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Experimental study and theoretical analysis of partially encased continuous composite beams

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A R T I C L E I N F O

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A B S T R A C T

The mechanical behavior and the law of moment redistribution of the partially encased continuous composite beam (PECCB) are investigated in this paper. One common continuous composite beam and three PECCBs were tested. The main variable parameter of the three PECCB specimens is the amount of longitudinal reinforcement in the concrete slab of hogging moment region. Owing to the contribution of the web encasement, PECCBs have much slower crack propagation speed in the hogging moment region and higher ultimate capacity. The web encasement also contributes to postponing the yielding of the bottom flange, and therefore prevents local buckling in the steel girder. As the amount of reinforcement in the concrete slab of hogging moment region increases, the degree of moment redistribution of PECCBs decreases. On the basis of analyzing the moment redistribution requirement for plastic design and the ultimate rotation capacity of hogging moment section, the required and available moment redistribution factors of PECCBs are obtained. A parameter R_p is introduced to evaluate the relative relationship between the longitudinal reinforcement in the concrete slab and the rest part of the partially encased section, and the value of R_p should be restricted within 0.35 to enable full moment redistribution for plastic design of PECCBs.

1. Introduction

The use of simply supported steel-concrete composite beams can take full advantage of both materials, as the concrete slab is mainly in compression and the steel girder is in tension. However, a large number of composite beams used in the practical engineering are continuous beams, which can improve the overall performance of the beam especially in terms of deformation. In the area near the internal supports, large bending moments and shear forces exist, and the concrete in tension does not contribute to the bending capacity. For the common composite beam, the steel girder in compression is sensible to local buckling and lateral-torsional buckling [1,2].

Partially encased beams are elements in which the web of the steel section is encased with reinforced concrete. Hooks, studs or shape steel are often used as shear connectors between the reinforced concrete and the steel components [3–5], ensuring the effective cooperation of the two parts. Beams of this section form were originally designed to improve fire performance. However, as research and application continued, people further realized that, besides good fire-resistant performance, the web encasement also contributes to the enhancement in bearing capacity and stiffness under sagging moment without enlarging the overall size of the cross section [4,6]. When this section form is used in a continuous beam, not only the bending and shear strength of steel girders around the internal supports increase, but also the buckling of web and flange in compression can be prevented [7,8].

So far, there have been a lot of studies on partially encased beams with or without the concrete slab. Kindmann [2] performed static experimental tests on twelve partially encased beam specimens with different shear connection and with different cross sections. Two of the twelve beam specimens were integrated with concrete slabs. Hegger [6] evaluated the load carrying behavior of concrete encased steel girders with and without longitudinal shear connection, and the results of three-dimensional finite element analysis describing the interaction between concrete encasement and steel girder are introduced. Kvočáka [7] conducted a comparative study between thin-walled steel beams and partially encased composite thin-walled steel beams. Nakamura [8–10] proposed the use of partially encased composite I-girders as bridge girders, and performed bending and shear tests on this kind composite girder. In addition, Piloto [11,12] investigated the fire resistance of partially encased beams.

At present, there are few reports about the mechanical behavior of the partially encased continuous composite beam (PECCB). Also, there are only a small number of researches covering the following aspects: the influence of concrete encasement on the strength and rotation capacity near the internal support section; the moment redistribution of PECCBs. Eurocode 4 [3] allows a limited degree of moment redistribution in the elastic analysis, depending on the classification of steel girder. According to Eurocode 4, cross-sections of partially encased beam

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can also be divided into four classes and the limits of moment redistribution for Section 1 suggested by Eurocode 4 is 40% (uncrack analysis).

In this paper, experimental studies and theoretical analyses are conducted to investigate the mechanical behavior and rule of moment redistribution of PECCBs. Three PECCB specimens are tested, and the only changing parameter is the amount of longitudinal reinforcement in the concrete slab in the hogging moment region. For the comparison of the partially encased specimens, there is made a common composite beam with the same steel girder section. On the basis of analyzing the moment redistribution requirement for plastic design and the ultimate rotation capacity of hogging moment region, the required moment redistribution factor β_r and the available moment redistribution factor β_a are obtained.

2. Experimental program

2.1. Beam specimens

A total of four continuous composite beam specimens were designed for testing. Beam SCCCB1 is a two-span common continuous composite beam, and beams PECCB1-3 are two-span partially encased continuous composite beams. Each span of beam specimens is 3900 mm. The cross-sections of beam specimens are shown in Fig. 1. In all beam specimens, two rows of 19 mm diameter by 80 mm long studs are welded on the top flange plate symmetrically about the centerline of the top flange, with the transverse spacing of 80 mm and the longitudinal spacing of 100 mm. Full shear connection is achieved between the concrete slab and the steel girder in accordance with Eurocode 4. The web encasement of the PECCB is connected to the steel girder with studs welded on the central position of the steel web. The studs on the web are in the same type with those on the top flange, with a longitudinal spacing of 200 mm.

The details of the reinforcement for beam specimens are given in Table 1. The three PECCBs had a varying amount of longitudinal reinforcement only in the hogging moment region of the slab. There are nine, thirteen and seventeen longitudinal reinforcing bars of 14 mm in diameter in the hogging moment region of beams PECCB1-3 respectively.

The mean compressive strength of three concrete cubs (150 mm × 150 mm × 150 mm) f_{cu} is given in Table 2. The tensile strength of concrete $f_{t.}$ is used to predict the cracking resistance of beam specimens. The tensile properties of the steel girder and the steel bars are also summarized in Table 2.

2.2. Test set-up and loading process

As shown in Fig. 2, all beam specimens were subjected to one point loading in each mid-span. The static load was applied by two hydraulic jacks sharing the same hydraulic circuit by the bleeder. The load was monotonically applied in three stages. At the beginning, the load was applied at the rate of 15 kN per step. When beam specimens were approaching yield, the load was reduced to 10 kN per step. When reaching approximately 75% of the expected ultimate bearing capacity of the specimens, the load applied was reduced to 5 kN per step. During the loading process, the test measurements included vertical load, reaction at supports, deflection in the mid-span, strains near both the mid-span and support sections, relative slip between the concrete slab and the steel girder, relative slip between the web encasement and the steel girder (Fig. 2(c)).

Table 1
Reinforcement of beam specimens.

Specimen no.	Reinforcement in the slab		Reinforcement in the web encasement	
	Longitudinal	Transverse	Longitudinal	Stirrups
SCCCB1	9Φ14(H[a]),14ϕ8(S[b])	ϕ10@150	–	–
PECCB1	9Φ14(H),14ϕ8(S)		4ϕ8(Top) +	ϕ8@120(ϕ10@80)
PECCB2	13Φ14(H),14ϕ8(S)		4Φ18(Bottom)	
PECCB3	17Φ14(H),14ϕ8(S)			

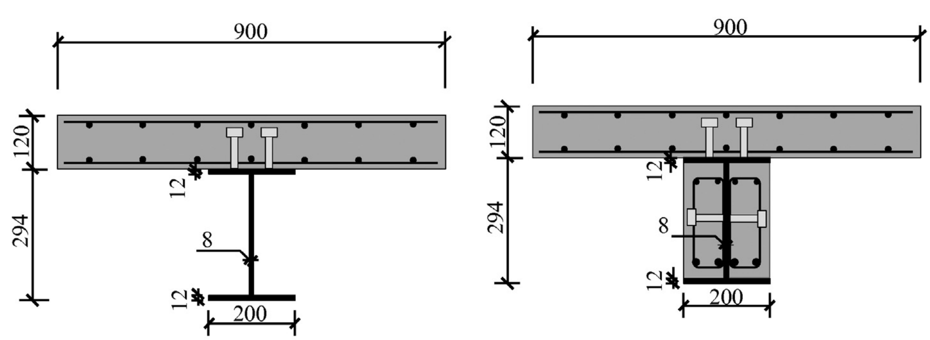
[a] Hogging moment region.
[b] Sagging moment region.

3. Test results and discussion

3.1. General observations and failure modes

For beam SCCCB1, the first flexural crack appeared in the slab near the internal support at approximately 13% of its measured peak load. With the increase of load, additional flexural cracks formed and the former cracks further propagated. When approaching the peaking loading, the cracks near the internal support penetrated the slab (Fig. 3(a)). At the ultimate failure state, concrete slab near the mid-span crushed and the bottom flange near the internal support section buckled locally (Fig. 3(b), (c)). Eventually, flexural failure was observed in the common continuous composite beam SCCCB1 (Fig. 3(d)).

The three PECCB specimens vary in the amount of longitudinal reinforcement only in the hogging moment region of the slab, and their experiment phenomena and failure modes were similar: at low loading level about 10% of the measured peak load, there exhibited the first flexural crack on the concrete slab near the internal support. Like beam SCCCB1, cracks of beams PECCB1-3 also increased in the number and developed downwards as the loading increased, eventually penetrating the slab as well (Fig. 4(a)). Afterwards, at approximately 30% of the peak load, the first flexure-shear crack appeared in the web concrete at the internal support section and the amount of cracks increased gradually with a 45°angle to the vertical direction (Fig. 4(a)). When the load increased to 47% of the measured peak load, near-vertical flexural cracks appeared in the web concrete near the



(a) SCCCB1 (b) PECCB1-3

Fig. 1. Cross-sections of beam specimens (unit: mm).