Engineering Structures 56 (2013) 664–672

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental and analytical progressive collapse assessment of a steel frame building

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ARTICLE INFO

Article history:
Received 19 August 2011
Revised 19 June 2012
Accepted 31 May 2013
Available online 2 July 2013

Keywords:
Progressive collapse
Steel buildings
Column failure
Load redistribution
Collapse experiment

ABSTRACT

A field experiment and numerical simulations were performed to investigate the progressive collapse potential of an existing steel frame building. Four first-story columns were physically removed from the building to understand the subsequent load redistribution within the building. Experimental data from the field tests were used to compare and verify the computational models and simulations. Due to the scarcity of data from full-scale tests, the experimental data produced during this research is a valuable addition to the state of knowledge on progressive collapse of buildings. The progressive collapse design guidelines typically recommend simplified analysis procedures involving instantaneous removal of specified critical columns in a building. This paper investigates the effectiveness of such commonly used progressive collapse evaluation and design methodologies through numerical simulation and experimental data.

1. Introduction

Progressive collapse is generally defined as small or local structural failure resulting in damage and failure of the adjoining members and, in turn, causing total collapse of the building or a disproportionately large part of it. Progressive collapse of building structures is initiated by loss of one or more vertical load carrying members, usually columns. After one or more columns fail, an alternative load path is needed to transfer the load to other structural elements. If the neighboring elements are not designed to resist the redistributed loads, failure will happen with further load redistribution until equilibrium is reached, resulting in partial or total collapse of the structure.

Progressive collapse is triggered by abnormal loading that causes local failure of one or more columns if the building lacks sufficient ductility, continuity and/or redundancy. The local or complete collapse may cause significant casualties and damage disproportionate to the initial failure. A notable example is partial collapse of the Ronan Point apartment building in London. An accidental gas explosion in a corner kitchen on the 18th floor initiated progressive collapse of the 24-story building in 1968. This event triggered extensive progressive collapse research and led to development of design guidelines for the prevention of progressive collapse [13].

The World Trade Center 7 (WTC 7) in New York City was a 47-story office building adjacent to the WTC towers (WTC 1 and 2) that collapsed following the terrorist attacks of September 11, 2001. WTC 7 collapsed several hours after the collapse of twin WTC towers. The NIST report [11] concluded that: "An initial local failure occurred at the lower floors (below floor 13) of the building due to fire and/or debris induced structural damage of a critical column (the initiating event) which supported a large span floor bay with an area of about 2000 square feet. Vertical progression of the initial local failure occurred up to the east penthouse, as the large floor bays were unable to redistribute the loads, bringing down the interior structure below the east penthouse. Horizontal progression of the failure across the lower floors triggered by damage due to the vertical failure, resulting in a disproportionate collapse of the entire structure." The FEMA 403 [6] study emphasized the significance of fires on the collapse. This is a good example of disproportionate collapse caused by debris and/or fire induced failure of a column or columns in a tall steel building. In this research, several columns were sequentially removed from a building, which can resemble the initial debris damage and gradual and intensifying fire damage or a various other loads.

Failure of one or more columns in a building and the resulting progressive collapse may be a result of a variety of events with different loading rates, pressures or magnitudes. The magnitude and probability of natural and man-made hazards are usually difficult to predict. Therefore, most of the current progressive collapse design guidelines are threat-independent and do not intend to prevent such local damage, e.g., ACI 318 [1]. Rather, their purpose

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http://dx.doi.org/10.1016/j.engstruct.2013.05.050

is to provide a level of resistance against disproportionate collapse and to increase the overall structural integrity. Design guidelines typically require minimum level of redundancy, strength, ductility and element continuity. The codes typically prescribe simplified analysis procedures requiring instantaneous removal of certain critical columns in a building, e.g., GSA [8]. In this paper, effectiveness of such commonly used progressive collapse evaluation and design methodologies is investigated through numerical simulations and experimental testing of the building.

A large number of numerical studies have been conducted to evaluate the effectiveness and consistency of the current progressive collapse design guidelines. However, very limited experimental research has been performed to validate the results of these computational studies and to verify the methodologies prescribed in the guidelines. This is mainly because it is difficult to construct and test full-scale building specimens and such large-scale testing is discouragingly expensive. In this study, an existing steel frame building, Ohio Union building, was tested by physically removing four first-story columns. The building was instrumented and the experiment was conducted prior to its scheduled demolition. The building was also modeled and analyzed using the computer program, SAP 2000 [15], following the requirements of the current progressive collapse evaluation and design guidelines. The results from static and dynamic analysis of the building were compared with the experimental data.

2. Progressive collapse guidelines

American Society of Civil Engineers (ASCE 7, [3]), General Services Administration [8], Department of Defense (Unified Facilities Criteria, [4], and National Institute of Standards and Technology [12] have developed criteria and guidelines to evaluate, design and improve structural integrity and progressive collapse resistance of existing and new buildings. ASCE 7 [3] provides design load combinations including abnormal loads and associated probabilities. It also presents general direct and indirect design approaches to ensure structural integrity following local damage to a primary load-carrying member. In this paper, the collapse resistance of the test building is evaluated using the load combinations recommended by the ASCE 7 standard and GSA guidelines [8].

General Services Administration [8] provides guidelines for evaluation of existing buildings and design of new buildings against progressive collapse. A simplified threat independent methodology is recommended for buildings with fairly regular plans and up to ten stories above ground. A linear elastic static analysis of the building is required after the instantaneous removal of a first story column located near the middle of longitudinal and transverse perimeter frame or at the corner of the building. Progressive collapse and possible subsequent failure of elements are investigated using the calculated demand-to-capacity ratio (DCR) for each structural element. DCR is defined as the ratio of the force (moment, shear, or axial force) calculated after the instantaneous loss of a column and the corresponding capacity of the member. In this study, the test building was analyzed using the load combinations specified by the GSA and the corresponding DCRs were calculated. The acceptance criteria provided by the GSA was then used to assess the potential for progressive collapse.

3. Building experiment

The Ohio Union building, shown in Fig. 1, was located on the Ohio State University campus. The four-story moment frame building was constructed in 1950. The building included a rectangular floor plan with three columns on each transverse axis and nine columns along the longitudinal axes. Column and beam section properties and the longitudinal test frame geometry are shown in Table 1 and Fig. 2, respectively. In Table 1, the first and last numbers are the depth (in inch units) and nominal weight (lb/ft) of the columns or beams, respectively (1 in. = 25.4 mm, 1 ft = 305 mm, and 1 lb = 4.448 N). The letters WF and B are wide-flange (WF) shaped I-beam and light I-beam, respectively, which were commonly used in the 1950s [2].

Before the building's demolition, four first-story columns were removed in the following order: (1) two columns near the middle of the longitudinal perimeter frame, (2) column in the building corner, and (3) column next to the corner column. As shown in Figs. 1 and 3, four of the nine exterior columns were first torched near the top and bottom. Only a small portion of the flange was left intact when the cross sections were cut. The middle column segment between the torched sections was then pulled out by a bulldozer using a steel cable (Fig. 3).

The columns were removed within a very short time period representing an instantaneous column removal as recommended in the design guidelines. As shown in Fig. 4, 15 strain gauges were installed on the columns and beams closely linked to the removed columns to monitor the redistribution of gravity loads using the change in strains measured during the removal of columns. During the column removal process, a portable data acquisition system and a scanner connected to a laptop computer recorded the strains. No significant visible damage was observed in the building even after the four columns were removed. Detailed description of the test building, instrumentation, experimental procedure and recorded data can be found in Song [16].

During the field experiment, strains in members neighboring the removed columns were measured as each column was torched and removed. In this study, universal general purpose strain gauges with a resistance of 120 ± 0.3% Ohms were used. All strain values dropped to negative values after each column was torched or removed, and then stabilized after a certain amount of time. These negative strain values indicate that the structural members contracted and compressed when the neighboring columns were torched. Most of the measured strain values dropped more when the columns were torched than when they were removed during the experiment. The largest drop of strain values was observed when the last column was torched.

4. Analysis procedures and results

Numerical simulations of the test building were performed using the computer program SAP2000 [15] to investigate the progressive collapse performance of the building. At the time of testing, the frames carried only dead loads due to weight of walls, slabs, beams, and columns. In the linear static analysis, the dead loads were multiplied by 2.0 as recommended in the GSA guidelines [8]. The live load was assumed to be zero in all analyses because the test building was not occupied, and most of the partitions, furniture and other non-structural loads were removed from the building. To calculate the dead load of the walls, densities of glass and brick were assumed to be 2579 kg/m^3 and 1920 kg/m^3, respectively. Properties of frame members were obtained from the original structural drawings and design notes. Yield strength of all frame members of the Ohio Union building was assumed to be 345 MPa (50 ksi), as specified in the original design drawings. Details of the modeling and analysis assumptions and results are reported in Song [16] and Song et al. [17,18].

Two-dimensional (2-D) as well as three-dimensional (3-D) models of the building were developed to analyze and compare the progressive collapse response. Fig. 5 shows 2-D and 3-D SAP2000 models of the Ohio Union building with frame member numbers. As in the actual building experiment, four circled