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Flexural behaviour of externally prestressed beams. Part II: Experimental investigation

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Abstract

In Part I of this paper, a simple “pseudo-section analysis” method which accounts for second-order effects in a simply supported, externally prestressed beam subjected to two symmetrically applied concentrated loads was developed. In this paper, an experimental investigation of the flexural behaviour is reported. A total of nine simply supported prototype beams were tested to evaluate the effect of span-to-depth ratio and second-order effects. It was found that span-to-depth ratio has no significant effect on the flexural behaviour of the beams. For beams with span-to-depth ratio of up to 22.5, a single deviator provided at midspan section is effective in minimising second-order effects, that is, maintaining higher load-carrying capacity and ensuring ductility at the ultimate limit state for the beams. However, second-order effects prevailed in a longer beam with larger span-to-depth ratio of 30.0 despite the provision of a single deviator at midspan. This type of long beams would require at least two deviators placed at one-third span sections, hence reducing the deviator spacing in order to minimise second-order effects so that the beams would achieve the desired flexural performance with regard to beam strength and ductility. Theoretical predictions of the load–deformation responses using the proposed analytical model were found to agree well with the test results in this study and experimental data of other investigations.

Keywords: Analysis; Beam; External prestressing; Flexure; Strength; Second-order effects

1. Introduction

Experimental studies on flexural behaviour of externally prestressed beams are scarce based on a literature survey carried out by the authors in Part I of this paper. Most of the theoretical investigations reported that the span-to-depth ratio of the beams has a significant effect on the flexural behaviour, particularly on external tendon stress [1–3]. In a separate investigation [4], span-to-depth ratio was found to be insignificant in the external tendon stress of the beams if second-order effects are minimised. Therefore, more experimental data is required to address this issue. Another aspect of the flexural behaviour which is lacking in experimental data is the variation in external tendon depth, or normally termed as second-order effects.

The investigation reported herein aims at providing more experimental data on the behaviour of externally prestressed beams, particularly on the effects of span-to-depth ratio and number of deviators or second-order effects. The test results were also used for the validation of the analytical model proposed in Part I of this paper.

2. Test program

Nine prototype concrete T-beams with cross-sectional dimensions and reinforcement details shown schematically in Fig. 1, were prepared (see also Table 1). In all beams, the internal longitudinal reinforcement consisted of two T16 bottom bars and four R8 top bars, with average laboratory tested yield strengths, f_y and f'_y, of 530 MPa and 338 MPa respectively. The beams were reinforced with R6 or R8 mild steel stirrups throughout their lengths, with average laboratory tested yield strengths of 320 MPa and 338 MPa respectively. The design cube strength of the concrete used was 38 MPa at 28 days. No deviator was provided in beams T-0A and T-0B. In beams ST-1, ST-2, ST-3, ST-4 and ST-5, a 100 mm wide

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Notation

d_{ps}	tendon depth
d_{ps0}	initial tendon depth
f'_c	concrete cylinder compressive strength
f_{cu}	concrete cube compressive strength
f_{pe}	effective prestress of prestressing or external tendons
f_y	yield strength of internal tension reinforcement
f'_y	yield strength of internal compression reinforcement
L	effective beam span
M_{cr}	cracking moment
M_s	moment at serviceability limit state
M_u	ultimate moment of resistance
M_y	moment corresponding to yield load
P_{cr}	cracking load
P_s	load at serviceability limit state
P_u	ultimate load
P_y	yield load
Δf_{ps}	stress increase in external tendons

deviator at midspan was provided in each beam. In beam ST-5A, two deviators were provided, one each at the one-third span sections; and beam ST-5B had three deviators, each at the quarter span sections. The initial effective depth of the external tendons, d_{ps0}, for all the beams was kept to 200 mm, with span that led to span-to-depth ratios, L/d_{ps0}, of 7.5, 9.0, 15, 22.5 and 30.0 for beams ST-1, ST-2, ST-3, ST-4 and ST-5 respectively. Beam T-0A had the same span of 4.5 m as beam ST-4 and beams T-0B, ST-5A and ST-5B had the same span of 6.0 m as beam ST-5.

The beams were prestressed using external tendons one day before testing. Two straight seven-wire prestressing strands, with a diameter of 12.9 mm and an average tensile strength, f_{pu}, of 1900 MPa, were stressed to an effective prestress, f_{pe}, of about $0.4 f_{pu}$ or 760 MPa, one on each side of the beam. Technically, beams with a deviator provided at midspan would benefit from a draped tendon profile for the vertical component of the prestressing force would take effect in the load carrying capacity. However, the draping angle would vary with the variation in beam span while the tendon depth is kept constant. This is not desirable in this study as it introduces another parameter into the beam series. Therefore, all the test beams were provided with straight tendons so that the only varying parameters are the span-to-depth ratio, L/d_{ps0}, and number of deviators.

Each beam was instrumented to measure the deflections, curvature, concrete and internal steel strains, forces in the external tendons, and crack widths. Each beam was simply supported and loaded monotonically at third-points to failure, thus creating a constant moment region within the middle one-third span segment. Deflections were measured using strain gauge type displacement transducers. Curvature was measured using two clamping devices securing two displacement transducers with gauge length of 300 mm, one each near to the top and bottom faces of the beam being tested. These clamping devices were installed to measure the midspan curvature if there is no deviator at midspan, whereas for beams with a midspan deviator, these devices were installed to measure the curvature at a section 300 mm away from the midspan, which is still within the constant moment region. Strains were measured using electrical resistance strain gauges and forces in the external tendons were measured by load cells installed at the passive anchorages.

3. Test results and discussion on effect of span-to-depth ratio

From the literature review as described in Part I of this paper, it is noted that all the available equations for the calculation of stress increase, Δf_{ps}, or stress, f_{ps}, in the external tendons are functions of the span-to-depth ratio. Therefore, this part of the study was carried out to provide further validation. The five concrete T-beams designated ST-1, ST-2, ST-3, ST-4 and ST-5, with the same cross section, internal steel reinforcement, tendon configuration and span-to-depth ratios of 7.5, 9.0, 15.0, 22.5 and 30.0 respectively as shown in Fig. 1 and described in Table 1, were tested and the results compared. With third-point loading, these span-to-depth ratios correspond to shear span-to-depth ratios of 2.5, 3.0, 5.0, 7.5 and 10.0 respectively, well within the range of slender to very slender beam regimes in which beam action or flexural behaviour prevails [5].

3.1. *Load–deformation response*

Fig. 2(a) and (b) show the moment–curvature curves and the load–midspan deflection curves of beams ST-1, ST-2, ST-3, ST-4 and ST-5 respectively. Prior to cracking at M_{cr} or P_{cr}, all the beams assumed linear moment–curvature and load–deflection relations. The beam stiffness was reduced after the appearance of flexural cracks, but the beams resumed a linear load–deflection behaviour after the crack development had stabilised. The approximate linear cracked behaviour ended when the internal steel reinforcement began to yield (at M_y or P_y). Beyond this point, the curvature or deflection increased dramatically without any significant increase in external load up to the maximum moment or load carrying capacity, M_u or P_u, of the beams.

All these test beams failed in flexure. The larger ultimate curvatures of beams ST-1 and ST-2 shown in Fig. 2(a) were probably due to multiple large cracks passing through the curvature measuring device, resulting in larger measured deformation. The smaller ultimate curvatures in beams ST-4 and ST-5 were probably due to the beams failing at sections outside the measured regions, but still within the constant moment region.

Fig. 2(b) shows the load–midspan deflection curves of the test beams. The four beams with span-to-depth ratio of up to 22.5, namely ST-1, ST-2, ST-3 and ST-4, exhibited approximately the same deflection ductility ratio, which were 2.15, 2.23, 2.70 and 1.96 respectively. Deflection ductility ratio is defined as the ratio of deflection at the ultimate limit state