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Investigations of tensile membrane action in beam-slab systems under progressive collapse subject to different loading configurations and boundary conditions

Anh Tuan Pham, Namyo Salim Lim, Kang Hai Tan *

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Although catenary action in beams and tensile membrane action in slabs are generally believed as high-level analyses to mitigate progressive collapse in a reinforced concrete building, previous research studies did not clearly differentiate the contributions of the two mechanisms in combined three-dimensional beam-slab systems. Besides, most of the recent experimental studies on column removal scenarios focused on point load application as it is more difficult to apply the more realistic uniform distributed loads in the laboratory. In this paper, numerical analyses were first employed to investigate the combined effects of beams and slabs under both point load (idealised) and uniform distributed load (more realistic) conditions. The results show that differences between these two loading methods not only affect overall structural capacities, but also influence vertical deflections and failure modes. It is also observed that tensile membrane action in slabs was less sensitive to boundary conditions compared to catenary action in beams. Moreover, catenary action in beams which showed limited development in beam-slab structures can be conservatively neglected. Besides, under uniform distributed loading condition, scenarios with different locations of column removal were numerically investigated, showing that the loss of a penultimate column, rather than a corner column, could be the most critical case, contrary to conventional wisdom. In fact, in a corner-column removal scenario, tensile membrane action can still be partially mobilised owing to the presence of two stiff discontinuous edge beams. This phenomenon was well observed in a beam-slab test conducted in this study.

1. Introduction

Progressive collapse is defined as an accidental or man-made event starting from a local damage of a supporting component which may lead to disproportionate collapse of a large part or an entire building structure. From the last few decades, although the number of such events is very limited, once a progressive collapse incident occurs, the consequences in terms of loss of human lives are dire and grave. After the collapse of the Ronan Point building (1968), the concept of single column removal was developed and is now generally accepted by the engineering community for progressive collapse analysis of buildings [1,2]. In a reinforced concrete (RC) structure, although beam-column frames have significant importance in resisting the sudden column loss event, contribution of the slab system to overall structural resistance is substantial. The neglect of slab behaviour when assessing progressive collapse potential can lead to an uneconomical design of beam and column sections. Moreover, besides catenary action (CA) in beams, tensile membrane action (TMA) in slabs is considered as an upper-bound mechanism to enhance structural capacity at large deformation stage [3]. While the development of CA is normally denoted by the change of axial force in the beam from compression to tension [4], mobilisation of TMA is indicated by the formation of a tensile net at the middle of the slab and a peripheral compressive ring arching the tensile net [5,6].

Regarding experimental investigations under quasi-static loading conditions, several tests have been conducted for RC structures employing the single column loss assumption. Two types of system are generally considered, including two-dimensional (2D) beam-column structures [4,7–11] and three-dimensional (3D) beam-slab structures [12–15]. Studies on 2D skeletal frames demonstrate the contribution of compressive arch action (CAA)

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* Corresponding author.
E-mail addresses: atpham@ntu.edu.sg (A.T. Pham), namyolim@ntu.edu.sg (N.S. Lim), ckhtan@ntu.edu.sg (K.H. Tan).

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and CA in mitigating collapse. However, most of these tests were conducted by applying a point load at the middle joint following a displacement-controlled manner. Hence, the development of CA under distributed loads, even though such loading condition is closer to reality, has not yet been conducted for any 2D structures. Compared to 2D structures, laboratory tests on 3D slab and beam-slab systems apply both concentrated loading (CL) [12,13,16] and uniform distributed loading (UDL) [14,15,17] methods. In most 3D tests, distributed loads on slabs are represented by a multi-point loading system [6]. The 3D beam-slab tests, whether conducted under UDL or CL condition, showed enhancement in structural resistance beyond predicted yield-line capacity. However, such studies did not clearly delineate the respective contributions of CA and TMA to overall structural resistance. Moreover, experimental investigations on the sensitivity of TMA to boundary restraint conditions of slabs are constrained by costs and laboratory space, and have not been comprehensively studied. In addition, when assessing the vulnerability of a structure under progressive collapse threats, the engineer is required to consider various scenarios of column removal [1,2]. Among all the cases considered, loss of a corner column is generally believed to be the most critical scenario due to a lack of restraint from two adjacent sides of the corner slab, as shown in the CL static tests of Qian and Li [12]. In their work, CA and TMA are conservatively neglected for corner-column loss and only flexural mechanism is considered for both beam and slab members. Nonetheless, this paper shows that under UDL condition, corner column removal may not be the most critical case; instead, penultimate column removal may be the governing scenarios. This finding agrees with a study on steel and composite grillage frames (without slabs) conducted by Stylianidis et al. [18].

This study presents a numerical and experimental investigation on the effects of TMA in beam-slab systems under different boundary and loading conditions. In Section 2, simulations based on detailed finite element method (FEM) were employed and validated by a quasi-static test series, which included both the sub-assemblages (2D and 3D beam-only) and the 3D beam-slab structures [13]. Comparison studies of structural responses subject to either CL or UDL conditions, contributions of CA and TMA in beam-slab systems, and sensitivity of TMA to horizontal and rotational restraints, were carried out in Sections 3 and 4. Section 5 focused on the effects of different column removal locations on progressive collapse resistance to identify the most critical scenario for analysis and design. In Section 6, a beam-slab structural test under corner-column removal applying UDL condition was conducted to confirm the possibility of TMA mobilisation, compared to a similar test under CL condition. Overall conclusions are presented in Section 7.

2. Numerical models of beam-only and beam-slab structures under progressive collapse

2.1. Quasi-static tests on RC structures under internal-column removal scenario

To investigate the beam-slab effect against progressive collapse, Qian et al. [13] conducted a series of quarter-scale quasi-static tests on beam-only and beam-slab systems under an internal column loss scenario using CL method. The tests from [13] included 2D beam-only specimens, 3D beam-only specimens (grillage), and 3D beam-slab specimens. While the 2D and the 3D beam-only specimens included double-span beams with a middle joint and a column stub at each beam end, the beam-slab systems included a 2 × 2-span panel with internal and edge beams plus slab extensions equal to a quarter of the beam span. In the present paper, numerical models were developed and validated by one planar 2D beam-only test (P2), one 3D beam-only test (T2), and one beam-slab structural test (S2). These specimens (P2, T2, and S2 from [13]) had the same centre-to-centre span of 1.5 m and the same beam section of 140x80 mm^2. All the beams had continuous longitudinal reinforcement consisting of top and bottom rebars. Bottom reinforcement of the slabs was continuous throughout the slab in two directions. On the other hand, top reinforcement was only provided at the edge regions. Fig. 1 illustrates the test setup for T2 and S2 specimens. In the beam-slab tests from [13], boundary conditions were simulated by connecting concrete column stubs to steel circular hollow sections, which in turn were fixed to the strong floor. Removal of the middle column was simulated by gradually increasing the displacement of the middle joint using a hydraulic jack.

2.2. Numerical model

In this study, an explicit finite element software LS-Dyna [19] was used to simulate the RC member tests of P2, T2 and S2. Concrete was simulated using 8-node solid elements with reduced integration scheme. Reinforcing bars were explicitly modelled by the 2-node Hughes-Liu beam element with 2 × 2 Gauss quadrature integration. Continuous surface cap model MAT_159 was employed to simulate the behaviour of concrete material. Although element erosion is not a physical phenomenon for concrete material, this attribute allows modelling of spalling and separation of concrete under extremely high tensile force. In this study, the criterion for erosion of elements was based on the maximum principal strain value of 0.1. It was shown from a previous study [20] that MAT_159 model, together with the application of erosion criterion of maximum principal strain, can efficiently simulate actual responses as well as damage modes of RC structures under both quasi-static and blast conditions. MAT_159 can effectively capture post-peak softening, shear dilation, confinement effect, and strain-rate hardening. An isotropic elastic–plastic material model "Mat Piecewise Linear Plasticity" (MAT_024) was used for steel material which was assumed to be identical in tension and compression. Two mesh sizes were applied for solid elements of beams, including 10 mm for joint regions and 20 mm for the other non-critical regions. Only one mesh size of 20 × 20 × 6 mm was used for the concrete slab. All rebar elements had a mesh size of 20 mm length. A sensitivity study showed that the adopted mesh size yielded reasonably accurate results. Full models of the beam-only tests were developed, whereas only a quarter model of the beam-slab test was simulated.

Composite behaviour between reinforcement and concrete material in the beams was simulated by applying the bond-slip model in CEB 2010 [21] into Contact_1D function of LS-Dyna [19]. Such an application improves the accuracy of simulations compared to actual tests and prevents premature fracture of rebars in concrete due to localised stress concentration [20,22]. A comparison of the bond-slip response for deformed bars in beams between the CEB model and the proposed model using LS-Dyna Contact_1D is presented in Fig. 2. Details of the modelling procedure using Contac_1D keyword to consider bond-slip behaviour can be found in Pham et al. [20]. For the reinforcement in slabs, since mild-steel bars with high ductility were used in the tests [13], fracture of this reinforcement occurred much later than the high-yield deformed bars used in the beams. As a result, simulating bond-slip behaviour for such round bars would be complicated and yet not necessary. Therefore, to simplify the modelling and to save computational time, perfect bonding was assumed between steel reinforcement and concrete slabs.