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A simplified model for alternate load path assessment in RC structures

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ABSTRACT

To assess the robustness of reinforced concrete structures under progressive collapses, alternate load path method by introducing a single column removal has been widely adopted by structural engineers. Numerical analyses of structures under several possibilities of single column removal may be time consuming, especially when non-linear finite element analyses are employed which require high computational costs and modelling skills. Towards this end, a simplified analytical model is proposed in this paper to facilitate engineers in predicting resistance of the affected substructure (frames or frame-slabs above the removed column), and allow them to perform a quick check on the adequacy of progress collapse resistance of the structure to stop or prevent the damage propagation to the remaining structure. The proposed model considers development of different bridging mechanisms in RC structures under a concentrated loading above the removed column, including compressive arch action, catenary action, and tensile membrane action. In addition to validation against test results, applications of the proposed analytical model to predict the bridging capacities of a 2-D two-storey frame and unsymmetrical double-span beams are also presented.

1. Introduction

In the design of buildings against progressive collapse, the threats or triggering actions are frequently unknown or unforeseeable as progressive collapse is a low-probability event. Thus, threat independent approaches [1–3], such as prescriptive tie force (TF), enhanced local resistance of key elements, and alternate load path (ALP) methods are preferred by engineers. ALP method is generally accepted as one of the most reliable ways to assess the progressive collapse potential of a structure as it could explicitly determine the ability of structures to safely bridge over an initiating damage action, such as a single missing column. In addition, TF magnitudes are derived from ALP analyses to verify the reliability of the proposed values [4], and a column is only required to be designed as enhanced key element when its removal (ALP method) generates an extensive damage exceeding the code prescribed limits [1]. On the other words, ALP method serves as a basis for the threat-independent design approach, and hence, researchers can focus on the structural behaviour under a single column removal. Several bridging mechanisms of reinforced concrete (RC) structures, on top of flexural resistance, have been identified from previous researches, such as compressive arch and catenary actions in beams and frames [5–10], compressive and tensile membrane actions in slabs [11,12], as well as their combinations in beam-slab structures [9,10,13,14].

In ALP method, removal of a single column at several critical locations should be considered [1,2], and the evaluation of structural behaviour and resistance under these different scenarios through experimental studies may not be cost and time effective, which lead engineers to resort to numerical and/ or analytical approaches. Although numerical analyses using sophisticated finite-element-method (FEM) modelling, either with physics-based solid elements [15,16] or with fibre elements [17,18], may provide reasonable predictions, a simplified analytical model is generally preferred as it does not require high-level modelling skills and FEM knowledge, such as selections and inputs of material models and mesh size analyses. Moreover, a simplified analytical model allows engineers to make quick predictions of the affected substructure (above or connected to the removed column) resistance and to ascertain whether bridging mechanisms can be mobilised to prevent spreading of failures to adjacent bays.

A number of analytical prediction methods have been proposed for bridging mechanisms in beams, such as compressive arch [19] and catenary actions [20,21], but there are very limited models which could predict the overall development of bridging mechanisms, including the transition from flexural and/or compressive arch actions to catenary action, as well as their capacities with increasing deformations. Pham et al. [21] proposed a semi-analytical model to predict the overall development of bridging mechanisms in 2D RC double-span beams, which was obtained through comprehensive parametric studies. The model is

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yet to be validated in 3D beams and the idealisation of the beam non-linear response into a piecewise multi-linear curve consisting of 18 critical parameters may be too complicated and time-consuming for engineers. Pham et al. [22] proposed a simplified approach to assess progressive collapse resistance of RC beam-slab systems. However, the load resistance in the model was only limited to flexural capacity (calculated based on plastic hinge and yield line theories) without considering compressive and tensile membrane actions. To the best of the authors' knowledge, there is only a few or almost no publication on the analytical prediction of frame-slab systems which could consider contribution of bridging mechanisms in frames and slabs developed at different stages.

The development of the simplified analytical model presented d in this paper was based on a systematic study on RC structures conducted by Lim et al. [23,24]. The tests were systematically conducted from 2D to 3D RC frames to identify interactions among beams, and fully extended to RC frame-slab systems to investigate the slab contributions towards the development of bridging mechanisms. Many reliable analytical methods for prediction of bridging mechanisms, such as compressive arch action (CAA) and catenary action (CA) in beams, or tensile membrane action (TMA) in slabs are available in publications [9–12,19,21,22,31]. However, the prediction of each bridging mechanism could not provide a comprehensive representation of the progressive collapse potential of the structure, as different bridging mechanisms would develop at different stages, and in beam-slab systems, the co-existence of bridging mechanisms in beams and slabs should be considered. Hence, the main objective of this paper is to present a simplified analytical approach to predict the development of different bridging mechanisms in RC frames (2D and 3D) and frame-slab systems through proper integrations of identified bridging mechanisms developed in beams and/or slabs. The proposed model focuses only on bridging mechanisms of RC structures subject to concentrated loading above the removed column under quasi-static conditions.

In the proposed analytical model, the prediction of each bridging mechanism was either adopted from or modified by referring on an existing analytical/semi-empirical models. For bridging mechanisms in beams, the CAA analytical model from Yu [19] was complemented to include its transition from beginning of load application to the CA stage. In addition, the semi-empirical model for CA prediction by Pham [21] was simplified by expressing CA as a straight line, developing with a constant gradient. Finally, Bailey's analytical model [31] for TMA in slabs under uniform distributed loading was modified to predict the TMA in slabs under concentrated loading.

Most of the existing analytical models for bridging mechanisms in beams were only developed or validated for single-storey symmetrical double-span beams, which was not always the case in actual building. Hence, the analytical model to predict the development of bridging mechanisms in unsymmetrical double-span beams and two-storey frames were also proposed and verified through numerical studies on two-storey frames and unsymmetrical double-span beams utilising fibre elements. Simplified analytical models for individual frame and slab were first introduced. Thereafter, the prediction of frame-slab overall load resistance by combining frame and slab capacities calculated from the proposed simplified analytical model was presented.

2. Analytical model of RC frames

Experimental studies on RC frames by Lim et al. [23,24] and numerical studies on 2D RC frames serving as bases of the analytical model development were first presented, followed by descriptions and validations of the analytical model.

2.1. 2D and 3D RC frame tests by Lim et al. [23,24]

A 2D RC double-span beam (FR) [23], 3D skeletal frames under corner (COR) and exterior (EXT) column removal scenarios [24] were extracted from a prototype RC frame building designed for gravity loads [29] in accordance with EC2 [25], and were scaled to a two-fifth model. The scaled-down frames consisted of 180 mm deep by 100 mm wide beams with a single span length of 2.4 m on each side, and 180 mm square columns at a height of 1.6 m. The reinforcement detailing of all beams were identical as shown in Table 1. Each column was seated on a pin base, and restraints from adjacent structures were represented by two steel horizontal restraints, i.e. one placed at the column top and another at the beam-end. The reactions at the pin and the axial forces

Table 1
Details of RC frame tests and numerical studies.

Concrete			Longitudinal reinforcement		
f_c = 32 MPa, E_c = 26 GPa			f_{sy}, f_{su} = 507, 610 MPa, E_s = 200 GPa; $\varepsilon_{s,frac}$ = 11%		
Case	**Name**	**Span length (mm)**	**Curtailment length (mm)**	**Top reinforcement**	**Bottom reinforcement**
FR, COR, EXT (original)		2400	720	3T10 (1.52%)	2T10 (1.01%)
1	FR(0.75L)	1800	540	3T10 (1.52%)	2T10 (1.01%)
2	FR(0.5L)	1200	360	3T10 (1.52%)	2T10 (1.01%)
3	FR(+0.25ρ)	2400	720	2T10 + T13 (1.87%)	2T10 + T8 (1.34%)
4	FR(+0.5ρ)	2400	720	2T13 + T10 (2.22%)	3T10 (1.52%)

Note: The details of unsymmetrical double-span beams, i.e. FR(0.75L), FR(0.5L), FR(+0.25ρ), and FR(+0.5ρ) presented in Table 1 refer to the adjusted span. The other span is unadjusted (maintained as original)

Material parameters for concrete and steel model

Concrete model	COM3	Steel Model	COM3
Compressive strength (σ'_{ck})	32 MPa	Yield Strength (σ_{sy})	507 MPa
Tensile strength (σ_{bt})	3.5 MPa	Broken Strength (σ_{su})	610 MPa
Young Modulus (E_c)	26,000 MPa	Young Modulus (E_s)	200 MPa
Stiffening factor (C)	0.4	Poisson's Ratio (ν_s)	0.3
Poisson's Ratio (ν_c)	0.167	Initial Shear Modulus (G_s)	76,900 MPa
Initial Shear Modulus (G_c)	11,100 MPa	Expansion Coefficient (α_s)	10^{-5}
Expansion Coefficient (α_c)	10^{-5}	Unit Weight (γ_s)	77 kN/m^3
Unit Weight (γ_c)	24.5 kN/m^3	Yield strain (ε_{sy})	0.0025
Compressive strain at σ'_{ck} (ε_{cc})	0.003	Yield elongation (ε_{sh})	0.025
Compressive strain at 0.75 σ'_{ck} (ε_{cu})	0.006	Hardening Modulus (E_2)	1500 MPa
Tensile strain at σ_{bt} (ε_{tu})	0.00035		