Journal of Constructional Steel Research 110 (2015) 182–190

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Effects of floor slab on progressive collapse resistance of steel moment frames

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ARTICLE INFO

Article history:
Received 26 February 2014
Accepted 25 February 2015
Available online 15 April 2015

Keywords:
Progressive collapse analysis
Steel moment frames
Floor slab
Column missing event
Energy-based method
Finite element analysis

ABSTRACT

In this paper, an analytical modeling of the effect of floor slabs on progressive collapse resistance of steel moment frames is presented. To this end, the behavior of the double-span floor slab under the column missing event is first investigated using the advanced nonlinear finite element analysis. The functional form of the deformed shape of the double-span floor slab is derived from the numerical analysis and used to analytically model the energy absorption contribution of the floor slab under the column missing event. The application of the proposed model can be used in conducting more refined energy-based progressive collapse analysis of steel moment frames.

1. Introduction

As was well illustrated in the collapse of the Ronan Point precast apartment building in London in 1968, small triggering events can cause catastrophic consequence in structures susceptible to progressive and disproportionate collapse. Progressive collapse may be described as the spread of an initial local damage or failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it [1]. The most viable design approach to resist progressive collapse is to provide sufficient integrity, redundancy and ductility in the structural system such that the surrounding structural elements could mobilize their reserve capacity to bridge over the damaged area. In this sense, ductile steel moment frames may be a good structural system to resist progressive collapse.

Current representative design guidelines (for example, [2,3]) recommend several methods of progressive collapse-resistant design. The UFC 4-023-03 [3] presents the tie force method, the alternate path method, and the enhanced local resistance method. The tie force method is the empirical prescriptive methodology to keep the integrity of structural system under the event of an abnormal loading so that structural members and joints withstand the tie force required in vertical deflection of 20% of the span length. The alternate path method is the most preferred and common method in many design guidelines. In this method, a single column is typically assumed to be suddenly missing, and an analysis is conducted to determine whether or not the structure can bridge across the missing column. The enhanced local resistance method is to provide the perimeter structural members with sufficient strength and ductility in order to prevent from the abrupt brittle failure of the members. This study focuses on the analysis issue when using the alternate path method.

Many experimental and analytical studies on the role of the reinforced concrete and composite floor slabs in the alternate path method have been conducted. For example, Astaneh-Asl et al. [4] carried out the experimental research on the composite floor slab of steel moment frames reinforced with the pre-stressed steel wires as a way to improve progressive collapse resistance. Yu et al. [5] numerically examined the contribution of various connections and floor slab to catenary action of the double-span beams and proposed a design method which uses the pre-stressed steel wire as the strategy for reinforcing the structural system. Izzuddin et al. [6] proposed a framework for a simplified progressive collapse analysis of composite multi-story steel buildings by assembling the responses of individual floors. Main et al. [7] proposed a modeling approach that can be used for computational nonlinear progressive collapse analysis based on the study of several steel moment connections and composite slab system. Dat and Hai [8] investigated the behavior of the reinforced concrete beam-slab subjected to the penultimate-internal missing column scenario using quasi-static numerical analysis. Their numerical study demonstrated that membrane actions of slab and catenary action of double-span beams significantly enhance the load-carrying capacity of the structure when vertical displacement becomes large. Alashker and El-Tawil [9] proposed a

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http://dx.doi.org/10.1016/j.jcsr.2015.02.013
0143-974X/

progressive collapse-resistant design method including the slab effect by utilizing the deformed shape of the floor system based on numerical analysis results. All these experimental and analytical studies have mainly focused on the internal column-missing scenario. However, for structures without underground parking or other uncontrolled public ground floor areas, design based on external column removal scenario is permitted as a minimum [3]. In average practice, the effect of floor slab has commonly been ignored because of the lack of the practical procedure to consider it in analysis and design.

In this paper, an analytical modeling of the floor slabs under the external column-missing event is presented that can be used for more accurate evaluation of progressive collapse resistance of steel moment frames. A simplified axial tensile force–deformation relationship of the double-span floor slab under the external column-missing event is first developed based on the finite element analysis results. Then, by adding the energy absorption contribution of the floor slab to the energy balance equation, a simple but more accurate energy-based nonlinear static progressive collapse analysis procedure is proposed.

2. Kinematics of floor slab under external column-missing event

2.1. Finite element modeling

Finite element analyses were conducted to understand the kinematics of the floor slab facing the perimeter of a building under the external column-missing event. As shown in Fig. 1, when a middle column is removed from a perimeter steel moment frame, the frame may be divided into the directly affected part (DAP) and the indirectly affected part (IAP). A subassembly representing the DAP in Fig. 1 was modeled in this study.

A material and geometric nonlinear finite element analysis was conducted for the subassembly by using the ABAQUS/Explicit program [10]. Fig. 2 shows the dimensions and details of the subassembly model. The subassembly model consists of steel columns, steel beams (a double-span beam and a transverse beam) and the floor slab formed on the ribbed steel deck [see Fig. 2(a)]. The ribs of the metal deck were modeled to be oriented perpendicular to the transverse beams. The floor slab consists of the ribbed metal deck (a thickness of 1.2 mm, a depth of 75 mm, and a pitch of 300 mm), the topping concrete of 100 mm-deep, and the welded wire mesh [see Fig. 2(b)]. Welded wire meshes of WWF #6 (diameter = 4.8 mm) with a spacing of 150 mm × 150 mm are modeled by the *embedded option in ABAQUS. The H-shaped columns of H-428 × 407 × 20 × 35 (section depth × flange width × web thickness × flange thickness), the H-shaped double-span beam (H-700 × 300 × 13 × 24) and the H-shaped transverse beam (H-506 × 201 × 11 × 19) were selected for numerical analysis. All steel shapes satisfy the seismic compactness requirements in the AISC-LRFD seismic provisions [11]. It is assumed that the horizontal shear between the beam and the slab is fully transferred by shear connectors, or the full composite action is assumed.

Fig. 3 shows the finite element model of the subassembly model. The beams, the columns and the metal deck in the floor slab were modeled using the quadrilateral four-node shell elements with reduced integration (S4R). The topping concrete in the floor slab was modeled using the eight-node solid elements with reduced integration (C3D8R). Truss element (T3D2) was used for the welded wire meshes embedded in the concrete. The three inside edges of the floor slab were laterally restrained in order to simulate the axial restraint effects provided by the continuous floor slabs and adjacent structural elements.

For a concrete material model used in the floor slab, a compressive strength of 24 MPa, an elastic modulus of 15 GPa, and Poisson's ratio of 0.15 were used. A stress–strain relationship in Fig. 4(a) was applied for compression. The secant stiffness was used for simplicity and the brittle crushing of the concrete was developed by the *brittle cracking option in ABAQUS. For tension, a linear stress–strain relation up to the modulus of rupture (f_r) in Eq. (1) per ACI 318–10 [12] and the tension softening after it were applied.

$$f_r = 0.7\sqrt{f'_c} \tag{1}$$

where f'_c is the compressive strength of the concrete.

In addition, the shear retention was considered at the cracked surface where the shear modulus is reduced due to cracks. The shear retention factor reflects the dowel action of rebars and the aggregate interlock phenomenon.

For steel material model of the welded wire mesh and the metal deck, an elastic-perfectly plastic stress–strain relationship was applied as shown in Fig. 4(b). The welded wire mesh has an yield strength ($\sigma_{wire,y}$) of 400 MPa and the metal deck has an yield strength ($\sigma_{deck,y}$) of 283 MPa. An elastic modulus (E) of 2.06 × 10^5 MPa was used for both the welded wire mesh and the metal deck.

For a steel beams and columns, a tri-linear stress–strain relationship was applied and material nonlinearity with the von Mises yield criterion combined with nonlinear isotropic hardening was considered. Material properties followed the mean values of ASTM A992 steel, with a tensile

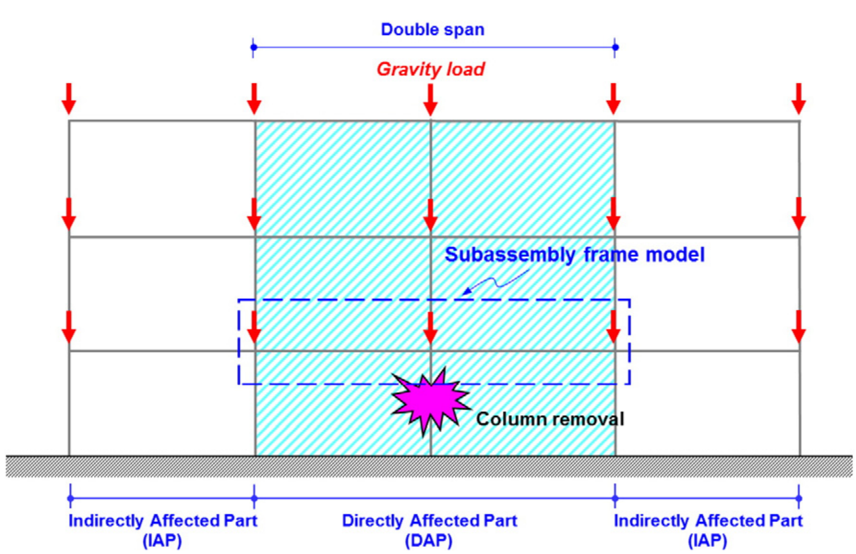

Fig. 1. Column-missing event of a perimeter moment frame.