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Development of arching action in longitudinally-restrained reinforced concrete beams

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HIGHLIGHTS

- Providing experimental results for longitudinally-restrained RC beams.
- Effect of longitudinal and transverse steel bars on the arching action is studied.
- Effect of end support rotation on the behaviour of restrained RC beams is studied.
- Investigating effect of strain penetration on the response of restrained RC beams.

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ABSTRACT

Membrane action of reinforced concrete (RC) beams is one of the primary mechanisms that enhances progressive collapse resistance of frames and influences the robustness of a structure under an unforeseen overload event. Compressive membrane action increases both the capacity and stiffness of longitudinally-restrained reinforced concrete members. In this study, six scaled reinforced concrete beam assemblages with longitudinal end restraints were tested under a monotonically increasing displacement applied at the mid-span. The longitudinal reinforcement ratio and configuration of stirrups were the main variables investigated in the experimental programme. The effect of support stiffness and strain penetration on arching behaviour is studied using a numerical model calibrated against the experimentally measured rotation of the end supports. It is concluded that, for RC beams, the longitudinal reinforcing ratio and stirrup configuration has only a minor influence on arching action, whereas compressive strength of the concrete and strain penetration have pronounced effects on the peak as well as post-peak response.

1. Introduction

Transverse deflection of a reinforced concrete (RC) beam, or slab, results in cracking of the section in the tensile zone and a change in the neutral axis (NA) position from its initial elastic position. This, in turn, causes an axial extension of the member as the neutral axis moves towards the compressive fibre [1]. If this extension is prevented by axial/lateral restraints, such as that provided by end span columns and adjacent beams, a compressive thrust is generated in the beam. This phenomenon, known as compressive membrane, or arching action can considerably increase the capacity of the member [2,3].

The behaviour of longitudinally-restrained RC members primarily depends on lateral and rotational stiffness of the end restraints, the span-to-depth ratio of the member, compressive strength of concrete, configuration, proportion and ductility of reinforcing steel and, in slabs, the number of restrained edges [4–13]. From the literature on longitudinally-restrained RC beams, it is concluded that compressive strength and corresponding crushing strain of concrete have beneficial effects on the arching action and this influence is lessened in members with large span-to-depth ratios [4,5,8–10,12–14]. Moreover, the stiffness of supports has been identified as the most influential factor on the response of RC members in developing compressive membrane action [1].

Typically, in the experimental test set ups for longitudinally-restrained beams, end restraints are taken to be fixed [14,15]. However, the end restraints provided by bolted or welded grip mechanisms are less than ideal due to looseness of bolts and the potential for slip in the connections, as well as movements in the reaction frame. Accordingly, in reality the stiffness of end supports can be less than the idealised fixed boundary conditions and in such a case accurate calibration of numerical models against experimental data cannot be achieved, unless the movements of

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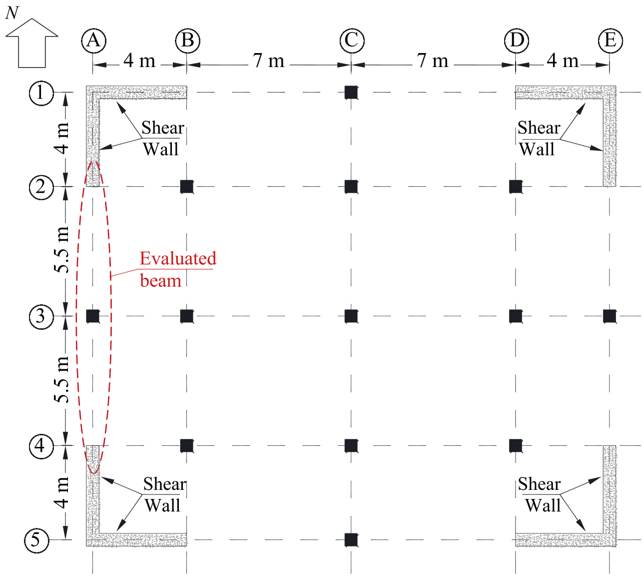

Fig. 1. Outline of the floor plan.

end restraints are measured during the test and are considered in the modelling.

Most of the studies on membrane action of RC elements are related to floor slabs, bridge decks and slab strips [3,6,8,10,16–20]; less attention has been paid to arching action of reinforced concrete beams within frames and the contribution of membrane action in progressive collapse resistance of framed structures [11,15,21–25]. In addition, the results obtained from some of the experiments on longitudinally-restrained RC members cannot be directly used or relied upon owing to small size of the tested samples [7,8,26]. Accordingly, there is a need for producing reliable baseline data on longitudinally-restrained RC beams developing membrane action.

Over the last two decades, several attempts have been made to develop simplified analytical methods as well as finite element (FE) models for analysis of longitudinally-restrained RC members that develop arching action [27–30]. However, application of FE models for capturing the membrane action of RC members has been hampered by numerical complexities associated with concrete crushing and cracking, geometrical nonlinearities and rupture of reinforcing bars [10,31,32]. In addition, effect of strain penetration in the supports on the response of RC members subjected to large displacement has not been sufficiently studied.

In this paper six 2/5th scale RC beam assemblages with lateral restraints are tested under a displacement-controlled pushdown force. The reinforcement ratio as well as the stirrup arrangement was the main experimental variables of the study. In addition to the applied load and vertical displacement, the rotations of the end supports as well as strain in longitudinal steel and in the concrete are measured at various locations. This provides the baseline date needed for proper calibration of the numerical models. The 1D frame model developed by Valipour et al. [1] is calibrated against the collected experimental data and extended to capture the effect of strain penetration on the arching action.

2. Experimental program

To study the response of longitudinal restraint on RC beams, a seven-story building was first designed according to Australian standard AS3600-2009 [33]. The plan of the building is shown in Fig. 1 and the floor is a one-way joist system in the North–South direction with permanent action (dead load) of $G = 4$ kPa. The permanent load of perimeter wall is $G_w = 5$ kN/m. The width of beams, thickness of shear walls and the total depth of all beams including floor system is 450 mm. For design of the building 500 MPa grade steel and concrete with a compressive strength of 25 MPa was used. The building is assumed to be a general office located in Sydney, NSW with an imposed action (live load) of $Q = 3$ kPa. In the experimental program, the response of the exterior beam on the first floor, in the North–South

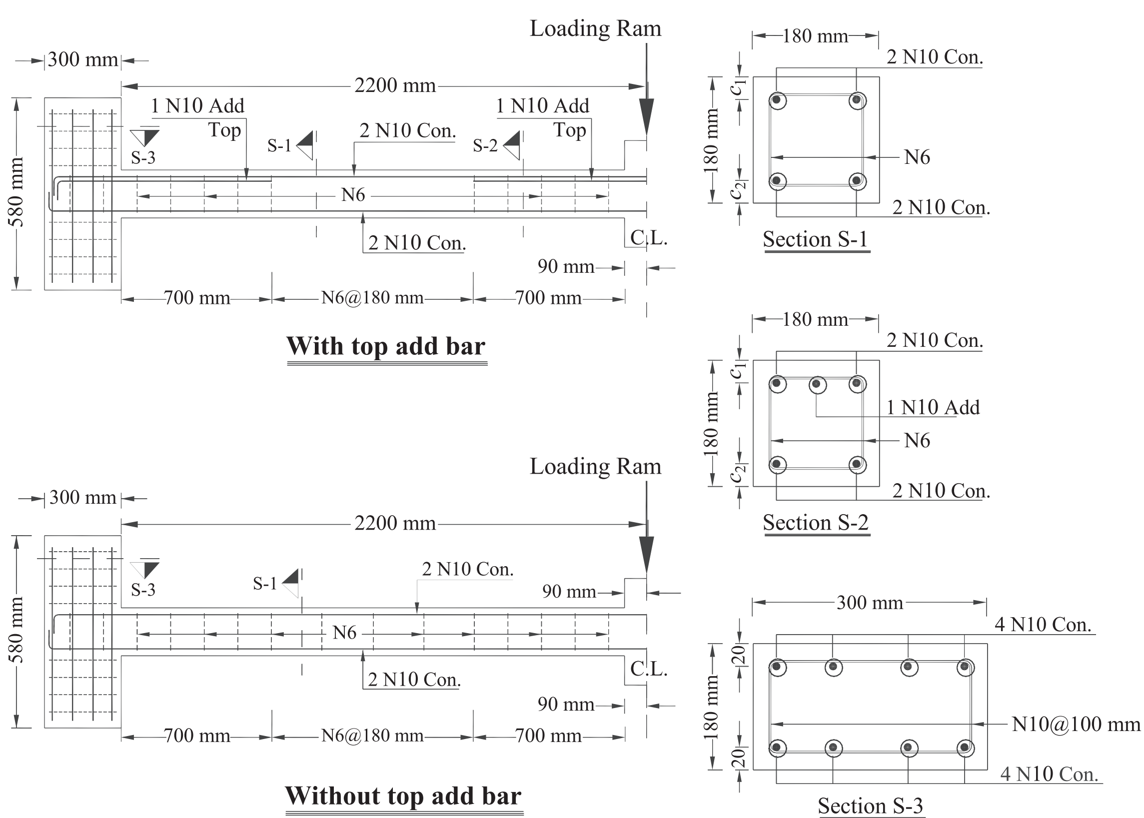

Fig. 2. Outline of the geometry, cross-section and reinforcing details for the beam assemblages with and without top add bars over the end supports and centre stub.