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Robustness of Reinforced Concrete Building Structures under Corner Column Loss Scenario

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Abstract

This short paper explores the potential enhanced activation of membrane forces within a floor system under the scenario of corner column loss via an alternative slab reinforcement arrangement, involving the placement of such reinforcement diagonal to the edges of the floor system. The activation of tensile membrane action is demonstrated via the comparison of high-fidelity numerical models against a novel analytical approach proposed for the assessment of tying resistance of floor systems under corner column loss. Initial outcomes demonstrate successful mobilisation of tensile membrane forces not only within a floor system with a diagonal reinforcement arrangement but also within a floor system with a standard reinforcement arrangement (i.e. parallel to the edges of the floor system), provided that the latter arrangement entails a continuous and orthogonal reinforcement mesh at both the top and bottom surfaces of the floor system. This encourages further research and validation to confirm the potential beneficial contribution from membrane effects to the resistance of floor systems under corner column loss, which is often conservatively neglected. The proposed analytical method also demonstrates to be a promising practical means to estimate the tying resistance of floor systems with diagonally arranged reinforcements, though the method as it currently stands presents some outstanding shortcomings, with further refinement of the method currently underway to address these shortcomings.

Keywords: structural robustness, progressive collapse of RC buildings, corner column loss, horizontal tying, membrane action, diagonal reinforcement.

1 Introduction

Initially driven by the partial collapse of Ronan Point in 1968 and gaining international significance with the collapse of the WTC Twin Towers in 2001, the concept of structural robustness has become widely recognised, where standard tests of robustness typically consider the sudden loss of a column as the main local damage scenario [1-6]. In this respect, under corner column loss scenario, the assessment of reinforced concrete (RC) floor systems with typical reinforcement arrangements (i.e. parallel to the edges of the system) usually considers only the flexural resistance capacity [7]. The potential resistance contribution from membrane effects under large displacements is often conservatively neglected given the uncertainty in the activation of tying within the corner slab reinforcement, due to insufficient, if not absent, planar restraint at the free edges of the floor system. Notwithstanding, some experimental tests available in literature [e.g. 8, 9] provide evidence on the mobilisation of tensile membrane action, even if this is not as significant as for column loss scenarios with adequate planar restraint from the surrounding structure, such as scenarios dealing with interior or edge column loss.

This short paper explores the potential enhanced activation of tensile membrane forces under an alternative reinforcement arrangement, with the reinforcement placed diagonally to the edges of the floor system, as illustrated in Figure 1a.

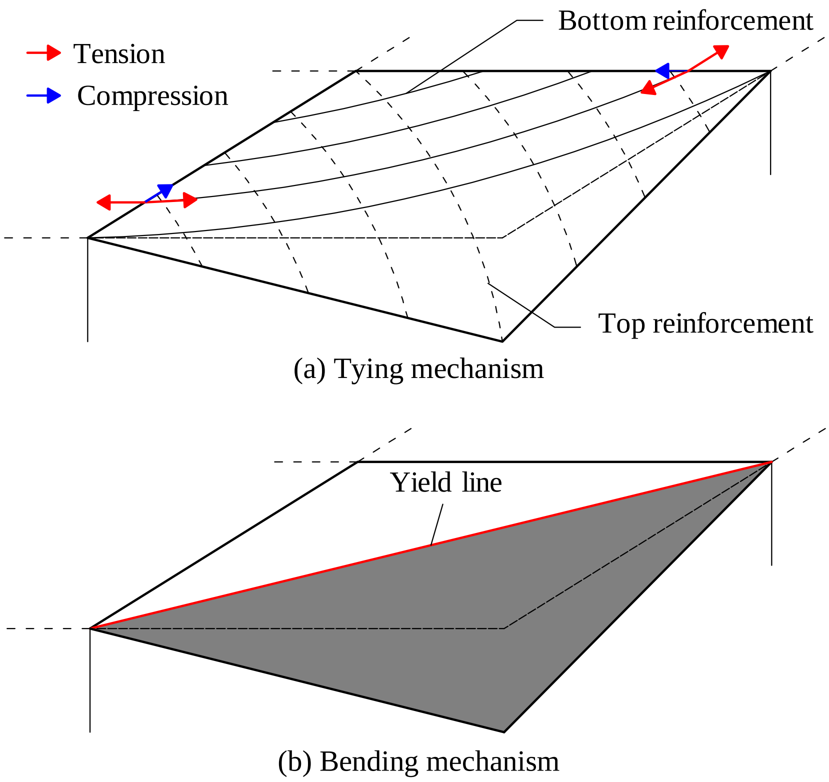


Figure 1: Mechanisms developed for a RC corner slab with diagonally arranged reinforcement.

With such an arrangement, the bottom slab reinforcements are anchored at the continued edges of the floor system instead, where the surrounding structure can equilibrate the tie forces from the bottom reinforcement according to the strut and tie model also illustrated in Figure 1a. On the other hand, the top slab reinforcement, which is placed orthogonally to the bottom reinforcement, provides flexural resistance to prevent the failure mechanism illustrated in Figure 1b.

Evidence of tensile membrane action is then demonstrated via the comparison of high-fidelity numerical models in the nonlinear structural analysis program ADAPTIC [10] against the predictions from an initial adaptation of the horizontal tying method developed by Izzuddin & Sio [11], which in turn paves the way to a novel rational analytical approach in assessing the tying resistance of floor systems under corner column loss, thus addressing the absence of prescriptive treatments in current design regulations [1-4] for such a column loss scenario.

2 Methods

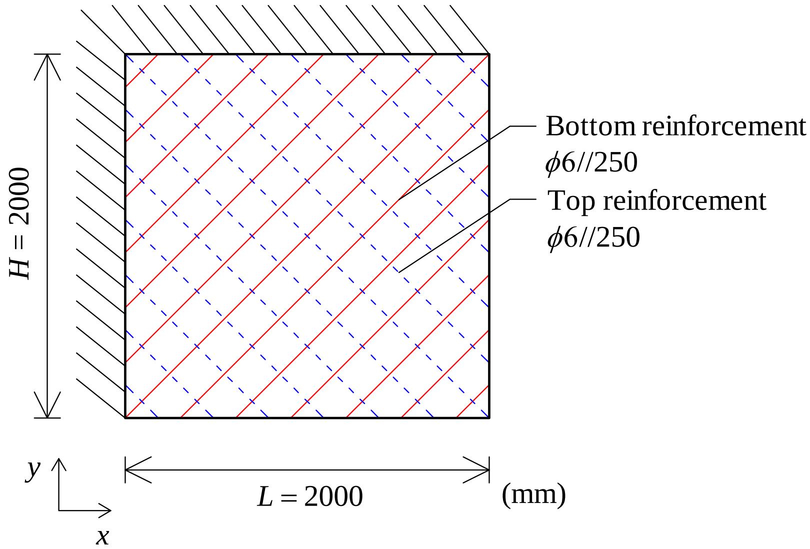
Figure 2a illustrates the corner floor panel and the reference quantity of reinforcement considered for the comparison under uniformly distributed load (UDL) between numerical models and the predictions from the initial adaptation of the tying method. The slab of the floor system has a thickness of 55mm and the concrete cover is 7mm. The mean compressive strength of the concrete is 23.3MPa (with an elastic stiffness modulus of 28.4GPa), whereas the yield strength of the steel reinforcement is 355MPa.

The numerical models are developed with the nonlinear structural analysis program ADAPTIC, the applicability of which has been previously validated against experimental results on a reinforced concrete floor system in [11]. The corner floor panel, which for the current comparison entails only the slab, is modelled with an enriched shell element accounting for geometric and material nonlinearities [12]. Rigid links are also assigned to the free edges of the floor system to represent the geometric constraint of beams, rendering a linear transverse deformation for the free edges. The continued edges are restrained according to the boundary conditions illustrated in Figure 2b. The steel reinforcement material response is assumed elastic-perfectly plastic, whereas the concrete is modelled as a biaxial material with an elastic compressive response and a negligible tensile strength.

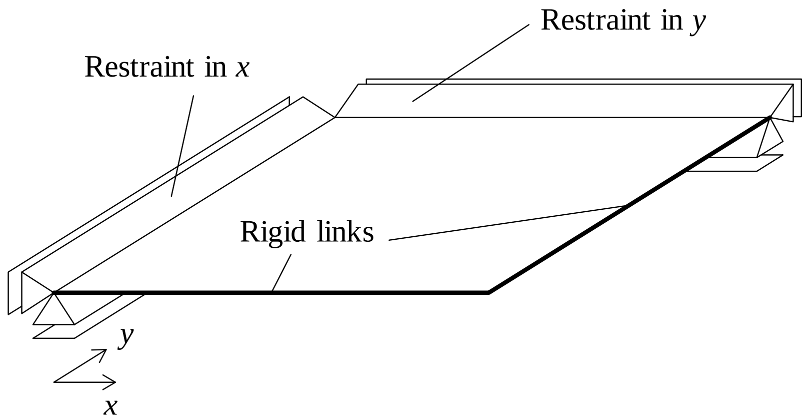
The proposed analytical formulation considers two failure mechanisms for the floor system. The first one involves a tying mechanism where the floor system follows a bilinear deformation mode, under which the distributed load resistance can be shown using the virtual work principle [11] as:

$$w_t = \frac{2v\, f_b}{3\left(L^2 + H^2\right)} \tag{1}$$

where v is the tip displacement, f_b is the distributed force from the bottom slab reinforcement, and L and H represent the dimensions of the floor system illustrated in Figure 2a. It is worth noting that the above expression considers that all bottom slab reinforcement contributes to tying.



(a) Geometry and reference reinforcement detailing of the considered corner floor slab



(b) Boundary condition

Figure 2: Reference RC corner slab and modelling considerations.

The second mechanism is the flexural mechanism illustrated in Figure 1b, where the distributed floor load can be shown in the most conservative form (considering the diagonal yield line to remain undeformed) as:

$$w_b = \frac{12\, f_t\, d_t}{L\, H} \tag{2}$$

where f_t is the distributed force from the top slab reinforcement, d_t is the distance from the top slab reinforcement to the bottom face of the slab, L and H remain the same as the expression for the tying mechanism. A further tentative refinement is also presented in the subsequent results accounting for the additional flexural resistance due to the transverse deflection of the diagonal yield line.

3 Results

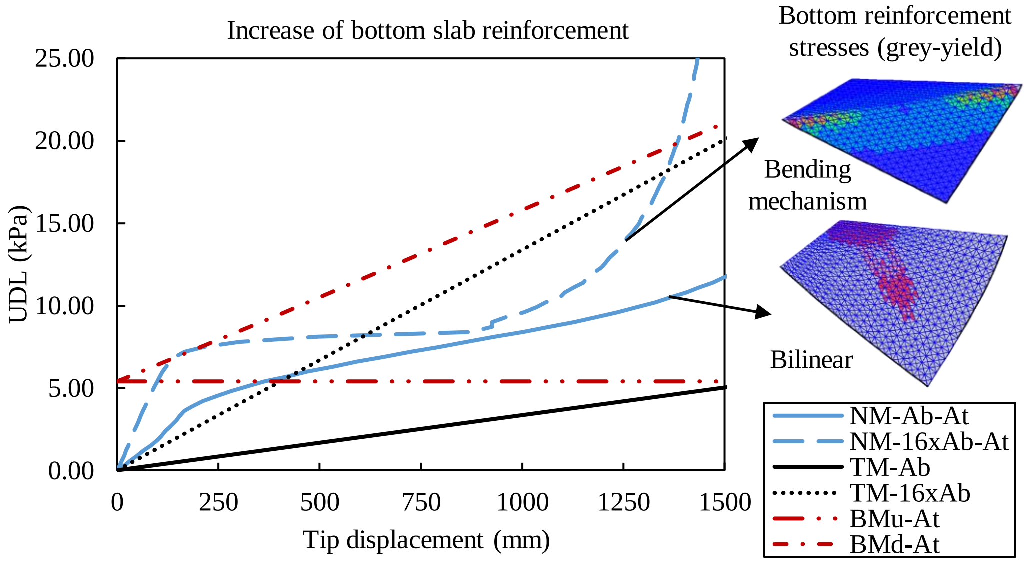
Figure 3a-b illustrates the comparison between numerical and predicted load responses of the corner floor system respectively for increasing bottom and top slab reinforcements, where the keys NM, TM, BMu and BMd respectively refer to numerical model, tying mechanism, bending mechanism considering the undeformed yield line and bending mechanism considering a deformed yield line. On the other hand, Ab and As refer respectively to the reference quantity of bottom and top reinforcement.

For the case with the reference quantity of reinforcement, the numerical response of model NM-Ab-At not only exceeds the load resistance predicted by BMu-At, but the ensuing load resistance also increases linearly with the tip displacement, characterised by a slope similar to the response predicted by TM-Ab. Such observations suggest the development of tensile membrane action. Furthermore, the results also suggest that the tying mechanism TM-Ab and the bending mechanism BMd-At respectively establish a lower and an upper bound for the numerical response of NM-Ab-At, where the load resistance underpredicted by the tying mechanism can be attributed to the neglect of additional resistance contributions to tying.

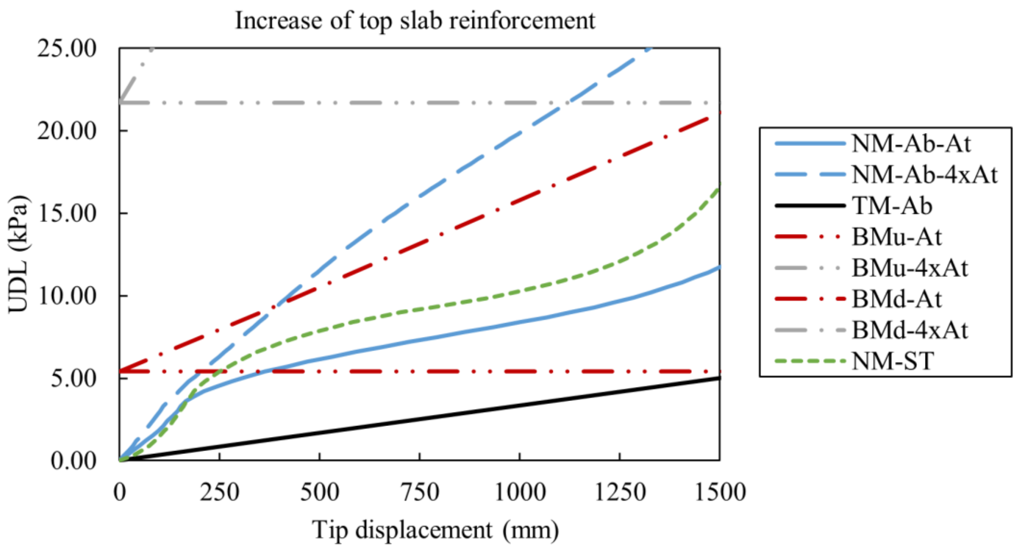
Interestingly, the increase of bottom reinforcement counter-intuitively leads to a significantly shallower slope within the tensile membrane action stage, almost approximating to a flexural-type response. Indeed, with significant increase of bottom slab reinforcement, the failure mode of the floor system transitions to a bending mechanism with a relatively low transverse deflection of the diagonal yield line, the response of which is better represented by the bending mechanism BMu-At than the tying mechanism TM-Ab.

It is also worth noting that, given the neglect of the contribution of the top reinforcement to tying, the current formulation for the tying mechanism does not fully reflect the influence of the top slab reinforcement on the load resistance of the floor system. In this respect, the numerical models suggest an increase in tying resistance with an increase in top reinforcement.

Lastly, Figure 3b also illustrates the response of the corner floor system with reinforcement placed parallel to the slab edges (NM-ST), suggesting a similar level of tensile membrane forces, though at the expense of doubling the quantity of reinforcement in relation to the case with diagonally arranged reinforcement (i.e. placement of an orthogonal mesh for both bottom and top reinforcements).



(a) Bottom slab reinforcement



(b) Top slab reinforcement

Figure 3: Assessment for different quantities of slab reinforcement.

4 Conclusions and Contributions

Under the considered assumptions for the corner floor system, both diagonal and standard reinforcement arrangements are shown to mobilise tensile membrane forces. The successful mobilisation of tying forces in the latter arrangement is most likely due to the use of continuous reinforcement also at the top surface of the slab, as opposed to the outcomes reported in [7]. Such findings encourage further research on the potential beneficial contribution from membrane effects to the disproportionate collapse resistance of corner floor systems. Notwithstanding, further validation should also be carried out against actual experimental tests to confirm such findings.

On the other hand, the proposed tying method demonstrates promising outcomes, establishing lower and upper bound estimates to the load resistance of the floor system with the tying and bending mechanisms, respectively. However, the method as it currently stands does not fully reflect the transition between mechanisms with increasing levels of bottom reinforcement as well as the contribution of the top reinforcement to tying. Further refinement of the proposed method is currently underway to address these outstanding shortcomings.

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