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Analytical modeling on collapse resistance of steel beam-concrete slab composite substructures subjected to side column loss

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ABSTRACT

This paper proposes an energy-based method to determine the structural responses of steel beam-concrete slab composite substructures under side 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 side 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 70% of the total energy dissipation capacity. The contribution from the slab at the collapse limit state is mainly influenced by its reinforcement ratio.

1. Introduction

The term “progressive collapse” is defined as “the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionate large part of it” [1]. Considering the enormous potential losses of life and treasure in the event of collapse, it is paramount to investigate the structural robustness against collapse 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 [1–3]. 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 [2]. The direct methods explicitly investigate the ability of the structure to prevent the spread of initial localized damage [2]. 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. According to the design code GSA [3], removal of columns at the corner, at or near the middle of the building edges is specified in the alternative path method since they have the highest possibility of causing progressive collapse.

When a framed building suffers from column removal scenarios, the secondary load carrying mechanisms, including tensile membrane action in slabs and catenary action in beams, will become an effective alternative to resist progressive collapse of the structure. Numerous investigations have been launched on three-dimensional (3D) [4,5] and two-dimensional (2D) [6–13] frames, where floor systems were not simulated and thus no membrane action was considered. Stylianidis et al. [5] investigated the progressive collapse mechanics of 3D frames with simplified beam models. This method could produce effective estimations on dynamic structural responses of beams under sudden column loss by simple calculations. Jiang et al. [9] studied the possible progressive collapse mechanisms of planar steel frames when one column failed under elevated temperatures. Three collapse mechanisms were found including cantilever beam mechanism, pull-in force induced

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Nomenclature

L	long span of the beam-slab substructure
l	short span of the beam-slab substructure
h	thickness of the concrete slab section
h_0	effective depth of the slab section
W	width of the concrete slab section
E	elastic modulus of the steel
f_y	yield strength of the steel
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
T_0, KT_0	yield tensile bearing capacity in reinforcing bars per unit width of the slab in long and short span
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	coefficient considering the interaction between the axial force and bending moment
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
$M_x{}'$	negative yield sectional bending moment in unit width of the slab about Y direction
M_{0LP}	positive plastic sectional bending moment in longitudinal (X) beam
M_{0LN}, M_{0TN}	negative plastic sectional bending moment in longitudinal(X), transverse(Y) beam
F_{uL}	yield tensile bearing capacity of the beam in X 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}	parameter denotes the contribution due to the extension of reinforcing bars and steel beams
C_{ya}, C_{ya}	parameters denote 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

mechanism and high load-ratio failure mechanism. They further examined the effect of various bracing systems on the fire-induced progressive collapse resistance of steel-framed structures [10]. 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 (braces arranged on the top floor of structures) system was recommended in practical design.

Although these investigations were capable of capturing some key issues of the collapse mechanisms of structures, they failed to fully consider the tensile membrane action in concrete slabs. In real circumstances, however, membrane actions in floor systems of buildings can significantly enhance its robustness and load redistribution capability in case of collapse. Several researches have been carried out to study this phenomenon in the last two decades [14–21]. Bailey [14] presented a force-equilibrium-based method to calculate the enhancement factor due to the membrane action 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. [17] 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 limited to membrane actions in slabs, wherein catenary actions in beams were not accounted for.

Recently, growing attention has been paid to the global performance of 3D steel framed structures with concrete slabs [22–29]. Fu et al. [22] tested a 3D composite substructure under an internal-column removal scenario. It was found that the contributions of composite slabs with steel beams at the collapse limit state accounted for at least 1/3 of the total vertical load. Guo et al. [23] 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. [27] experimentally studied two beam-joint-beam composite subassemblies suffering from sagging and hogging deflections, respectively. It was found that the membrane action in slab contributed more than 39% to the total collapse resistance of the composite subassembly. Numerically, Jiang and Li [29] studied the progressive collapse resistance of 3D composite frames exposed to localized fires. The results showed that the collapse modes were dominated by the uneven load redistribution in the two horizontal directions and the fire locations, which could not be simulated by a 2D 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 proposes an energy-based method to determine the resistance-displacement response of composite beam-slab substructures under a side column loss. Three contributions to internal energy dissipation 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, and the sectional bending moment along the yield lines of the slab. The accuracy and effectiveness of the proposed method were verified against numerical analyses. 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 side column loss, the axial force imposed originally in the removed column is mainly redistributed by the two neighboring substructures. The most reliable approach for