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Flexural tests on externally post-tensioned lightweight concrete beams

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ABSTRACT

The present study examined the flexural behavior of externally post-tensioned lightweight aggregate concrete (LWAC) beams under symmetrical top one-point, two third-point, and analogous uniform loading systems. With respect to the test parameters, eccentricity of prestressing strands and configuration of deviators for the harped strands varied under different loading conditions. All the test beams had the same geometrical dimension and amount of mild longitudinal bars and prestressing strands. The flexural capacity, stress increase (Δf_{ps}) of the unbonded strands at the ultimate state, and displacement ductility ratio (μ) measured in the present beams were compared with those of the internally post-tensioned LWAC one-way members. The comparisons clearly indicated that Δf_{ps} and μ measured in the externally post-tensioned beams were lower than those of the internally post-tensioned one-way members with the same reinforcing index. This trend was independent of the loading type. Although the design equations for Δf_{ps} specified in American concrete institute (ACI) provision are conservative in the present beams, the safety level exhibits a significant decrease when compared with the results obtained in the internally post-tensioned LWAC beams. The nonlinear analysis indicates a good agreement for the load–displacement with test results, although a slight overestimation in terms of the flexural strength was observed for beams under an analogous uniform load.

1. Introduction

It is widely accepted [1–3] that artificial lightweight aggregates constitute a practically sustainable alternative to natural aggregates due to their sound environmental performance including the recycling of by-product materials and preservation of resources. Additionally, when compared with normal-weight concrete (NWC), it is known [4,5] that lightweight aggregate concrete (LWAC) has several advantages such as lower self-weight and higher thermal and acoustic insulations. A lower density of LWAC allows the production of smaller and lighter-weight structural members, which results in more available space and higher seismic resistance capacity of building structures. Specifically, smaller and lighter elements are preferred for precast concrete structures due to their reduced costs in the handling and transporting system. As a result, the application of LWAC has gradually grown by a large proportion in the construction industry and off-shore structures.

Lower tensile resistance and modulus of elasticity of LWAC are the main parameters that constitute obstacles in the design of structural long-span members [6]. Yang et al. [7,8] explored the effectiveness of and limitations in introducing prestressing forces to reduce the deflection and crack width under a service load and to enhance the strength and ductility of LWAC beams. Based on the test results, they indicated that the application of the prestressing force to LWAC is very promising and that the flexural design of LWAC beams can be conservatively created by the procedure recommended in the ACI 318-14 provision [9]. However, the range of test parameters and available information on the structural performance are extremely limited with respect to prestressed LWAC members. In terms of the reliable design and expanding the practical application of prestressed LWAC members, further investigations are necessary from various perspectives including the position and profile of tendons.

The use of the external prestressing technique is quite common in applications involving either the strengthening of existing structures or the construction of long-span beams, since the 1990s [10–15]. The external prestressing approach has several advantages over the internal post-tension system in terms of the following: lower friction losses in the unbonded tendons, simpler and more economical construction, and easier and more convenient maintenance for tendon inspection and replacement [11,16,17]. The behavior of externally post-tensioned members is conceptually similar to that of members with internal unbonded tendons with the exception of the second-order effect due to the change in tendon eccentricity and friction loss at deviators based on the high deflection of a member [18,19]. Ng and Tan [20] suggested that the stiffness and ultimate strength of externally post-tensioned

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Nomenclature

A_p	total area of strands
A_s	total area of the mild longitudinal tensile reinforcement
A'_s	the area of the mild longitudinal compressive reinforcement
b_{eff}	width of the beam flange
b_w	width of the beam web
$c(i,1)$	neutral axis at extreme fibers at loading stage i
$c(i,j)$	neutral axis at extreme fibers at each loading step and integration point
d_e	effective depth of tensile bars
d_p	effective depth of prestressing strands
d_s	effective depth of mild longitudinal tensile reinforcement
E_c	elastic modulus of concrete
E_p	elastic modulus of three wire strand
E_{sh}	elastic modulus of mild reinforcement in hardening region
e_{pm}	initial eccentricity of external prestressing strands at the mid-span of the beam
f_p	tensile stress of three-wire strand
f_{pe}	effective prestress
f_{ps}	stress of prestressing strands at the ultimate member strength
f_{pu}	tensile strength of the strands
f_{py}	yield strength of the strands
f_r	rupture modulus of concrete
f_s	tensile stress of mild reinforcement
f_{su}	tensile strength of mild reinforcement
f_y	yield strength of the mild longitudinal tensile reinforcement
f_c	stress of concrete in compressive stress
f'_c	concrete compressive strength
f'_y	yield strength of the mild longitudinal compressive reinforcement
h	overall depth of the beam section
h_f	depth of the beam flange
i	loading step in the nonlinear analysis
j	integration point in the nonlinear analysis
L	beam span between the centers of both end supports
L_a	length between both end anchorage sets
L/d_p	span-to-effect tendon depth ratio
M_n	flexural strength of the beam
$M_x(i,j)$	externally applied moment at each integration point calculated from $M(i,1)$
$M(i,1)$	moment of the mid-span with respect to the externally applied moment of at each integration point
$M(i,j)$	internal moment calculated by using the section lamina method at node j
n	number of integration nodes in the nonlinear analysis
P_{cr}	initial flexural cracking load
P_y	yielding load
P_n	peak load
PPR	partial prestressing ratio
w_c	concrete density
α	ratio of the distance of deviators to the beam span
γ_m	mean of the ratios of the measured and predicted moment capacities
γ_{mp}	mean of the ratios of measured to predicted stress increases at the peak load
Δ_{cr}	deflection at the initial flexural cracking load
Δf_{ps}	stress increase at the peak load
$\Delta f_{ps}(i)$	incremental stress at loading stage i
Δ_n	deflection at peak load
Δ_y	deflection at the yielding of the longitudinal tensile reinforcement
$\Delta\varepsilon_p(i)$	incremental strain in the unbonded tendon calculated from integrated elongation of the tendon
$\Delta(i)$	midspan deflection at each loading step
ε_c	strain of concrete in compressive stress
$\varepsilon_c(i,1)$	concrete strains at extreme fibers at loading step i
$\varepsilon_c(i,j)$	concrete strains at extreme fibers at each loading step and integration point
ε_o	concrete strain at maximum compressive stress
ε_p	strain of three wire strand
ε_s	strain of mild reinforcement
ε_{sh}	initial strain of mild reinforcement in hardening region
ε_t	concrete strain at maximum tensile stress
μ	displacement ductility ratio of the beam
$\varphi(i,1)$	curvature of the beam corresponded to $M(i,1)$
$\varphi(i,j)$	curvature of the beam at each loading step and integration point
ρ_p	ratio of the prestressing strands
ω	reinforcing index

members are reduced if the second-order effect is considered in the tendon eccentricity. Alkhairi and Naaman [10] mentioned that the second-order effect is more significant in beams with a higher span-to-depth ratio and the maximum strength reduction can correspond to 25% for beams with a span-to-depth ratio of 45. Harajli et al. [15] further examined the load-deflection performance of externally prestressed members by using non-linear numerical analysis and stated that external prestressing is a very effective approach for strengthening concrete flexural members given that moderate deviators are configurated along the span. Additionally, Au et al. [19] indicated that the friction loss at deviators is significant under a high deflection of the beam due to the kink deformation of unbonded tendons at the deviators. As such, the second-order effect and friction loss at the deviators constitute primary interests in the design of externally post-tensioned members.

However, there is a paucity of information on the ductility of externally post-tensioned flexural members, although the post-peak behavior of these types of members will be significantly affected by the configuration of deviators and initial eccentricity of the unbonded tendons as well as the longitudinal reinforcement index [8,21]. Furthermore, simple equations to calculate the ultimate stress (Δf_{ps}) in external prestressing tendons are still insufficient, although several investigations [19,21] examined the applicability of the equations derived for the internal unbonded prestressing tendons to predict Δf_{ps} in the external tendons. For the safe and reliable design of the externally post-tensioned beams governed by flexure, it is necessary to compile further experimental data under various parameters and compare the same code provisions on the moment capacity of the beams and stress increase in the external tendons. Specifically, extant studies have not investigated the behavior of these types of beams that are constructed by using LWAC, although a higher Δf_{ps} in the external tendons is expected because of the lower elastic modulus of the concrete material.

The present study prepared nine externally post-tensioned LWAC beams under symmetrical top one-point, two third-point, and analogous uniform loading systems. The effect of the configuration of deviators and initial eccentricity of the external tendons were examined with respect to reducing the deflection and crack width and enhancing moment capacity and ductility of LWAC beams. The measurements of flexural capacity, Δf_{ps}, and displacement ductility ratio in the present beams were compared with those of the internally post-tensioned LWAC one-way members as obtained in an experiment in previous studies [8,22] and predictions obtained using the flexural design