost due to extreme loadings. It is also important to study the likelihood of progressive collapse of buildings in Riyadh to avoid catastrophic events. The paper presents progressive collapse analysis of a typical multi-storey steel framed building in Riyadh to establish its vulnerability when subjected to accidental or terrorist attack blast scenarios. A commercial finite element (FE) package (LS-DYNA) was used to simulate the building response under blast generated waves. The numerical modeling was validated using the results of a published example of tubular steel beam subjected to blast load. Based on the FE analysis results, recommendations are given to mitigate (or control) the progressive collapse potential of steel buildings.

1. Introduction

Progressive collapse refers to the phenomenon in which the local damage of a primary structural element leads to total or partial structural system failure, without any proportionality between the initial and final damage. Even if the probability of structural collapse is low, if it occurs, it can cause significant losses. In the past few decades, many incidents of the total or partial collapse of structures due to fire, explosions or impacts have occurred.

The progressive collapse phenomena was first brought to engineers' attention due to the collapse of a 22-storey building in Ronan Point, London (UK), as a result of a gas explosion in 1968 [1,2]. The research in this area accelerated due to two significant terrorist attacks in the United States that resulted in the structural collapse of the buildings: the Alfred P. Murrah Federal Building collapse in Oklahoma City (USA) bombing in 1995 [3] and the destruction of the World Trade Center (WTC), in New York (USA) in 2001 [4–7].

Most of the published progressive collapse analyses of entire buildings or their components are based on the alternate load path method with column removal. The DoD criteria [8] and the GSA 2003 Guidelines [9] regarding load configurations and quantification of collapse are usually adopted. However, differences are encountered in the numerical technique applied to predict structural behavior.

In Marjanishvili and Agnew [10], an explanation of four methods used to perform progressive collapse analysis (LS: Linear Static; NLS: Nonlinear Static; LD: Linear Dynamic; and NLD: Nonlinear Dynamic) in SAP2000 is presented. Fu [11] performed nonlinear dynamic analyses of a 20-storey 3D structure and found that the columns that are adjacent to the removed column should be designed with an axial force twice that of the static axial force obtained when applying the DL + 0.25LL (DL: Dead load and LL: Live load) load combination. Furthermore, Fu [11] found that column removal in the top stories leads to higher vertical deformations because fewer stories participate in the absorption of the released energy. Mohamed [12] analyzed 3D concrete structures and investigated the shear stresses that resulted from the torsion in the beam connected to the corner column being removed. The shear stresses in these scenarios lead to brittle failure of the beam, but the 2D analysis models could not trace them.

Khandelwal et al. [13] analyzed the progressive collapse potential of seismically designed steel-braced frames, using explicit transient dynamic simulations. The study used the alternate path method on previously designed 10-storey prototype buildings. The structural response was predicted using calibrated 2D macro-models built as a combination of beam-column and discrete spring finite elements.

Ruth et al. [14] analyzed 2D and 3D steel frames and illustrated that using a load factor of 2 may be conservative, whereas using a load factor of approximately 1.5 captures better dynamic effects when static analyses are performed. However, they stated that using a load factor of 2 may be more appropriate for structures of high ductility provided the behavior of the materials was not elastic-perfectly plastic and the materials harden after yielding. As a result, their research suggested

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http://dx.doi.org/10.1016/j.jcsr.2014.05.005
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that a load factor of 2 should be used for important structures and 1.5 for other structures.

Powel [15] compared LS, NLS, and NLD analyses and found that if a load factor of 2 is used in static analyses, it can display very conservative results. Tsai and Lin [16] evaluated the progressive collapse resistance of reinforced concrete (RC) buildings and demonstrated that nonlinear static analyses provide more conservative estimate for the collapse resistance than nonlinear dynamic analyses. They also found that the load factor decreases with the increase in the displacement of the removed column point. Sucuoglu et al. [17] found that the 2D frames that contained a removed column sustained most of the load that was created due to the column removal. Therefore, to evaluate the vertical displacement, the plastic hinge distribution, and rotation in 3D frames, it is sufficient to analyze the 2D frames that contain the removed column.

Kim and Kim [18] studied the progressive collapse of the steel moment resisting frames. It was observed that the linear static analyses provide lower structural responses than nonlinear dynamic analyses and the results varied more significantly depending on the variables such as applied load, location of column removal, or number of building storey. However, the linear static analysis procedure provides a more conservative decision for the progressive collapse potential of model structures.

Kim and Dawoon [19] investigated the effect of the catenary action on the progressive collapse potential of steel moment frame structures. According to the nonlinear static push-down analysis results, the contribution of the catenary action to the progressive collapse demonstrated that the potential of the structures increases as the number of stories and bays increase. Grierson et al. [20] presented a method for conducting a linear static progressive collapse analysis. They modeled the reduced stiffness during the progressive collapse using an equivalent spring method.

Izzuddin et al. [21,22] presented a simplified method for nonlinear static analysis of steel structures. In their research, simplifications were applied to the method. Lee et al. [23] also developed a simplified trilinear model for the relationship between the vertical resistance and chord rotation of the double span beam. This model depends explicitly on the beam length (l) and beam section depth (d). A response was obtained for three values of l/d: 10, 15, and 20. Lee et al. [23] state that for other values of l/d, linear interpolation should be used.

Naji and Irani [24] presented a simplified analysis procedure for the progressive collapse analysis of steel structures using the load displacement and capacity curve of a fixed end steel beam. The results of the proposed method were in good agreement with nonlinear dynamic analysis results. Finally, an explicit expression for the dynamic increase factor (DIF) was established for elastic-perfectly plastic and elastic plastic with catenary action behavior.

Almusallam et al. [25] carried out progressive collapse analysis of a commercial RC building located in the city of Riyadh and subjected to different blast scenarios. A 3-D FE model of the structure was created using a ready-made commercial package. Blast loads were treated as dynamic pressure-time history curves applied to the exterior elements. It was depicted that the shortcomings of notional member removal requirements of many codes might be addressed by improved blast analysis through the use of solid elements with the provision of element erosion. Thus, the regulatory requirements of approximate static structural response for the failure of vertical members under blast load got replaced in the analysis by the improved dynamic phenomenon of the collapse of members. Effects of erosion and cratering were studied for different scenarios of the blast. It was found that the effect of cratering has quite an impact on the behavior of a structure subjected to a close-in detonation as evident from the two scenarios; with and without cratering.

A search of literature has revealed numerous numerical studies on the vulnerability of existing steel buildings to progressive collapse. However, only a limited number of studies are available on the assessment of progressive collapse potential of existing steel buildings when subjected to blast threat scenarios. Major drawback of the code provisions for the assessment of progressive collapse potential of buildings is the absence of appropriate criteria for deciding the column removal which is primarily related to the threat scenarios for the building. In fact, a validated numerical analysis procedure that is simple, yet accurate, and investigates the effect of different blast threat scenarios on the vulnerability of existing steel buildings to progressive collapse could not be found. The lack of such research creates a challenge for the investigation of numerical modeling using the FE method, despite FE being an efficient and cost-effective numerical tool to model the structural behavior of steel buildings under blast loads.

In this study, a simplified nonlinear dynamic (NLD) analysis procedure was conducted to establish the vulnerability of a typical multi-storey steel framed building in Riyadh when subjected to accidental or terrorist attack blast scenarios. A ready-made commercial FE package LS-DYNA [26] was used to simulate blast loads for this purpose. The FE modeling was carried out in two stages – the local model stage to assess the individual columns performance against blast pressures [27] and the global modeling stage to assess the overall response of the structure due to the failure of the critical columns. The numerical modeling was validated using the results of a published example of tubular steel beam subjected to blast load.

2. Building description

A typical six storied (G + 5) commercial steel building taken for the present investigation is located in a congested urban area in the city of Riyadh. The building is adjacent to two other buildings in the North and East directions. The front of the building is located in the South direction and is overlooking a main street of 30 m width. The main street is normally abuzz with hundreds of cars lining the traffic lights and huge numbers of pedestrians walking along the walkway which gives it an impression of being congested although the street is fairly wide. The West side of the building is overlooking a side street of 15 m width. The building is a steel framed structure with the layouts of beams and columns as shown in Fig. 1. The structure has a RC core for lift. The floors consist of one-way joist steel floor system. The peripheral facade consists of in-filled brick masonry with glazed windows. The typical cross section of beams and columns at a typical floor level is shown in Fig. 1. There are a total of fifteen outer and three interior columns. There are no expansion joints in the building.

3. Blast threat scenario identification

The assessment of blast resistance of a building requires defining the level of threat. The possible threats may be numerous but the present study considers the terrorist bombing involving the intentional explosion outside the building. The threat for a conventional bomb is defined by three equally important elements, namely the type of explosive, charge weight and the stand-off distance. There are many explosive devices such as Ammonium-Nitrate Fuel Oil (ANFO) mixture, Trinitrotoluene (TNT), C4 and Semtex, etc. that may be used by terrorists, but so as to standardize the criteria, the charge weight of an explosive device in terms of the equivalent weight of TNT was considered. Thus there are only two parameters to be considered in the blast analysis i.e. the charge weight and the stand-off distance.

The layout of the building is rectangular in plan. The main entrance and exit of the building is located in the South side. The building is located on a major road with the South face of the building facing the road. The front face has street-side parking and sidewalk. The major threat to the building from terrorist bombing is through explosion in a parked vehicle. The layout of the building and its surroundings suggest that a vehicle may be parked close to the building on the South face which is facing the road. Thus the minimum stand-off distance of the location of explosion for the building was taken as 2 m. Two possible critical