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Flexure of continuous HSC beams with external CFRP tendons: Effects of fibre elastic modulus and steel ratio

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ABSTRACT

The results of a theoretical study on the flexural behaviour of continuous high-strength concrete (HSC) beams prestressed with external fibre reinforced polymer (FRP) tendons are presented. A previously developed numerical model is extended to the analysis of continuous HSC beams with external FRP tendons. A numerical test is conducted on two-span externally prestressed beams made of HSC with compressive strength of 90 MPa. The external tendons are assumed to be carbon FRP (CFRP) composites covering a wide range of modulus of elasticity. Various levels of nonprestressed steel ratio are used. Comprehensive aspects of behaviour of such type of beams are examined. The results show that CFRP with high elastic modulus of 500 GPa mobilizes quite different structural responses compared to those with normal elastic modulus, and that the amount of nonprestressed steel affects remarkably the behaviour of such beams. The study also indicates that some moment redistribution knowledge valid for conventional continuous concrete beams may not be applicable to continuous HSC beams with external FRP tendons.

1. Introduction

External prestressing has been very common in application to either the strengthening or the construction of multi-span concrete girder bridges. Such type of structures, where the strength and durability are of particular importance, is often made of high-strength concrete (HSC). Although HSC is more fragile than normal-strength concrete (NSC), the ductile behaviour of HSC members may not be inferior to that of NSC members if a proper choice of the amount and location of steel is made [1–4].

Due to their advantages of non-corrosive property and high tensile strength, fibre reinforced polymer (FRP) composites are widely used in concrete structures instead of conventional steel reinforcement [5–7]. The use of FRP materials as external tendons is expected to be increasingly popular, as these tendons are often exposed to exterior environment and therefore need a very high anticorrosion protection. For external FRP tendon systems, the major concerns arise from the bond at anchorages, since the anchorages in such systems are extremely critical for prestress transfer and interaction between external tendons and the member over the entire life of the structure. Many efforts have been made to the development of safe and reliable anchorage systems for FRP tendons, and some achievements have been reached [8]. Three basic FRP composites are typically available for prestressing tendons, namely, aramid FRP (AFRP), carbon FRP (CFRP) and glass FRP (GFRP) [8–11]. The common GFRP composites have poor resistance to alkaline environment and, therefore, they are not permitted for internal bonded tendons. GFRP composites are also susceptible to creep rupture under sustained loads and can indefinitely sustain only about 30% of their ultimate strength [12]. AFRP and CFRP are both desirable for prestressed concrete applications, while the latter generally exhibits better mechanical properties than the former [12]. A recent numerical study by the authors [13] showed that the behaviour of concrete beams with external CFRP tendons (having elastic modulus of 147 GPa) is very similar to that of the ones with external steel tendons. This observation is consistent with an experimental study by Bennitz et al. [14].

The accurate analysis of beams prestressed with external tendons is rather complicated, attributed to the lack of compatibility of the strains between external tendons and the adjacent concrete and to the variation in eccentricities of external tendons with varying beam deformations (second-order effects) [15,16]. For continuous HSC beams with external FRP tendons, some additional difficulties arise due to the existence of redundant restraints and the distinctive material properties of HSC and FRP. So far, few

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theoretical efforts [17,18], as well as a very limited experimental works [19–21], have been carried out to identify the behaviour of continuous external tendon systems, particularly the ones with combined HSC and FRP materials. Because of the lack of experimental data and theoretical studies, the behaviour of continuous HSC beams prestressed with external FRP tendons has yet to be well understood.

This article describes a numerical investigation of flexural behaviour of continuous HSC beams prestressed with external CFRP tendons, focusing on the effects of CFRP modulus of elasticity and nonprestressed steel ratio. Comprehensive aspects of behaviour of such beams are evaluated, including the stress increase in external tendons, the curvature ductility, the variation of neutral axis depth, the redistribution of moments, and the failure mode and crack pattern. The present numerical study is performed using a finite element model developed specifically for externally post-tensioned beams.

2. Method of numerical analysis

A finite element model for the full-range nonlinear analysis of externally prestressed concrete beams has been developed [22]. The basic assumptions adopted are: a plane section remains plane after deformations; nonprestressed steel completely bonds with the surrounding concrete; the frictions between deviators and external tendons are negligible; and the shear deformation is negligible. The numerical method is formulated based on the Euler–Bernoulli beam theory combined with the layered approach. According to the updated Lagrangian description, the stiffness matrix consists of the material stiffness matrix, which represents the material nonlinear effect, and the geometric stiffness matrix, which represents the large displacement effect. At each step during the solution process, the geometry (length and eccentricities) of external tendons are updated in terms of the current nodal displacements of beam elements (anchorage and deviator points are associated with the corresponding beam element nodes). The increment in tendon strain is calculated from the elongation of the entire tendon. The contribution of external prestressing to the concrete beam is made by transforming the current prestressing force into equivalent loads acting on the finite element model. Details of the numerical treatment of external or unbonded tendons can be seen in the references [22,23]. A load control or displacement control incremental method, together with the Newton–Raphson iterative algorithm, is used to trace the structural equilibrium path throughout the elastic, nonlinear and ultimate ranges. During the solution process, when the concrete strain at the critical section reaches the allowed maximum strain, the beam is assumed to be crushed.

In the finite element idealization, the concrete beam is divided into two-node beam elements and the external tendon is also divided into segments corresponding to the beam elements. The spacing between adjacent nodes is dependent on the precision requirement for an analysis; generally, a spacing of one-half to two times (smaller at critical regions and larger at noncritical regions) the cross-sectional depth is acceptable. Each element is subdivided into a number of concrete and reinforcement layers to include the different material properties across the depth of the section. The number of layers relies on the section shape; in general, 10, 12 and 16 concrete layers can be respectively used for rectangular, T- and I-beams.

The previously developed model [22], however, is limited to the analysis of NSC beams prestressed with external steel tendons, because the constitutive laws introduced in the model are valid only for NSC and steel materials. These laws are inadequate to simulate the behaviour of HSC and FRP materials. To allow the proposed numerical method to predict the behaviour of continuous HSC beams prestressed with external FRP tendons, the following material models are adopted in the present study:

The stress–strain relationship for concrete in compression recommended by Eurocode 2 [24] has been proved to be applicable to both NSC and HSC, and is adopted here. It is expressed as follows:

$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta} \tag{1}$$

where $\eta = \varepsilon_c/\varepsilon_{c0}$; σ_c and ε_c are the concrete stress and strain, respectively; $k = 1.05E_c\varepsilon_{c0}/f_{cm}$; ε_{c0} is the concrete strain at peak stress, and $\varepsilon_{c0}(‰) = 0.7f_{cm}^{0.31}$; E_c is the modulus of elasticity of concrete (in GPa), and $E_c = 22(f_{cm}/10)^{0.3}$; f_{cm} is the mean compressive strength (in MPa), and $f_{cm} = f_{ck} + 8$; f_{ck} is the characteristic cylinder compressive strength (in MPa). Eq. (1) is subject to the condition that the concrete strain is not greater than the ultimate compressive strain ε_u, which for HSC is determined by

$$\varepsilon_u(‰) = 2.8 + 27[(98 - f_{cm})/100]^4 \tag{2}$$

The stress–strain diagram for concrete in tension is assumed to be composed of a linearly ascending branch before cracking and a linearly descending branch after cracking up to zero stress, as indicated by

$$\text{Prior to cracking,} \quad \sigma_c = E_c\varepsilon_c \tag{3a}$$

$$\text{After cracking,} \quad \sigma_c = f_t\left[1 - \frac{\varepsilon_c - \varepsilon_{cr}}{\varepsilon_{tu} - \varepsilon_{cr}}\right] \tag{3b}$$

where f_t = concrete tensile strength; $\varepsilon_{cr} = f_t/E_c$; and ε_{tu} = concrete tensile strain corresponding to zero stress. When the concrete strain is greater than ε_{tu}, the tensile stress is equal to zero. According to Eurocode 2 [24], the tensile strength f_t for HSC is calculated from

$$f_t = 2.12\ln(1 + f_{cm}/10) \tag{4}$$

The prestressing FRP tendons are linearly elastic up to rupture and, therefore, the stress σ_f is related to the strain ε_f by

$$\text{Prior to rupture,} \quad \sigma_f = E_f\varepsilon_f \tag{5a}$$

$$\text{After rupture,} \quad \sigma_f = 0 \tag{5b}$$

where E_f = FRP tendon modulus of elasticity. The nonprestressed steel is assumed to be elastic-perfectly plastic in both tension and compression.

A computer programme incorporating the aforementioned numerical procedure and material models was written. The programme is able to take care of simply supported and continuous beams made of NSC and HSC and prestressed with external steel and FRP tendons, under symmetrical and unsymmetrical loading. It requires the input of geometry and boundary condition, loading data, material properties, etc. The output includes nodal displacements (axial, transverse displacements and rotation), support reactions; section moments and curvatures; stresses and strains in external tendons, nonprestressed steel and concrete.

In order to validate the proposed model, six two-span continuous externally post-tensioned beams tested by Harajli et al. [19] have been investigated. These beams were B6D1, B6D2, B12D1 B12D2, B10S1A and B10S1B. The experimental and computational values of the ultimate load and ultimate tendon stress are given in Table 1. Fairly good agreement can be observed for the specimens. The average discrepancy for the ultimate load is −0.5%, with a standard deviation of 2.4%; and the average discrepancy for the ultimate tendon stress is 5.6%, with a standard deviation of 5.7%. The comparison between the numerical and exprimental results ragarding the load–deflection curve and the response of load vs.