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Numerical evaluations of codified design methods for progressive collapse resistance of precast concrete cross wall structures

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ABSTRACT

Progressive collapse of building structures typically occurs when an abnormal loading condition causes a sudden loss in the structural capacity of one or more critical members, which leads to a chain reaction of failure and ultimately catastrophic collapse. The tensile tie force (TF) method is one of the main design approaches for considering progressive collapse. As this method does not take into account factors such as dynamic effect, the load redistribution mechanism, the effect of steel–concrete interfacial properties, or the size and embedment length of tie bars on bond behaviour, it can be considered as a simplified method, and hence a thorough examination of the adequacy of this method is needed. This paper reports such a study including numerical evaluation of the codified methods of progressive collapses for precast concrete cross wall buildings. To this end, detailed three-dimensional finite element models of the pull-out behaviour of strands in the keyway of precast concrete blocks and of the ductility behaviour of floor joints subjected to uniform and line loads exerted from upper walls were developed. Through a calibration process for a series of laboratory pullout tests carried out by the Portland Cement Association (PCA), the interfacial bond properties were established using numerical modelling. The same modelling method was then used in the subsequent three dimensional non-linear numerical analyses to simulate the ductility behaviour of precast concrete floor joints in the absence of underlying wall supports. In both modelling processes, the simulation of the bond–slip behaviour at the steel–concrete interface was realised by using the "translator" element embedded in ABAQUS. The numerical analyses showed a close agreement between FE analyses and test results. The tie force developed during the collapse process was particularly examined. Discrepancies in the tie force between the numerical and the codified specifications have suggested an underestimate of tie force in the TF method that may lead to an unsafe design. Finally, an improved model based on the numerical results has also been proposed to address this problem.

1. Introduction

As is defined by the Portland Cement Association (PCA) [1], the term "large-panel" concrete structure is used to describe a building system consisting of vertical wall panels together with precast concrete floors and/or roofs. Large panel buildings are featured as examples of wall panels being used as the load-bearing structure. In the usual arrangement, a wall that is perpendicular to the longitudinal axis of a structure is referred to as the cross wall and that is parallel to the longitudinal axis is termed the spine wall. In the cross wall system, floor/roof slabs are typically one way hollow core precast concrete slabs, and only cross walls carry the floor loads (see Fig. 1).

To avoid the progressive collapse of a precast concrete cross wall structure, in the event of a sudden loss of a support wall, it is required that damage will be limited to the affected zone only, e.g. in the vicinity of the damaged wall (see Fig. 2). This means that the remaining structures will stay in place without any chain-reaction type of collapse. One of the typical responses of floor-to-floor joints in the above scenario is that, due to the dynamic nature of the event, the

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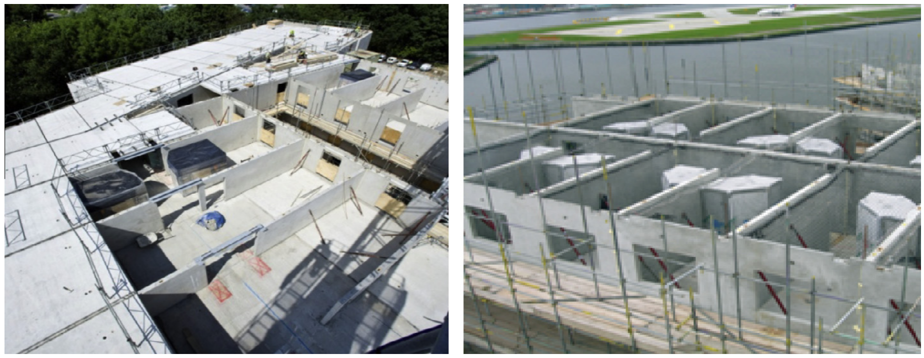


Fig. 1. Examples of precast concrete wall construction (courtesy of Bison).

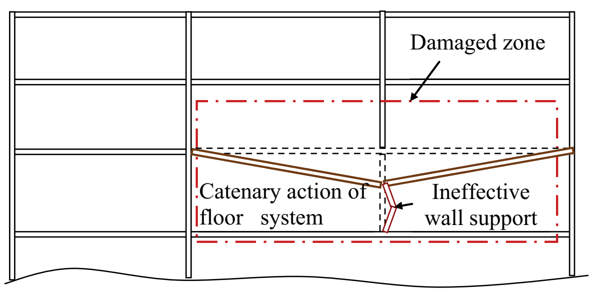
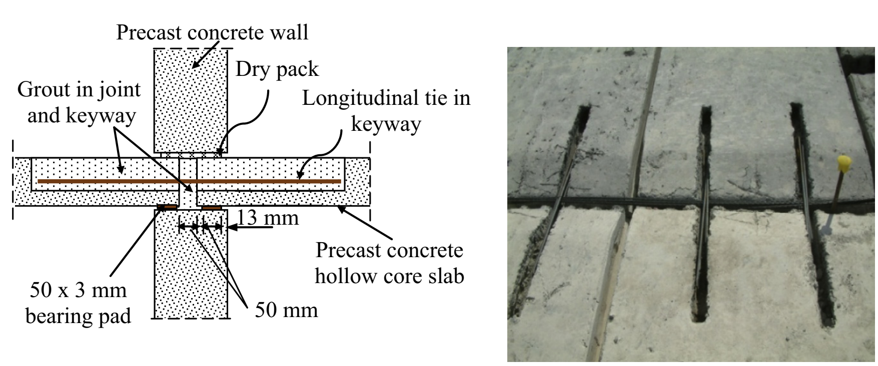


Fig. 2. A typical damage scenario for a cross wall structure.

impact force from the upper floors will exert on the floor-to-floor joint immediately above the damaged wall. This impact force will rapidly crush the in-situ filled grout and produce a large deflection in the floor joint. The damage to the grout and the development of a large deflection will dissipate the impact energy. The latter also renders a reduction in the force from the upper walls and diverts loads to the adjacent walls. In so doing, a catenary action is developed in the floor slabs adjacent to the damaged wall. It is believed that the key for the catenary action to work successfully is that longitudinal ties at the joint have sufficient strength and deformation capability, which closely depends on the bond performance of ties in the grout (see Fig. 3).

Following the partial failure of a precast concrete building based in London, Ronan Point apartment [2], in 1968, the British Standards for concrete structures [3] started to incorporate provisions to deal with the problem of progressive collapse. The Portland Cement Association [1] conducted a series of comprehensive investigations to form an underpinning knowledge basis supporting the stipulated minimum detailing requirements to ensure the development of an alternative load path (ALP) in the event of any local damage [4–6]. These attempts led to a tie-force (TF) design method which is a first of its kind in the world. This method, which is mainly of a prescriptive nature, requires the inclusion of internal, peripheral and vertical ties (see Fig. 4) to provide different "alternative load paths", e.g. catenary, cantilever, vertical suspension and diaphragm actions, in the event of the loss of underlying wall support. These prescriptive tie requirements may have proven adequate in engineering practice but are not fully scientifically justified, so substantial efforts are still needed to improve the understanding, at a fundamental level, of how the mechanism of post-collapse resistance is developed through these tie provisions. This need has also been supported by a number of researchers in the last decade.

Dusenberry [7] indicated the necessity of a better understanding of the mechanism by which progressive collapse can be resisted. The UK Building Research Establishment (BRE) has conducted a series of quarter-scale tests to verify the adequacy and reliability of the tie force method [8]. To show the adequacy of the codified methods for progressive collapse, an evaluation on three well known collapsed building cases was performed by Nair [9] based on five current codes of practice or standards. Results revealed that all three studied structures are susceptible to progressive collapse. Abruzzo et al. [10] has also indicated the inadequacy of the TF method to prevent progressive collapse of structures. The necessity of developing an improved TF method has also been recommended by the US Department of Defense (DoD) [11]. According to experimental study on single beams, Merola [12] showed that the tie rules are effective against progressive collapse when steel of ductility class C is used. To investigate the efficiency of the TF design method, Li et al. [13] also conducted comprehensive numerical studies on two reinforced concrete (RC)



(a) Section view of a floor-to-floor joint (b) Examples of horizontal ties

Fig. 3. Typical longitudinal ties arrangement at the floor-to-floor joint.