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Numerical simulations on three-dimensional composite structural systems against progressive collapse

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ABSTRACT

In this paper, three-dimensional steel frame-composite slab systems (3-D composite floor systems) are simulated by verified macro-based models to investigate the structural performance under internal column removal scenarios. The authors have studied the load-transfer mechanisms of 3-D composite floor systems under internal column-removal scenarios, such as flexural action, compressive arch action, tensile membrane action and catenary action, and the final failure mode. In addition, both displacement-based and force-based dynamic increase factors (*DIF*s) are obtained and their applicability for predicting progressive collapse resistance is discussed. Moreover, the force-based increase factor (DIF_p) for 3-D composite floor systems are compared with those for 2-D steel frames and also compared with the values calculated based on DoD design guide. Based on dynamic analyses, several conclusions are found. Firstly, the dynamic ultimate state does not correspond to the static ultimate state in terms of load and deformation. Secondly, the energy method can predict the maximum dynamic responses well but it does not give the failure mode for the dynamic ultimate limit state. Lastly, comparing a 3-D composite floor system with the corresponding 2-D steel frame system, the former requires more ductility, and the DIF_p for the 3-D composite floor system is smaller than that for the 2-D steel frame.

1. Introduction

The American Society of Civil Engineers Standard 7 Minimum Design Loads for Buildings and Other Structures [2] defines "progressive collapse" as "the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it". Once progressive collapse happens, there will be huge economic losses and many casualties. Although it is impossible to prevent accidents of a random nature or deliberate actions from happening, structures can be designed to mitigate progressive collapse triggered by a local failure. Alternate load path method is one of the major design approaches recommended in DoD [7] to promote more resilient structural systems. The aim of this threat-independent design approach is to ascertain the resistance of structures when they are subject to column losses.

It should be noted that global responses of three-dimensional steel frame-composite slab systems (3-D composite floor systems) under column loss scenarios are so complex that the structural behaviour cannot be clarified in one step. Consequently, researchers and engineers investigate structural behaviour ranging from component levels such as beam-to-column connections, two-dimensional (2-D) frames, 3-D skeletal frames and 3-D frames with slab systems.

For steel frames under normal loads, such as gravity and wind, Thai et al. [26] have studied the system reliability of steel frames with semi-rigid connections. They adopted a refined plastic hinge model to predict the behaviour of frames and found that semi-rigid connections would highly affect the steel frame reliability. In 2010s, Yang and Tan [27,28] studied the behaviour of various types of beam-to-column connections under column loss scenarios through experimental tests and numerical simulations. They found that web cleat connections had better rotational capacities compared to other types of connections to resist progressive collapse. Besides, they proposed a component-based model of web cleat connections under large displacement [28], which paved the way for macro-model simulations as well as practical applications for progressive collapse analysis. To save computational time and effort, this model is adopted in this paper to simulate the web cleat connection behaviour.

Recent research works indicate that slab effects, especially tensile membrane action (TMA) at large deformation, can influence load redistribution mechanism and enhance progressive collapse resistance.

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To gain deeper insight into the complex structural behaviour to resist progressive collapse, current research studies should focus more on 3-D composite floor systems rather than simplified 2-D frames or steel and composite beam-column joints. However, there are extremely limited studies of 3-D slab effect on composite floor systems under progressive collapse scenarios. Dinu et al. [8] compared the ultimate capacities of bare steel frames and composite floor systems by finite element simulations. Only very few structural tests on 3-D composite floor systems against progressive collapse were conducted [9,14,16,25].

It should be mentioned that all of the above works were conducted under static loads. However, progressive collapse is a nonlinear dynamic process involving time. Under a sudden column loss scenario, a typical building structure exhibits a highly nonlinear dynamic response, which should be taken into account.

Izzuddin et al. [13] proposed a simplified approach to assess the robustness of multi-story frames under sudden column loss scenarios. Based on his method, quasi-static responses can be converted into pseudo-static responses to incorporate dynamic effects. Liu et al. [18–20] performed dynamic tests on web cleat, flush end-plate and top-and-seat with web angle beam-to-column connections subject to sudden column loss. Both displacement-based and force-based dynamic increase factors (*DIF*s) were presented and discussed. From the free-fall dynamic tests, it was found that *DIF*s depended on the connection type, deformation capacity and failure mechanism. Also, Liu et al. [18–20] proposed different *DIF*s for different types of connections. They also suggested that more specific *DIF* values should be provided in the design guide. Fu et al. [12] used Yang and Tan's [28] component-based model to simulate two types of beam-to-column connections, i.e. web cleat and top-and-seat with web angle connections. The models were verified by the test data [18]. Based on numerical simulations, Fu et al. [12] found that the force-based *DIF*s of these two types of connections were quite different from the corresponding recommendations in DoD [7]. Li and El-Tawil [22] modeled a global composite steel building to assess the collapse resistance mechanisms by deleting one or two columns at different stories and locations. Jahromi et al. [15] used Izzuddin's simplified frame work [13] to assess the pseudo-static capacities of composite buildings through comparing different modelling approaches.

In conclusion, there are only a few numerical studies and very limited experimental tests on 3-D composite floor systems subject to missing column scenarios. So far, there are no experimental tests on 3-D composite floor systems considering dynamic effects, which are urgently needed to improve the current design guide. Before the commencement of such costly tests, numerical simulations are necessary to gain deeper insight into the structural behaviour.

In this paper, the standard solver in commercial software ABAQUS [1] is used to simulate a 3-D composite floor system subject to both static and sudden column loss. The modelling method is calibrated at isolated slab and 3-D floor system levels. After the calibration with published test results, the following aspects are investigated in detail. Firstly, the 3-D composite floor system under static uniformly distributed loads (UDL) is simulated to study its final failure mode and load-transfer mechanisms. Meanwhile, the static load-displacement curve of the structure is obtained. Secondly, the authors simulated the 3-D composite floor system subjected to a range of UDLs under sudden internal column removal scenario, to obtain a number of dynamic displacement-time curves, and to further obtain the pseudo-static load-displacement curve. DIFs can be calculated through comparing the static and pseudo-static load-displacement curves. Furthermore, the force-based DIF_p for the 3-D composite floor systems is compared with those for corresponding 2-D steel frames and those recommended by DoD [7], allowing some conclusions to be drawn.

2. Verification of FE models

The FE models are calibrated by isolated slab tests and 3-D floor system results. For the isolated slab tests, six available experimental tests are simulated. In addition, the FE models are compared with the published test results of a 3-D composite floor system under two different column removal scenarios.

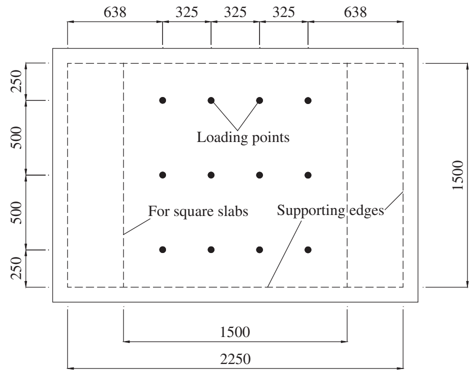
2.1. Verification of slab modelling

2.1.1. Referenced experimental tests

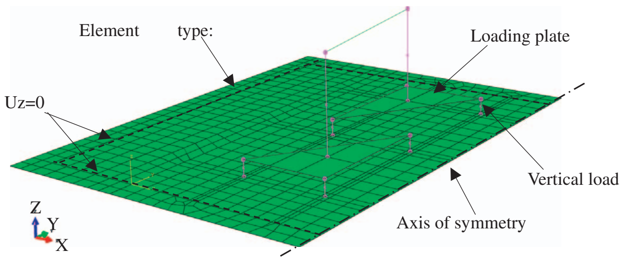
In 2010s, Cashell et al. [5] studied the behaviour of reinforced concrete slabs under extreme loading conditions, so as to identify the failure conditions of composite floors in a fire due to the early strength loss of steel deck. They focused on the responses of slabs with four parameters, which could be reflected by the names of the specimens. This study simulates six specimens of Cashell et al. [5] covering all four parameters. They are R-F60-D6-A, R-F60-M6-A, R-F60-M6-A (2), S-F60-M6-A, S-P120-M6-A, S-P120-D8-D. The first letter *R/S* represents rectangular or square slab. *F60* and *P120* denote flat 60 mm-deep slabs and profiled 120 mm-high slabs, respectively. The third field (*D6*, *D8* or *M6*) describes types of rebar, and *D6* and *D8* mean deformed bars with 6 mm and 8 mm of diameter, respectively, *M6* is welded mesh A142 which consists of 6 mm diameter bars with 200 mm central space. And *A*, *B*, *C* and *D* represent different reinforcement arrangements. More details of the six specimens can be found in Cashell et al. [5].

2.1.2. FE modelling

Since slabs are symmetrically loaded and supported in the tests (Fig. 1 (a)), only one-half of specimens are simulated (Fig. 1 (b)). As shown in Fig. 1, the slabs were vertically supported at perimeters and statically loaded through 6 points to failure. Besides constraint conditions and loading schemes, specimen details used in the simulations were consistent with the test specimens. It should be noted that the cross sections of the profiled slabs are replaced by the respective strong and weak equivalent rectangular cross sections with effective widths and thicknesses so that quadrilateral finite-membrane-strain S4R shell



(a) The dimensions and loading positions of slabs



(b) Overview of a FE model

Fig. 1. Information of the slab modelling.