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Effect of longitudinal reinforcement and prestressing on stiffness of composite beams under hogging moments

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ABSTRACT

To investigate the stiffness of steel–concrete composite beams subjected to hogging bending moments and their enhancement through prestressing using external tendons, laboratory experiments were conducted on five steel–concrete composite beams. Three of the beams were two-span continuous composite beams with box steel girders and the others were simply supported. The parameters investigated included the amount of longitudinal reinforcement and the arrangement of prestressing. From the experimental results, it was found that prestressing significantly improved the cracking moment of composite beams, and crack spacing was dominated by the transverse reinforcement spacing. The stiffness enhancement and crack control suggest the advantages to the mechanical performance of composite beams prestressed by external tendons. A theoretical model is proposed to estimate the effective stiffness of a composite beam subjected to hogging bending moments, taking into account the tension stiffening effect of concrete cracking.

1. Introduction

Continuous steel–concrete composite beams are more competitive than simply supported beams in many instances because the reduced sagging bending moment results in a higher span/depth ratio, less deflection, and higher fundamental frequency of vibration. However, hogging bending moments in the region of interior supports may cause cracking of the concrete slab and accordingly decrease the structure's stiffness and durability. In recent years, extensive experimental and theoretical studies have been conducted on many features of composite beams under hogging bending moment, including the cracking of concrete [1], slip at the steel–concrete interface [2], tension stiffening effect [1,2] and degree of shear connection between steel beam and concrete slab [3]. Allison [1] performed a series of experiments to study the flexural cracking of composite beams. The experimental results showed that the crack widths were much larger than expected, due to shrinkage in the concrete slab. A model considering shrinkage and tension stiffening was further proposed to calculate the mean surface strain in the concrete slab. Fabbrocino et al. [2] developed an analytical model for composite beams under hogging bending moment. This model considered the tension stiffening effect by taking into account the slip at both the steel–concrete interface and the concrete–reinforcement interface. Loh et al. [3] also developed an iterative program based on cross-sectional analysis. That program was able to model the behavior of simply supported composite beams under hogging bending moment. Comparison of the modeling and experimental results demonstrated satisfactory accuracy of the proposed program. Furthermore, a parameter study of composite beams with different numbers of shear connectors also showed that partial shear connection may be acceptable because of an increased rotational capability without a considerable decrease in strength in regions of hogging moment in continuous composite beams.

Composite beams prestressed using external tendons are often used in practice to reduce tension stresses generated, especially in the top concrete slab. This method is effective for both new bridge construction and bridge upgrading, because the induced prestressing through external tendons can reduce the stresses caused by dead or living load. Therefore, the load-carrying capacity and the stiffness of the structure can be improved. In the case of simply supported composite beams or sagging bending regions of continuous composite beams, prestressing the steel girder along the bottom flange can improve the structural performance in both elastic and ultimate stages and reduce the use of structural steel [4]. In the hogging bending regions of continuous composite beams, prestressing the concrete slabs can prevent or alleviate the cracking of concrete, with benefits of improvement in the stiffness and durability of the structure.

Since the 1950s, considerable research work has been conducted on prestressed composite beams using experimental [5–8] and theoretical [6,9] methods. Saadatmanesh et al. [5] tested two simply supported prestressed composite beams, one of which was subjected to sagging bending moment and the other to hogging moment. Ryu et al. [6]

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investigated the inelastic behavior of an externally prestressed continuous composite box-girder bridge with prefabricated slabs and carried out a simple analysis to estimate the ultimate flexural capacity. Chen et al. [7,8] conducted experiments on four full-scale continuous composite beams, two of which were equipped with a straight-line external tendon. These results showed significant increases in the ultimate strength and stiffness by prestressing. Nie et al. [9] developed a simplified analytical model to calculate the deformation of prestressed continuous steel–concrete composite beams accounting for the slip at the steel–concrete interface. However, there have been relatively few relevant investigations of the cracking development in concrete, the shear lag of the cracked section, and the moment redistribution of continuous composite beams under hogging moments. These issues can be critical for design, particularly in the case of large spans used in bridge construction.

Furthermore, current approaches for estimating the effective stiffness of a composite section after concrete cracking have not been well established, for two main reasons. Generally applied methods specified in the standards are predominantly documented on a basis of experimental results only [12,13]. Slip at the steel–concrete interface, the shear lag of prestressed composite girders, and the tension stiffening effect of concrete after cracking have not been taken into account [14,15]. Moreover, numerical approaches based on detailed FE analysis may be too complex for design practice [2].

In this paper, experiments were conducted on five steel–concrete composite beams. Certain parameters, such as the amount of longitudinal reinforcement, arrangement of the fold-line external tendon, and beam boundary condition (simply supported or two-span) were taken into consideration. The main objectives of the experiments were: 1) to evaluate the mechanical performance of prestressed composite beams under hogging bending moments under different boundary conditions (simply supported and continuously supported); 2) to compare the corresponding strain distribution and concrete cracking development with and without prestressing; and 3) to study the slip at the steel and concrete interface and the shear lag of prestressed composite girders before and after concrete cracking. Furthermore, a theoretical model was proposed to estimate the effective stiffness of a composite section subjected to hogging moment, with consideration of the slip effects at the concrete–steel interface and the tension stiffening effect of the cracked concrete.

2. Experimental program

2.1. Specimens

Five composite beam specimens were designed and tested under two scenarios. Scenario 1 included two simply supported beams (designated SCB2 and SCB3) subjected to a point load from below to introduce hogging bending moments. This scenario represented the hogging bending regions of a continuous composite beam between two contra-flexure points on each side of an interior support. Scenario 2 included three two-span continuous composite beams (designated SCB4, SCB5 and SCB6). To each beam, point loads were applied at one-third of each span (only one span for SCB6) to represent more accurately a continuous beam under sagging and hogging moment.

The major geometries of the individual components (steel, concrete and steel reinforcement) are shown in Fig. 1 for all the specimens. The overall length was 3900 mm for simply supported specimens (SCB2 and SCB3, see Fig. 1a and b), and 9200 mm for continuous ones (see Fig. 1c and d). The steel girders' sections were all box-shaped, 180 mm in height and 100 mm in width. According to Eurocode 4, all the steel girders were classified as Class I and could be designed using plastic theory. The nominal cross-sectional dimensions of the concrete slabs were 600 mm in width and 70 mm in thickness for all specimens. The stud spacing was 120 mm for SCB2 and SCB3 along the entire span length. For SCB4 to SCB6, 80 mm was designated as the stud spacing in sagging moment regions and 60 mm in the hogging moment region because of the difference in shear span length. According to Eurocode 4 [12], “a span of a beam has full shear connection when increase in the number of shear connectors would not increase the design bending resistance of the member.” To achieve full shear connection, 32 studs were needed per shear span as calculated on the basis of Eurocode 4, and we provided each region with at least twice as many (20% more in the hogging shear span of SCB4 to SCB6 limited by spacing specification) to guarantee the degree of connection and then decrease the value of slip at steel–concrete interface.

As shown in Fig. 1a and d, specimens SCB2 and SCB5 were equipped with one prestressed steel tendon of the type 7-ϕ15.20-1860 (i.e. the nominal diameter of the steel tendon was 15.2 mm in composition of 7 strands with a nominal yielding strength of 1860 Mpa), which was fixed at the ends of steel girder (see the position in C-C section in Fig. 1i). To avoid local buckling of the steel girders during the loading process, diaphragms were employed at a spacing of 550 mm for the simply supported specimens and 1500 mm for the continuous specimens. More diaphragms were added at the positions with large concentrated loads such as the supports and loading points.

For the other three specimens (SCB3, SCB4 and SCB6), no prestressing was provided, as they were designated as reference specimens. Specimen SCB3 had identical geometry, details, and loading configuration to those of specimen SCB2 as shown in Fig. 1b; Specimens SCB4 and SCB6 were the reference to SCB5 as shown in Fig. 1c.

2.2. Material properties

The material properties of all steel and reinforcements were determined by tensile coupon tests and the results are given in Tables 1 and 2. The modulus of elasticity of the steel beams and reinforcement was 206 GPa. The characteristic strength of the prestressing tendons was reported as 1860 MPa, and the nominal modulus of elasticity was 195 GPa.

Normal density aggregates and ordinary Portland cement were used in the concrete mixture. The properties of the concrete for the individual specimen beams are presented in Table 3, where f_{cu} represents the average compressive strength measured from three 150 mm concrete cubes, and the equivalent cylinder strengths f_c used in the latter part of this paper were calculated considering a conversion factor of 0.79 [10].

2.3. Loading setup and instrumentation

SCB2 and SCB3 were simply supported composite beams. As shown in Fig. 2a, an upward concentrated load was applied at the bottom of middle span to simulate the action of hogging moment between two contra-flexure points in a continuous composite beam. SCB4 to SCB6 were two-span continuous composite beams as shown in Fig. 2b and c. Concentrated loads at one-third of each span were applied on both SCB4 and SCB5, and on only one span of SCB6.

Displacement transducers were used to measure the vertical deflections at the mid-span of all specimen beams, and additional transducers were mounted at the positions of the loading points of the continuous beams. To measure longitudinal slip, displacement transducers were also mounted between the top flange of the steel girder and the bottom of the concrete slab at a spacing of about 600 to 750 mm. At critical sections, such as the maximum sagging and hogging bending sections, the strains of steel, concrete, and reinforcement were measured using strain gauges along the depth. The tendon forces during the test were measured using load cells at the fixed end for SCB3 and at both ends for SCB5. Load cells were also located at the supports of the continuous beams to ascertain the reaction forces and to control possible deviations of the jacking forces throughout the test. All the information obtained by the strain gauges, transducers, and load cells was automatically recorded by a data acquisition system at regular intervals during the tests.