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Evaluation of Ultimate Strength of Steel-Concrete Hybrid Girder Using 80-MPa High-Strength Concrete

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ABSTRACT: The typical composite girder bridge combines the I-shape steel girder and the concrete slab by means shear connectors. In this sectional configuration, the neutral axis is located in the slender steel section which makes the structure vulnerable to local buckling or lateral-torsional buckling when subject to flexure. However, this situation results in the ultimate limit state of the composite girder being determined by the ultimate strength of the steel girder. Accordingly, the steel-concrete (SC) hybrid girder was developed to solve this problem. The SC hybrid girder presents casing blocks made of concrete with compressive strength higher than 80 MPa between the steel girder and the concrete slab and is designed to let the neutral axis be located near the interface between the casing blocks and the steel girder so as to exploit efficiently each of the material properties. The present study examines the ultimate strength performance of such SC hybrid girder featured by two interfaces. To that goal, specimens exhibiting two different shear connection details were designed and fabricated and the flexural behavior was evaluated up to the ultimate limit state. The results show that the SC hybrid girder behaved elastically under the service load and satisfied the serviceability requirement for the allowable deflection. In addition, given that proper design is achieved, the SC hybrid girder secured sufficient structural stability in view of the facts that the slab failed first through compression because of the action of the rebar even under tension generating partial cracking of the casing and that the section yielded at 3.2 to 3.6 times the service load.

KEYWORDS: SC hybrid girder, steel girder, concrete slab, two interfaces, shear connection

I.INTRODUCTION

The composite girder of the bridge is composed of the I-shape steel girder resisting to tension and the concrete slab resisting to compression. These two members are typically connected by means of shear connectors. In the so-formed section, all the parts below the compression flange and below the web neighbouring the compression flange are in the tensile zone which reduces significantly the risk of local buckling and can be regarded as a compact section. However, the adoption of the slender steel girder makes the structure vulnerable to local buckling or lateral-torsional buckling. This situation results in the ultimate state of the composite girder being determined by the ultimate strength of the steel girder. Especially, there are numerous overseas examples of accidents caused by the lateral-torsional buckling during the fabrication of the slab before composition.

The steel-concrete (SC) hybrid girder shown in Fig. 1 was developed to solve the problem encountered in the composite girder. In the SC hybrid girder, the I-shape steel girder is first composed at its upper chord to concrete with compressive strength of 60-100 MPa to improve the ultimate strength of the composite girder and its resistance to buckling. This structure achieves efficient and rational arrangement of the materials by allowing concrete to resist to compression in the upper chord and steel to resist to tension in the lower chord. Moreover, the confinement of the slender steel section by the concrete in the compression zone complements the structural vulnerability to local buckling or lateral-torsional buckling in the compression zone before the composition with the slab. The position of the centroid in the upper part of the I-shape steel girder increases the buckling stability and can minimize the cross-section of the top flange with relatively less material need for the member.

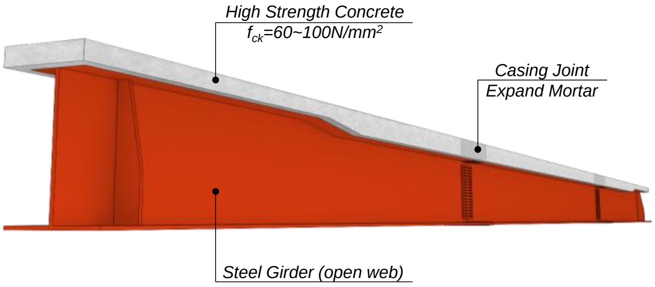


Fig.1: Composite of steel-concrete hybrid girder

The strengthening of the compression flange of the SC hybrid girder by high-strength (60-100 MPa) concrete brings relatively better buckling stability and higher torsional resistance compared to the conventional composite girder. For similar centroid, the SC hybrid girder experiences only minimal compressive stress in its compression flange whereas the high-strength concrete part takes charge of large compression. In addition, the SC hybrid girder presents a torsion constant 20 times larger than that of the conventional composite girder, which makes it very resistant to torsion.

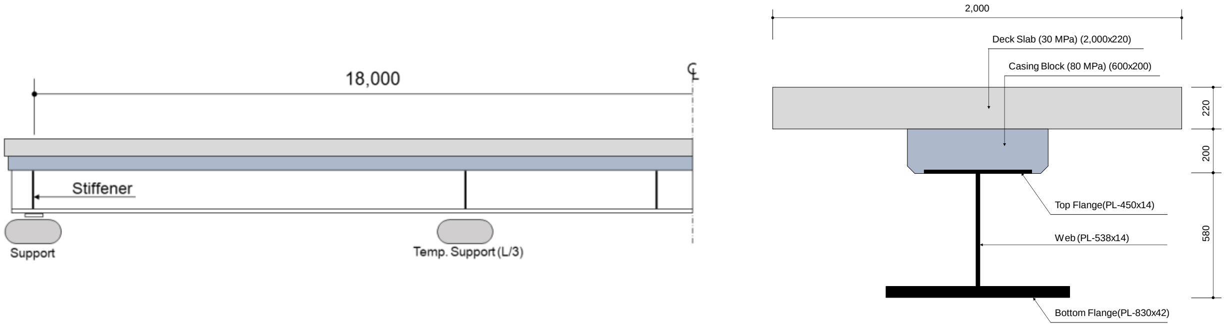
However, the performance of the SC hybrid girder must be verified experimentally prior to its actual application on site. Especially, the SC hybrid girder featured by the presence of two interfaces shall secure sufficiently perfect composite behaviour until both interfaces reach their ultimate strength. Accordingly, this study evaluates the flexural behaviour of the SC hybrid girder up to the ultimate limit state on specimens designed and fabricated with two different shear connection details.

II. STRUCTURE TEST

A. Design of Specimens

The specimens were designed in compliance with the Korea Bridge Design Code (limit state design). The design was conducted for the most unfavourable stress case under application of the standard truck load KL-510 on 2 traffic lines. The sections and materials were selected to satisfy the ultimate and service limit states and the shear connection was designed for fatigue including an impact factor of 15%. As shown in Fig. 2, the specimens have a total length of 18.8 m and the slab presents a width of 2 m identical to the beam spacing. This is a compact section with a total depth of 1.0 m including the slab in which the steel girder is 580 mm high and the casing has dimension of 600×200 mm. In the upper part, the top flange is confined by high-strength concrete that keeps the stress to a low level and its width is set to a size allowing shear connection. The thickness of the web was chosen with respect to the shear strength of the non-strengthened web. The section of the bottom flange was decided considering that the bottom flange will be subjected to relatively large stress as well as the position of the centroid and the safety against overturning. Stiffeners are disposed at the supports to be L/3 from both ends. The stiffeners were designed for the ultimate load to prevent the occurrence of local buckling during loading. Table 1 lists the properties of the materials used in the fabrication of the specimens.

The specimens shall develop sufficient stiffness and strength to let the shear connection achieve satisfactory composite behaviour until the ultimate state of the section. Even if Kang et al. [1,2] conducted various experiments to derive the shear connection condition of the SC hybrid girder, this study considers only the two different shear connection configurations shown in Fig. 3 to fabricate the specimens for the evaluation of the performance of the SC hybrid girder. In Fig. 3(a), the shear studs connect the top flange and the slab by passing through the casing. In Fig. 3(b), the shear studs connect the steel beam and the casing, and the casing and the slab are connected by means of horizontal shear reinforcement as usually done in prestressed concrete beams. For convenience, the specimen with the configuration of Fig. 3(a) is designated as SG (stud-connected) specimen and the one with the configuration of Fig. 3(b) as RG (reinforcement-connected) specimen.

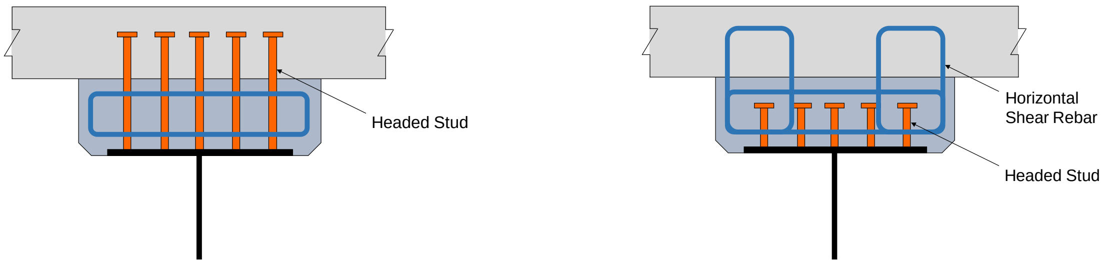


(a) Longitudinal section (b) Cross-section

Fig.2: Dimension of specimens

Table 1: Properties of major materials

Member		Material properties		Remarks
Concrete	Slab	Design strength, f_{dk}	30 MPa	Normal concrete
		Elastic modulus, E_{dk}	27,515 MPa	
	Casing	Design strength, f_{ck}	80 MPa	SUPER Concrete
		Elastic modulus, E_{ck}	37,490 MPa	
Steel SM400	I-shape girder	Yield strength, f_{sy}	235 MPa 215 MPa	t > 40 mm 40 mm < t ≤ 100 mm
		Tensile strength, f_{su}	400 MPa	–
		Elastic modulus, E_s	205,000 MPa	–



(a) SG specimen (b) RG specimen

Fig.3: Shear connection of specimens

B.Fabrication of Specimens

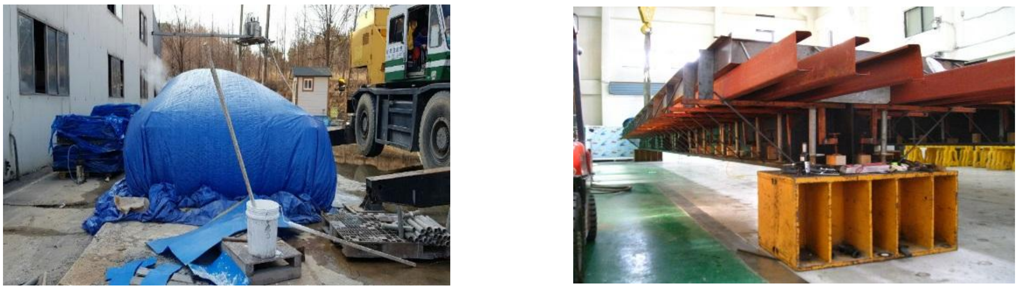
The specimens were fabricated by supporting the I-shape steel girder at L/3 from both ends using H–300×300 beams and placing the casings afterwards. In order to make the girder sustain the load, the form was assembled by supporting it with falsework installed over the bottom flange before placing 80 MPa-concrete mixed in factory. Steam curing was performed after 1 day to avoid the very high hydration heat expected immediately after the placing of high-strength concrete. The completed SC hybrid girders were then transported indoor and the slab was fabricated. Here also, the fabrication was conducted to let the composite girder sustain the load of the slab. Fig. 4 depicts the fabrication process of the specimens.

C.Layout of Sensors

LVDTs (linear variable differential transducers) were installed at the two L/3 sections from both ends, and one LVDT and a wire displacement sensor were installed at the L/2 section to measure the deflection. Steel gages and concrete gages were attached in 3 sections. The relative slip between the steel girder and the casing and between the casing and the slab was measured by means of horizontal displacement sensors installed at both ends. Mold gages were embedded in the supports before the placing of the casing concrete. These mold gages were intended to measure the strain that would develop under the occurrence of slip between the two concretes placed at different times. By embedding the gage at half distance from the surface of the placed concrete, this strain can be obtained by reading the value of the tension generated by the flexure of the gage due to the slip.

(a) Assemblage of casing form

(b) Placing of 80 MPa-SUPER Concrete



(c) Steam curing

(d) Assemblage of slab form

(e) Arrangement of slab reinforcement

(f) Placing of slab concrete

(g) Removal of slab form

(h) Test setup

Fig. 4: Fabrication of SC hybrid girder specimens

D.Structure Test

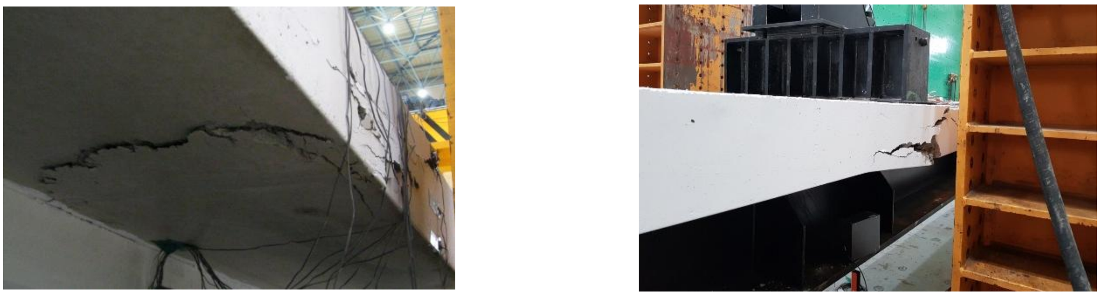
The simply supported specimens were installed to be loaded at mid-span. A frame with width of 25 cm and length of 1.5 m was installed at the loading spot along the width of the slab to receive a 300-ton actuator at its centre. At the start of the test, loading was applied through displacement control at speed of 0.050 mm/s. Thereafter, from stage 3 of Table 2 and until the end of the test, loading was applied at speed of 0.075 mm/s. The load was increased by increment of 50 kN beyond 1,500 kN expected to be the yield load of steel. After each loading increment, the load was held and the eventual occurrence of cracking in the casing concrete, local buckling of the compression flange and relative displacement was checked.

Table 2: Loading stages

Stage	Load (kN)			Loading speed	Content
1	0	→	500	0.050 mm/s	Service load
2	0	→	1,000		–
3	0	→	1,500	0.075 mm/s	–
4	1,500	→	1,600		Hold & check
5	1,600	→	1,650		Hold & check
6	1,650	→	1,700		Hold & check
7	1,700	→	1,750		Hold & check
8	1,750	→	1,800		Hold & check
9	1,800	→	End		Failure of slab

III. TEST RESULTS

Both SG and RG specimens developed cracks in the bottom chord of the casing concrete after reaching the yield strain of the steel girder and tension flange. As shown in Fig. 5, both types of specimen broke through compression failure of the slab.

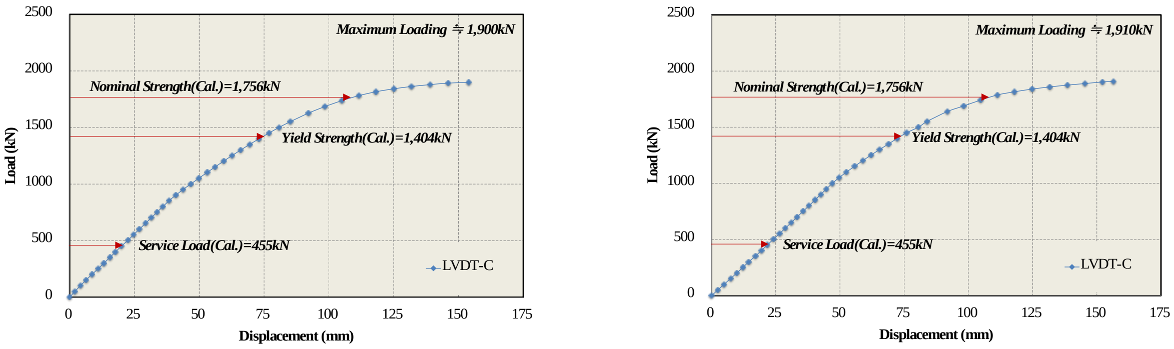


(a) SG specimen (b) RG specimen

Fig. 5: Failure patterns of SC hybrid girder

Fig. 6 plots the load-deflection curves measured during the test of the specimens. It appears that the service load of the specimens is 455 kN and lies within their elastic region. The deflection measured under the service live load reached 12 mm, which represents 53% of the deflection criterion L/800 (=22.5 mm)specified in the design code. This indicates that the SC hybrid girder satisfies the serviceability requirement. The nominal strength considering the load combination suggested by the design code is 1,756 kN.Both specimens develop strength larger than the theoretical ultimate strength by 8.2% to 8.8%.

In Table 3, the yield load of the tension flange computed with respect to the design code is 1,404kN. The yield point cannot be distinguished clearly in Fig. 6 but the strain measurement could verify that yielding occurred around 1,630 kN for SG specimen and 1,475 kNfor RG specimen. These values are larger than the computed ones by 7% to 16%, and larger than the service load by 3.2 to 3.6 times. In view of these results, the SC hybrid girder appears to secure sufficient structural stability.



(a) SG specimen (b) RG specimen

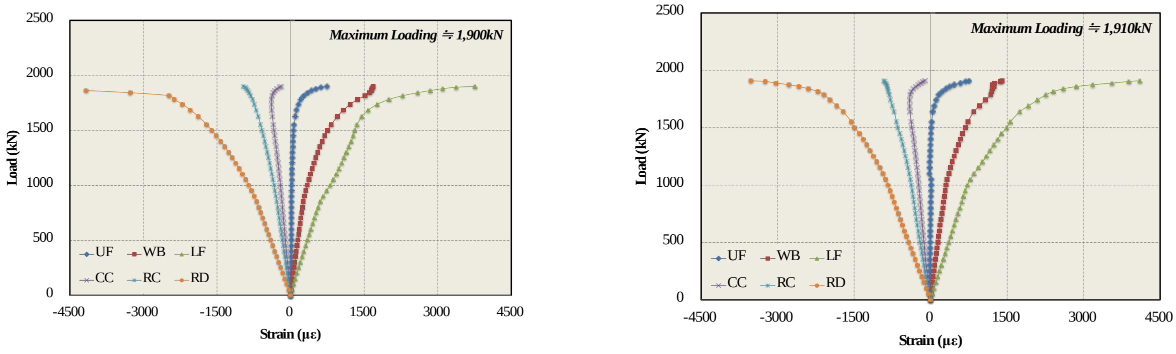
Fig. 6: Measured load-deflection curves

Table 3: Test results

Item		Yield load		Maximum load	
Calculation		1,404 kN		1,756 kN	
Test result	SG	1,630 kN	(1.161)	1,900 kN	(1.082)
	RG	1,475 kN	(1.051)	1,910 kN	(1.088)

Fig. 7(a) presents the strain distribution of SG specimen according to the increase of the load. The specimen starts to behave linearly below the service load and experiences steep deformation beyond 1,470με, the yield strain of the tension flange. The load at that time reaches 1,630 kN.It was verified that the centroid was located in the top flange and moved upward after the yielding of the tension flange. Cracking occurred in the lower chord of the casing around 1,780 kN.The test was interrupted when the strain at the lower chord of the slab reached the ultimate strain.

Fig. 7(b) presents the strain distribution of RG specimen according to the increase of the load and resembles that of the SG specimen. The specimen appears to develop linear behaviour even at the service load of 455 kN and the deformation experiences steep increase after the yield strain of the tension flange at 1,475 kN.The centroid was first located in the top flange and started to move gradually toward the tensile side after the yielding of the tension flange. Cracking occurred in the lower chord of the casing around 1,787kN. The test was interrupted when the slab reached the ultimate strain.



(a) SG specimen (b) RG specimen

Fig. 7: Load-strain curves at center of section

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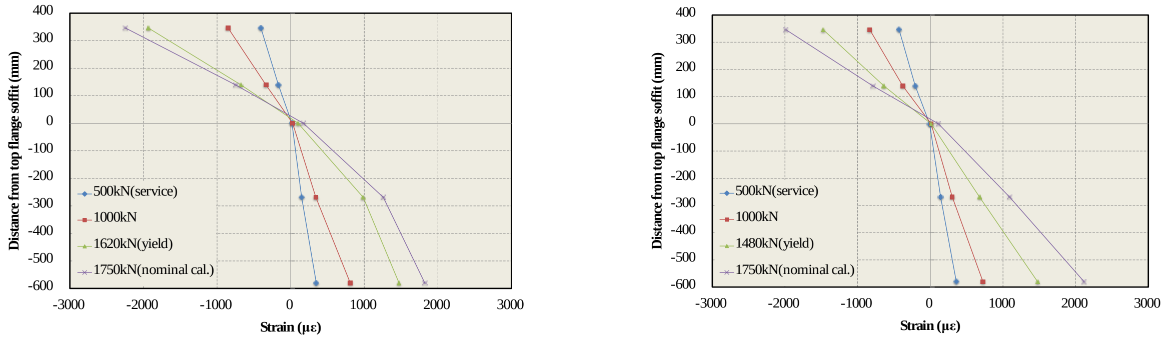
In Fig. 8, the strain distribution in the central section at each loading stage for the design load, yield load and maximum load shows almost linear patterns which indicate that the steel girder, casing and slab behave monolithically. The neutral axis at maximum load moved by about 25 mm upward from the bottom chord of the top flange. This value differs by 6% compared to that computed by plastic analysis and by 10% compared to that computed by the strain compatibility method. The relative slip reached about 0.02 mm and indicated that the structure developed performance near to perfect composition.



(a) SG specimen

(b) RG specimen

Fig.8: Strain distribution per loading stage

IV. CONCLUSIONS

The SC hybrid girder is a new type of composite girder that was developed to complement the problems of local buckling and lateral-torsional buckling observed in the conventional composite girder. The two interfaces of the SC hybrid girder should secure perfect composite action until the ultimate strength. Accordingly, two types of SC hybrid girder specimen were designed and fabricated with different shear connection details, and their flexural behaviour was evaluated experimentally up to the ultimate limit state. The following conclusions can be derived from the test results.

The SC hybrid girder behaved elastically under the service load and satisfied the serviceability requirement related to the allowable deflection.

The measured relative slip was verified to be smaller than 0.02 mm and indicated that the two types of specimen secured perfect composition. The difference in the shear connection details did not have noticeable effect on the stiffness. Given that perfect composition is achieved, it can be stated that no particular difference would appear in the behavior until the ultimate limit state.

Provided that proper design is done, the SC hybrid girder secured sufficient structural stability in view of the facts that the slab failed first through compression because of the action of the rebar even under tension generating partial cracking of the casing and that the section yielded at 3.2 to 3.6 times the service load.

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