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Shear-flexure interaction in the critical sections of short coupling beams

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ABSTRACT

Heavily-loaded short coupling beams with large amounts of transverse reinforcement fail in sliding shear or diagonal compression under the complex interaction between shear and flexure. These failure modes often occur after yielding of the flexural reinforcement and limit the displacement capacity of the member. To study such failures, this paper compares experimental results with predictions of models with various levels of complexity. It is shown that complex nonlinear finite element models (FEM) can capture adequately the entire behaviour of short coupling beams, while the classical flexural model produces unconservative strength predictions. It is also shown that strut-and-tie models are reasonably conservative provided that their geometry is selected to maximize the strength predictions. To produce similarly adequate strength predictions as those of the FEM – while at the same time maintaining the simplicity of the flexural model – the paper proposes a mechanical model based on strain compatibility. The main assumption of the model links the principal compressive strains in the critical section to the longitudinal strains in the tension zone. It is shown that the model captures well the effect of different test variables on the shear strength. When applied to a database of 24 tests, the model produced an average shear strength experimental-to-predicted ratio of 1.12 with a coefficient of variation of 8.4%.

1. Introduction

Coupling beams in reinforced concrete wall structures of buildings serve to link the individual walls in a stiff lateral-load resisting system. These members work in double curvature with high shear forces and often feature small span-to-depth ratios ($a/h \leq 2.5$). Such short members are susceptible to shear failures that occur along wide diagonal cracks with yielding of the transverse reinforcement as illustrated in the left diagram in Fig. 1a [1]. To suppress diagonal tension failures, the coupling beams are provided with large amounts of stirrups or diagonal reinforcement. However, when the opening of diagonal cracks is suppressed with stirrups, the failure develops in the end sections under the complex interaction between shear and flexure. This failure mode is characterized by crushing of the concrete prior to or after the yielding of the flexural reinforcement. The failure occurs with sliding deformations as illustrated in the right diagram in Fig. 1a (sliding shear failure) or with lateral bursting of the web (diagonal compression failure). This paper focuses on the modelling of sliding shear and diagonal compression failures in short coupling beams without diagonal reinforcement.

Short coupling beams do not obey the plane-sections-remain-plane hypothesis and therefore cannot be modelled based on the classical beam theory. Instead, such members are typically designed based on strut-and-tie models (STM) such as the one shown in Fig. 1b. In this model the shear force is resisted by two inclined struts linked by a vertical tie representing the transverse reinforcement. Such model was used for example in the design of the coupling beams of Burj Khalifa [2] based on the ACI strut-and-tie provisions [3]. In addition to the truss mechanism depicted in Fig. 1b, other more complex models also include a direct diagonal strut between the end nodes of the beam. According to the strut-and-tie models, the failure of the end sections can either occur due to yielding of the longitudinal tie or crushing of the inclined strut. If the failure is governed by strut crushing, this will indicate shear sliding or diagonal compression failure of the member. However, nonlinear finite element simulations performed by Lee et al. [2] showed that coupling beams can have significantly larger shear capacities than predicted by the strut-and-tie model in Fig. 1b. While such conservatism is usually appropriate in new design, more accurate models are required for the assessment of existing structures or in cases of heavily loaded coupling beams. Moreover, because strut-and-tie models are not well suited for calculating deformations, there is need for approaches that account for the strains in the critical end sections. Predicting these deformations is important for evaluating the ductility and displacement

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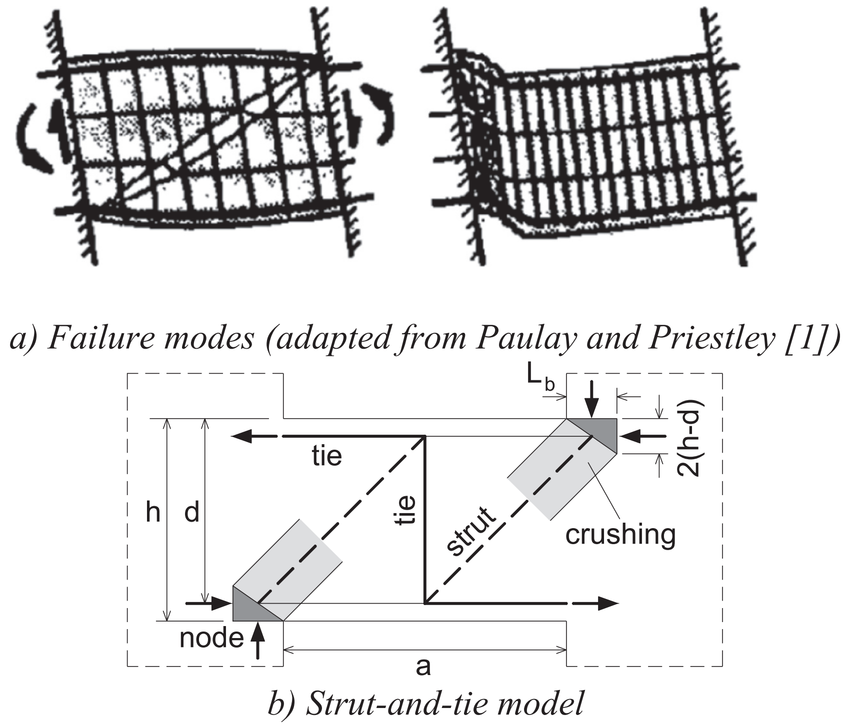

Fig. 1. Short coupling beams.

capacity of the coupling beams. Therefore, the main goal of this paper is to propose a simple and accurate model for evaluating the deformations and shear-flexure interaction in the critical end sections of short coupling beams. The model will be developed and validated with the help of data from experimental studies ([4–11]) and nonlinear finite element simulations.

2. Observed behaviour of coupling beams

The behaviour of short coupling beams will be first discussed with the help of a test from an early experimental program by Paulay [4]. The test specimen, named beam 312, had a 152 mm by 787 mm rectangular cross section and a shear span-to-effective depth ratio a/d = 1.42, see Table 1. The longitudinal reinforcement of the beam consisted of symmetrical top and bottom bars with a ratio ρ_l = 1.58%, while the transverse reinforcement consisted of stirrups with ρ_v = 1.65%. The specimen was subjected to symmetrical double curvature bending (zero moment at midspan) by forces applied on end blocks simulating portions of adjacent shear walls. The load was applied in a reversed cyclic manner with the amplitude of the cycles being close to the strength of the beam.

The global response of the test specimen in terms of shear force vs. chord rotation is shown in Fig. 2a. Following the initial stiff response of the uncracked beam, a significant reduction of stiffness occurred when the load reached about 20% of the maximum load. This change of behaviour was caused by the propagation of steep flexure and flexure-shear cracks near the end sections of the beam where the bending moment was maximum. As the load was increased further, more flexure-shear cracks developed in the shear span followed by the propagation of a major shear crack. As evident from Fig. 2b, this crack extended from corner to corner of the beam along the diagonal of the shear span. The first load reversal was performed soon after the flexural reinforcement yielded in the end sections resulting in a plateau in the global response at $V \approx 640$ kN. A similar loading protocol was followed in the "negative" direction until a complete symmetrical crack pattern developed across the shear span. The longitudinal reinforcement also yielded on the opposite side of the section, and the load-rotation curve developed a plateau at $V \approx -600$ kN. Limited yielding of the transverse reinforcement was also measured in the main diagonal crack. Following this initial loading, two additional full load cycles were applied on the specimen resulting in increasing plastic rotations. Eventually, the concrete in the end sections crushed under the combined action of shear and flexure limiting the displacement capacity of the member, Fig. 2c. This crushing was accompanied by visible sliding deformations in the end sections, and therefore the beam failed in sliding shear. In other tests from the same experimental program the crushing of the concrete did not occur with sliding but with lateral bursting of the compression zone. This latter type of failure is typically defined as diagonal compression or shear compression failure. It should be noted however that in many cases the difference between sliding shear and diagonal compression failure is very subtle. Both failure modes occur when the beam is provided with sufficient transverse reinforcement to suppress shear failures along the major diagonal crack.

Provided that the transverse reinforcement exceeds the amount required for suppressing a diagonal tension failure, the strength of the beam is not significantly influenced by the transverse reinforcement ratio. This is demonstrated in Fig. 3 with the help of specimen 312 and two companion tests (beams 311 and 313, see Table 1). The stirrup ratio of the specimens varied from 0.88% to 2.52% while the shear force at failure remained approximately constant. The three specimens failed with yielding of the longitudinal reinforcement and crushing of the concrete in the end sections. Because the reinforcement yielded, a first approximation to the failure load can be obtained based on the classical plane-sections-remain-plane approach for flexure which does not account for the effects of shear. While strictly speaking this approach is not applicable to short members, it is used here to provide a reference value for the strength of the end sections. The flexural strength calculated with the classical model is divided by one-