Journal of Constructional Steel Research 145 (2018) 471–488

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Collapse resistance of steel beam-concrete slab composite substructures subjected to middle column loss

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ARTICLE INFO

Article history:
Received 12 December 2017
Received in revised form 2 March 2018
Accepted 3 March 2018
Available online xxxx

Keywords:
Progressive collapse
Composite beam-slab substructure
Column loss
Membrane action
Catenary action
Energy-based method

ABSTRACT

An energy-based method is proposed to determine the structural responses of composite beam-slab substructures under middle column removal scenarios. A tri-linear resistance-displacement curve is proposed. Three factors contributing to the internal energy dissipation are accounted for, including the extension of reinforcing bars and steel beams, the additional bending moment induced from membrane forces in the slab and tensile forces in beams, and sectional bending moment along yield lines of the slab. Parametric studies are conducted based on validated finite element models to investigate the effect of slab planar aspect ratio, slab thickness, slab reinforcement ratio and beam section height on the behavior of composite beam-slab substructures subjected to middle column loss. The numerical results show that these four parameters have limited effects on the yield displacement of the substructure. The accuracy and effectiveness of the proposed method are verified against numerical results with errors less than 15%. It is found that the first two factors considerably contributed to the collapse resistance of the substructures at large deflections, by accounting for more than 65% of the total energy dissipation capacity. At the collapse limit state, the contribution from the slab is mainly influenced by its reinforcement ratio. The beam height has little effect on the beam contribution to the collapse resistance of the substructure.

1. Introduction

The term "progressive collapse" refers to the propagation of an initial local failure from element to element, which may lead to a disproportionate collapse of the structure [1]. The recent events occurring in United States [2,3] indicate that civil engineering structures are more likely to be exposed to extreme, rare and unforeseen conditions. Considering the enormous potential losses of life and treasure in the event of collapse, it is paramount to investigate the robustness of structures to ensure a sufficient collapse resistance for a reasonably adequate range of initial failure scenarios. Current building codes and guidelines have put forward both indirect and direct methods to prevent progressive collapse of structures [1,4,5]. The indirect methods require constructive measures (e.g. reasonable plan layout, redundant systems, ductile detailing) rather than structural analysis to ensure a minimum level of connectivity among various structural components [1]. The Tie Force method, as a typical indirect method, is to mechanically tie together the building components to enhance continuity, ductility, and development of alternate load paths [4]. The direct methods explicitly investigate the ability of the structure to prevent the spread of initial localized damage [4]. Typically, an Alternate Path Method is applied by instantaneously removing the potentially damaged member, and to assess the progressive collapse resistance of the remaining structure to ensure alternative load transferring paths to bridge over the missing member.

The three-dimensional (3-D) steel frame-concrete slab systems are widely used in residential, office, and industrial buildings. Complicated collapse resisting mechanisms, including compressive arching, flexural and tensile catenary actions in beams, as well as membrane actions in floor systems will be mobilized in composite frame structures under column removal scenarios [6]. Numerous investigations have been launched on 3-D skeletal [6–8] and two-dimensional (2-D) [9–14] frames, where floor systems are not simulated and thus no membrane action is considered. Stylianidis et al. [7] investigated the progressive collapse mechanics of 3-D frames with simplified beam models. This method could produce effective estimations on dynamic structural response of beams under sudden column loss by simple calculations. Jiang et al. [12] studied the possible progressive collapse mechanisms of planar steel frames when one column failed under elevated temperature. Three progressive collapse mechanisms were found: cantilever beam mechanism, pull-in force induced mechanism and high load ratio member failure mechanism. They further examined the effects of

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https://doi.org/10.1016/j.jcsr.2018.03.002
0143-974X/

Nomenclature

L	Long span of the beam-slab substructure
l	Short span of the beam-slab substructure
E	Elastic modulus of the reinforcing bar
h_L	Section height of the longitudinal beam
α	Parameter defining yield-line pattern
b	Parameter defining magnitude of membrane forces
k	Parameter defining magnitude of membrane forces
KT_0	Force in reinforcing bars per unit width
S	In-plane shear force at yield line
θ	Rotation about support of the segment
ξ	Relative compressive depth coefficient of a section
φ	Parameter defining yield-line pattern
χ	Parameter determined by inherent properties of a section
f_c	Ultimate compressive strength of concrete
T_x, T_y	Yield tensile bearing capacity in reinforcing bars per unit width of the slab in X, Y direction
M_x, M_y	Positive yield sectional bending moment in unit width of the slab about Y, X direction
M'_x, M'_y	Negative yield sectional bending moment in unit width of the slab about Y, X direction
M_{0LP}, M_{0TP}	Positive plastic sectional bending moment in longitudinal(X), transverse(Y) beam
M_{0LN}, M_{0TN}	Negative plastic sectional bending moment in longitudinal(X), transverse(Y) beam
F_{uL}, F_{uT}	Yield tensile bearing capacity of the beam in X, Y direction
M_a	Additional resultant bending moment considering the geometric nonlinearity
x, y	Longitudinal and transverse direction of the substructure
W_{in1}	Contribution of elongation of reinforcing bars and steel beams to internal energy dissipation
W_{in2}	Contribution of additional resultant bending moment to internal energy dissipation
W_{in3}	Contribution of slab sectional bending moment to internal energy dissipation
v_A	Vertical deflection at the column-removal location at the end of elastic-plastic stage
q_A	Resistance of the substructure at the end of elastic-plastic stage
v_B	Vertical deflection at the column-removal location at the end of transition stage
q_B	Resistance of the substructure at the end of transition stage
v_C	Failure vertical deflection at the column-removal location at the collapse limit state
q_C	Resistance of the substructure at the collapse limit state
C_{xe}, C_{ye}	Parameters denote the contribution due to the extension of reinforcing bars and steel beams
C_a	Parameter denotes the contribution of membrane forces-induced additional bending moment
C_{ym}, C_{xm}	Parameters denote the effect of membrane forces on yield bending moment of slab section

various bracing systems on the fire-induced progressive collapse resistance of steel-framed structures [13]. It was concluded that the application of vertical bracing systems alone on the steel frames was unsafe to resist progressive collapse and a combined vertical and hat bracing system was recommended in collapse resistance design.

Although these investigations were capable of capturing some key issues of the collapse mechanisms of structures, the tensile membrane action in concrete slabs was not fully considered. In real circumstances, membrane actions in floor systems of buildings can significantly enhance its robustness and load redistribute capability in case of collapse. Research has been carried out to study this phenomenon in the last two decades [15–22]. Bailey [15] presented a force-equilibrium-based method to calculate the enhancement factor due to the membrane actions in lightly reinforced concrete slabs. Based on the experimental results, another yield line at the center across the short span of the slab was assumed in the failure mode. Li et al. [18] established a series of formulae for calculating the load- bearing capacity of floor slabs under fire conditions by considering the effects of membrane actions. In the hypothesized failure mode, the slab was divided into four rigid plates and an elliptic-parabolic reinforcement net. The above-mentioned investigations were restricted to membrane actions in slabs, wherein catenary actions in beams were not accounted for.

Recently, growing attention has been paid to the global performance for 3-D steel framed structures with concrete slabs. The approaches of the research can be classified into three types: experimental investigations [23–30], finite element analyses [31–37] and theoretical studies [38,39]. Fu et al. [23] tested a 3-D composite substructure under an internal-column removal scenario. It was found that the contributions of composite slabs with steel beams accounted for at least 1/3 of the total vertical load at collapse limit state. Guo et al. conducted a test on a composite frame with rigid joints subject to an internal column loss. The experimental resistance-displacement curve showed that the progressive collapse mechanism of composite frame consisted of six stages: elastic, elastic–plastic, arch, plastic, transient and catenary stages. Wang et al. [29] tested two beam-joint-beam composite subassemblies suffering from sagging and hogging deflections, respectively. It was found that the membrane actions in slab contributed more than 39% to the total collapse resistance of the composite subassembly. Numerically, Jiang and Li [34] studied the progressive collapse resistance of 3-D composite frames exposed to localized fire. The results showed that the collapse modes were dominated by the uneven load redistribution in the two horizontal directions and the fire locations, which cannot be simulated by a 2-D model.

The experimental and numerical investigations on collapse resistance of steel framed structures suffer from great financial consumptions and computational costs, respectively. In contrast, relevant analytical studies (simple calculation methods) are rare in the literature. This impedes the development of quantitative guidance on safety design of structures against collapse.

This paper derived an energy-based method to determine the resistance-displacement response of composite beam-slab substructures subject to a middle column loss. Three contributions to internal energy dissipations were accounted for, including extension of reinforcing bars in the slab and steel beams; the additional resultant bending moment from membrane forces in slab and tensile forces in beams; the sectional bending moment along the yield lines of the slab. The accuracy and effectiveness of the proposed method were verified against numerical analyses with validated refined finite element approach. The three contributions to the collapse resistance of the substructure were quantitatively discussed. What's more, the contributions of concrete slab and steel beams obtained from the proposed method were also compared with numerical results.

2. Analytical method

If a framed structure is subjected to a middle column loss, the axial force imposed originally in the removed column is mainly redistributed by the four neighboring substructures. The most reliable approach for evaluating the robustness of the remaining structure is to directly analyze the structural responses of the original whole structure. However, this approach suffers from cumbersome calculations and huge