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Effect of floor joint design on catenary actions of precast floor slab system

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ABSTRACT

To prevent progressive collapse of building structures, the establishment of the catenary action mechanism of beams or slabs is crucial so that adequate post-collapse resistance can be attained. It is believed that the joint design of precast floor system, e.g. the tie design, plays a key role in facilitating such a mechanism. An experimental study has been undertaken to investigate the catenary behaviour of the precast concrete slab system following the removal of the intermediate wall supports. To this end, five large-scale concrete floor assembly tests have been devised and carried out. Each test consisted of two standard hollow core floor slab units with various tie arrangements at the joints, which resembled a single storey floor structure supported by cross walls. The floor joint ties were placed on the pre-existing keyways where the grout was cast after the test assemblies were set up. The grout strength was specified to be 20–30 MPa and 10 or 12 mm tie bars were used with an embedment length ranging from 250 mm to 350 mm. Test results indicated that specimens experiencing bar fracture failure patterns collapsed prior to the formation of the catenary action, but those specimens with the pull-out failure pattern showed clear evidence of catenary behaviour. Furthermore, the difference in the post-collapse behaviour and the failure patterns indicated the characteristics of the catenary action. Test results reveal that for the ties designed with inadequate embedment length, the slip and the resulting large deflection will effectively trigger the catenary action. However, the full bond will limit the development deflection and lead to the fracture of tie bars before the catenary action is trigged.

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1. Introduction

Following the partial failure of a precast concrete building in London, the Ronan Point tower block, in 1968, the British Standard, BS 8110-1:1997 [1] for concrete structures, was amended to incorporate provisions to address the issue of progressive collapse. To understand the behaviour of progressive collapse and to reduce the associated risks, a 3-year research programme was conducted by Popoff [2]. The Portland Cement Association (PCA) [3] also conducted a series of comprehensive investigations to gain a knowledge base supporting the stipulated minimum detailing requirements in the event of any local damage for precast concrete structures. These attempts led to the tie-force (TF) design method in British Standards [1], which was the first approach in the world to deal with the progressive collapse of concrete structures. Later on, the Eurocodes [4] adopted a similar method and the United States Department of Defence, DoD 2005[5], directly used the provisions of the British Standard.

The TF method, which is mainly prescriptive in nature, requires the inclusion of internal, peripheral, and vertical ties to provide different alternative load carrying mechanisms, such as catenary, cantilever, vertical and diaphragm actions, in the event of the loss of underlying supports. These prescriptive tie requirements have been demonstrated to work in engineering practice but have not been fully verified with rigorous scientific examination or in a quantitative manner. Therefore, substantial experimental, theoretical and numerical investigations are still needed to improve the accuracy of understanding, at a fundamental level, of how the mechanism of post-collapse resistance is developed with these tie provisions in the absence of wall supports. These needs have also been proposed by a number of researchers in the last decade.

Dusenberry [6] indicated the necessity of better understanding of the mechanism by which progressive collapse can be resisted. The UK Building Research Establishment (BRE) verified the adequacy and reliability of the TF method by conducting a series of

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quarter-scale tests which led to further amendments in the current guidance [7]. To show the adequacy of codified methods for progressive collapse, an evaluation of three well known collapsed building cases was performed by Nair [8], based on five current codes or standards. The results revealed that all three studied structures had been susceptible to progressive collapse. Abruzzo et al. [9] has also indicated the inadequacy of the TF method in preventing the progressive collapse of structures. The development of an improved TF method has also been recommended by DoD (2005) [5]. According to the analytical study of a single beam, Rudi [10] showed that the tie rules are effective for preventing progressive collapse when class C steel bars are used. To investigate the efficiency of the TF design method, Li et al. [11] also conducted comprehensive numerical studies on two reinforced concrete (RC) structures of 3 and 8 storeys, respectively; the results were verified by the experimental work of Yi et al. [12]. The numerical results revealed that the current TF method cannot provide a safeguard against progressive collapse for all RC structures that have different numbers of storeys and experience damage in different locations; accordingly, an improved TF method was proposed. Based on the numerical assessment results of a disproportionate collapse, Gerasimidis et al. [13] suggested that a structure could respond better if the damage is distributed across two adjacent elements rather than in only one element. Finally, based on the latest knowledge related to design practice for progressive collapse, DoD (2013) [14] has proposed significant revisions to the TF method in DoD (2005) [5] and the British Standard [1]. Li et al's numerical study [11] on the progressive resistance of precast floor connections following the removal of wall supports reveals that the British Standard [1] underestimates the tie force required at the catenary stage. However, their results are in a good agreement with the revised TF method proposed by DoD (2013) [14].

Compared with experimental studies on the catenary action of steel structures, only limited experimental studies are available which assess the catenary action in RC structures [15–17]. This is particularly the case for multi-storey precast concrete cross wall buildings [18]. The PCA's [3] experimental studies are the only published work on the performance of cross wall structures in terms of catenary action and progressive collapse which consider the floor joint behaviour. The previous research mainly focused on the behaviour of walls instead of floors [18,19]. The experimental study conducted by the PCA (1975–1979) [3] indicates that a catenary action can be achieved through the pull-out failure mode by using an appropriate embedment length, strand size and grout strength. As the only data that was recorded was the tie force and the middle joint deflection, the actual progressive collapse resistance mechanism of the floor assembly system was not attained through these large-scale tests.

Most experimental studies on the progressive collapse resistance of RC structures indicate that the specimens with detailing design in compliance with the seismic design rules are capable of establishing an effective catenary action, with an ultimate resistance higher than the yield resistance. Although it was found that the ultimate resistance significantly varies with different boundary conditions, most tests resulted in the same range of deflection/span ratio, i.e. $17 \leqslant \delta_s/l_b \leqslant 21$. However, there are noticeable discrepancies amongst the abovementioned experimental studies. Sasani and Kropelniki [16] concluded that the resistance of a two-span beam developed in the catenary stage is slightly less than the resistance due to the yield capacity. By using specimens with almost the same properties, Yu and Tan [15], Yi et al. [20], and He and Yi [21] obtained catenary/plastic resistance ratios of 1.75, 1.35 and 2.0, respectively. Meanwhile, Trung et al. [22] stated that the progressive collapse resistance of specimens with rebar detailing in compliance with the seismic design rules is more than twice that of specimens without seismic detailing; whereas Yi et al.'s experimental study indicated that there was no obvious difference between these two types of specimens. It is evident that there are significant discrepancies in the evaluation of the progressive collapse resistance of RC structures. Furthermore, in a study on RC beams, Orton [23] suggested that beams with continuous reinforcement cannot develop catenary action, and only beams with no continuous bars are capable of developing catenary action through stirrups. This conclusion is in contrast to all the other experimental work reported, but unfortunately there was no discussion to highlight the reasons for this behaviour. To investigate the progressive collapse behaviour of steel frame with composite floor, a comprehensive FE simulation was conducted by Yu et al. [24]. They concluded that retrofitting a structure with prestressed steel cables and an increase of crack resistance in the concrete near joints can effectively improve effective tying of a structure, which results in an enhanced structural capacity in preventing progressive collapse.

The literature survey reveals that there is a deficiency in studies, in particular from the experimental perspective, on the evaluation of progressive collapse resistance in the catenary action stage, while various FE models can successfully simulate the progressive collapse behaviour.

A research study on the mechanism of preventing progressive collapse in precast concrete cross wall structures under an accidental event such as an explosion or bomb blast is described in this paper. The concept that was adopted is based on the TF method specified by the BS Standard, which is commonly used in current cross wall structure design in the UK. The key to the TF method is to develop the catenary action mechanism that is expected to dissipate the energy arising from the event, and to divert the loads to the undamaged parts of the structure. The development of such catenary action is facilitated by the ties placed in joints. After a wall support is removed, the grout will very quickly be crushed under the suddenly increased loads, and the ties will experience tensile forces and develop large deflections at the floor slab joints. This process may lead to a catenary action mechanism. In this study, a series of floor assemblies containing longitudinal joints were fabricated and tested. Different longitudinal ties were placed in the floor joints. The test specimens were large-scale representations of precast hollow core slabs used in typical cross wall structures. The strains in the tie bars and the vertical deflections at the joints were recorded using pre-instrumented sensors, including strain gauges and Linear Variable Differential Transformers (LVDTs) during the loading process. It is understood that this is the first study that allows a rigorous evaluation of the realistic behaviour of precast concrete floor slab joint systems with catenary actions following the removal of wall supports, by considering the effect of tie bars in the keyways. The results presented in this paper concern the pre- and post- failure behaviours of floor joints.

2. Geometry and properties of test specimens

In multi-story precast concrete cross wall structures, the applied load is sustained by one way precast slabs simply supported on vertical wall panels (Fig. 1). In the case of damage from the supporting walls (Fig. 1a), the floor joint above the removed wall is the most critical element which can redistribute the applied loads to the undamaged parts of the system. Immediately after the removal of the joint support, the axial restraints at both sides will introduce a compressive arch action which can enhance the resistance of the system [15–23]. This arch action soon disappears and the system turns into one of flexural action once the deflection develops at the mid-joint. Under flexural action, the joint grout soon fails due to its low strength. While the deflection continues

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