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

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ABSTRACT: This study proposes the hybrid girder combining an 80-MPa high-strength concrete block with an I-shaped steel girder to replace the conventional steel girder used in bridge structures. Flexure test was conducted on a full-scale prototype of 25 m to evaluate the flexural behavior of this new girder type. The test results revealed that the hybrid girder developed linear elastic behavior under design loading and experienced yield of its lower flange at loading of about 3.1 times the service load. Differently from the expected rupture at mid-span, failure occurred by the sudden tensile failure of the concrete casing block caused by the occurrence of slip at the bolted connection. Nevertheless, the hybrid girder was verified to secure sufficient load bearing capacity since cracking did not develop in the concrete casing until failure and relative slip did practically not occur at the member connection.

KEYWORDS: high-strength concrete, steel-concrete hybrid girder, steel-concrete composite structure, flexural behavior, flexure test

I. INTRODUCTION

The depth of the traditional steel girder must be increased to secure flexural strength. In such case, the installation of stiffeners or the increase of the thickness shall be adopted to deal with the risk of buckling provoked by the compressive stresses developed in the upper flange and web of the girder. These measures result in larger quantities of steel and higher construction cost and limit the applicable span length of the girder.

Accordingly, this study proposes the hybrid girder combining an 80-MPa high-strength concrete block with an I-shaped steel girder to replace the conventional steel girder used in bridge structures. As shown in Fig. 1, the hybrid girder composes the upper flange of the steel girder with a high-strength concrete casing block over which the concrete slab is placed so as to position the neutral axis of the complete section within the concrete casing block. This disposition, which allows the concrete block to sustain compressive stresses and the steel girder to be in tensile stress state, diminishes the risk of buckling and reduces significantly the girder depth. Moreover, along the fabrication process of the girder shown in Fig. 2, the supports are disposed first at the center of the girder before placing the casing concrete to let negative moments develop, then the supports are moved to the ends of the girder before placing the slab to generate prestressing in the lower flange of the steel girder.
In such composite member, the composite behavior at the interface between the two materials is critical for securing the performance. A previous work by Kang et al [1] evaluated experimentally the shear strength of the connection. Besides, the present study designed, fabricated a simply-supported double girder bridge prototype with span length of 25 m and girder depth of 1 m, and conducted flexure test to evaluate the flexural behavior and failure mode of the steel-concrete hybrid girder.

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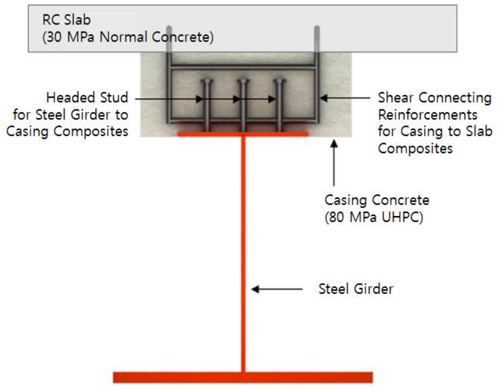
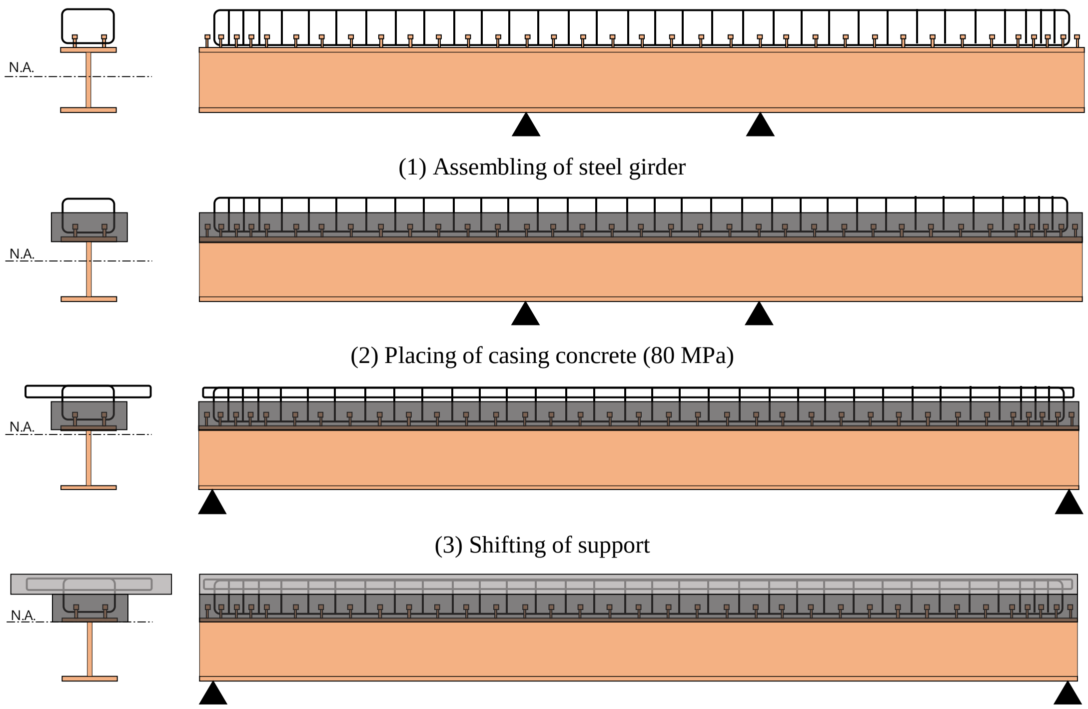


Fig. 1 Concept of Steel Girder-Concrete Casing Hybrid Girder



(1) Assembling of steel girder

(2) Placing of casing concrete (80 MPa)

(3) Shifting of support

(4) Placing of concrete slab

Fig.2 Fabrication process of hybrid girder

II. OVERVIEW OF PROTOTYPE AND TEST METHOD

The double girder prototype shown in Fig. 3 was designed to minimize as possible the occurrence of lateral displacements that could affect the accurate evaluation of the behavior under the application of the ultimate loading. The dimensions of the prototype are a length of 25 m, depth of 1 m, and slab width of 2.8 m. The design applied compressive strength of 80 MPa for the casing concrete, and SM490 steel with tensile strength of 490 MPa and yield strength of 315 MPa. Table 1 lists the actual material properties measured on the prototype. Following the large difference observed between the design and measured steel yield stress of the lower flange, Table 2 arranges the modified steel yield load of the design section based upon the measurements.

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The prototype was fabricated stepwise following the sequence shown in Fig. 4.

Table 1. Material properties (in MPa)

Concrete				Steel girder (SM490B)				
Casing		Slab		Design		Measured yield strength (from sample test)		
Design	Measured	Design	Measured	Tensile strength	Yield strength	Upper flange	Web plate	Lower flange
80	83.5	30	32.7	490	315	351	351	423

Table 2. Design check results.

Checked item		Original design	Modified design※
Service Load		572 kN (LSD) / 533 kN (ASD)	–
Load at $0.4f_{ck}$in slab		907 kN	907 kN
Load at $0.6f_{ck}$in slab		1,360 kN	1,360 kN
Yield load at steel lower chord		1,437 kN	1,680 kN
Limit State Design (LSD)	Plastic neutral axis	222.3 mm at top of slab	240.4 mm at top of slab
	Plastic moment	12,669 kN·m	13,677 kN·m
	Ultimate load	2,293 kN	2,475 kN

※Results using modified yield stress of lower flange of steel girder

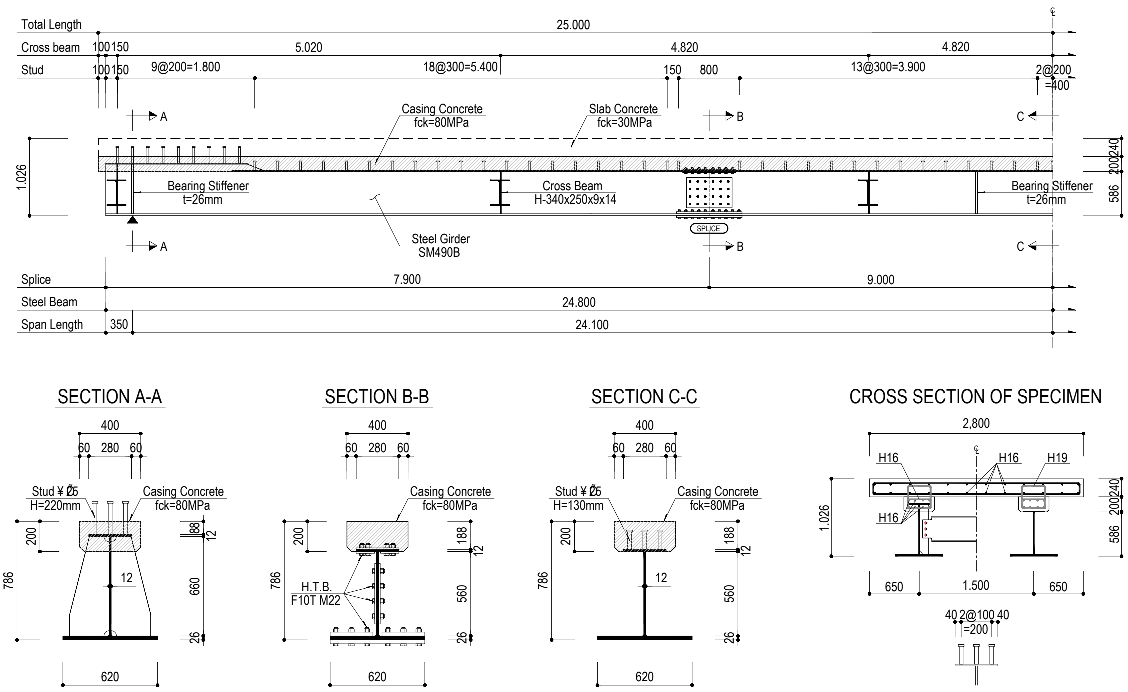

Fig. 3 Designed dimensions of hybrid girder

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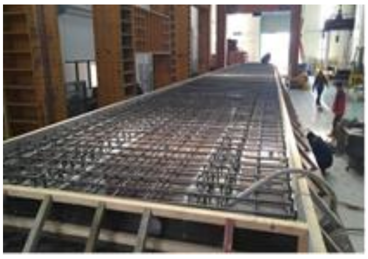
(1) Assembling of steel girder

(2) Installation of steel girder (inner supports)

(3) Assembling of casing reinforcement and placing of concrete (80 MPa)

(4) Steam curing of casing concrete

(5) Shifting of supports from center to ends



(6) Assembling of slab reinforcement

(7) Placing of slab concrete

(8) Completed prototype

Fig. 4 Sequential fabrication of hybrid girder prototype

Prior to the flexure test of the completed prototype, forced vibration test was performed using a vibrator and by human excitation to obtain the first natural frequency and damping ratio of the proposed bridge.
As shown in Fig. 5, the flexure test was conducted through 4-point bending with the loading points distant by2 m at the center of the girder. Loading was applied using an actuator with capacity of 350 kN. Strain gauges were installed at the central section with the layout shown in Fig. 6 to examine the change of the neutral axis.

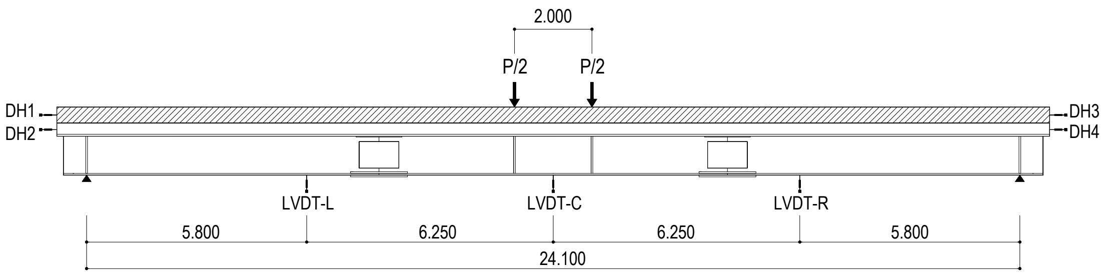


Fig. 5Loading position of 4-point bending test

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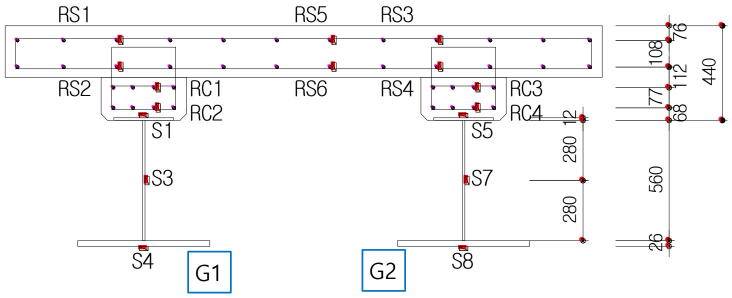
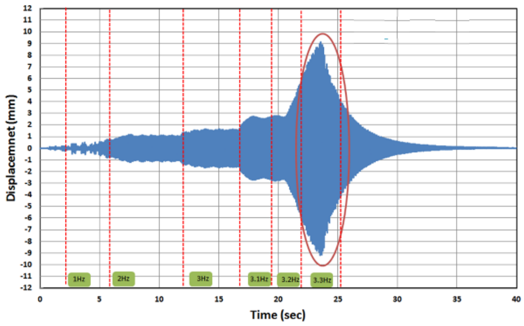


Fig. 6 Layout of strain gauges in central section

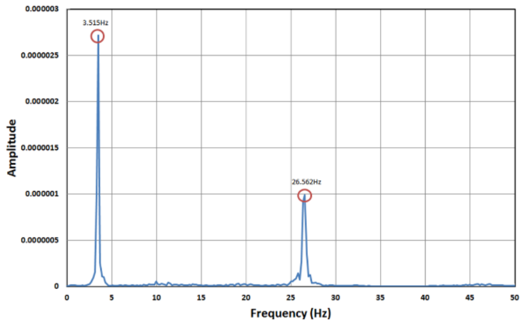
III. TEST RESULTS

A. RESULT OF DYNAMIC TEST

The natural frequency of the prototype was obtained by two methods. The first method varied the exciting frequency of the vibrator until the occurrence of resonance. The second method measured the vibration acceleration applied by the impact of human excitation and applied FFT on the measured acceleration. As shown in Fig. 7, the so-obtained natural frequency of the prototype is 3.3 Hz by forced vibration using the vibrator and 3.515 Hz by human excitation. The value of 3.515 Hz was selected since the forced vibration test using the vibrator was interrupted at 3.3 Hz for safety due to the large displacement developed when approaching resonance.



(a) Results from vibrator test



(b) Results from human excitation

Fig. 7 Results of forced vibration tests

The damping ratio was obtained by analyzing the acceleration response measured during the free vibration following the forced vibration test. The damping ratio calculated from 50 peaks is approximately 0.569, which falls within the acceptable range around 0.5 generally observed in steel girder bridges.

B. RESULT OF FLEXURE TEST

Fig. 8 plots the load-deflection curve measured in the bending test up to failure. The prototype is shown to develop linear behavior until the design load. Fig. 9 plots the load-strain curves measured in the central section. Yield behavior of the lower flange started near 1,800 kN corresponding to about 3.1 times the service load. From that point, the prototype exhibits nonlinear behavior which may indicate that the yield behavior of the lower flange governs the overall flexural behavior of the girder.

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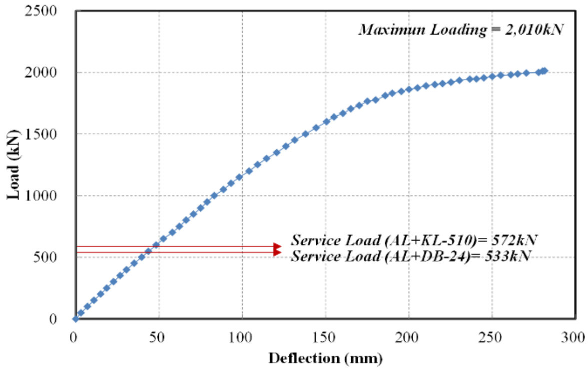
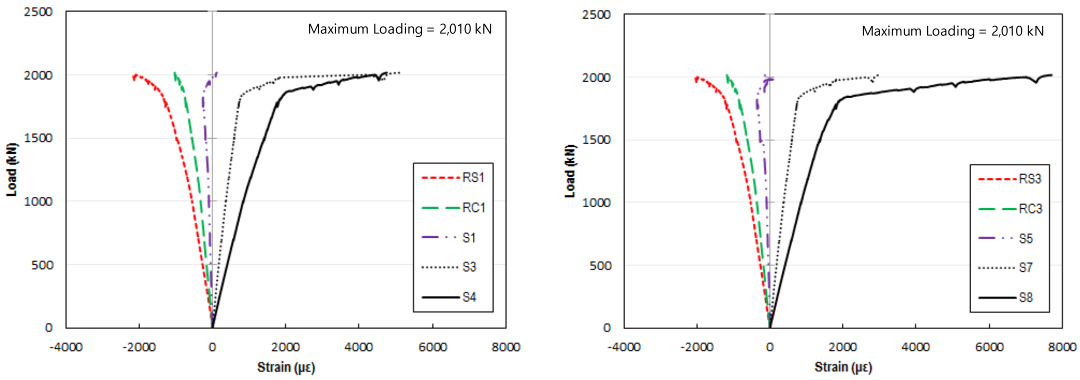


Fig. 8 Load-deflection curve measured at central section



(a) G1 (b) G2

Fig. 9 Load-strain curves measured at central section

After the start of the nonlinear behavior, failure occurred around 2,010 kN that is lower than the value of 2,475 kN computed for the ultimate load in the design check. At that time,sudden tensile failure occurred in the concrete casing at the bolted connection of the girder. This sudden failure was totally unexpected without anticipative cracking in the concrete casing, and appeared by the gaping in the butt connection of the girder due to the flexural deformation. This led to the appearance of a hinge in the concrete casing (Fig. 10) that resulted finally in the failure of the girder. Even if slip or gaping did not occur in the bolt holes drilled for the bolted connection after the pre-assembling of the girder, the actual fabrication of the prototype could not prevent some loosening by the fastening of the bolts in the pre-drilled holes.

Fig. 11 shows the variation of the neutral axis according to the increase of the load. Before yielding of the lower flange, the neutral axis did practically not change its position near the upper flange. After yielding of the lower flange, the neutral axis moved gradually toward the casing block.

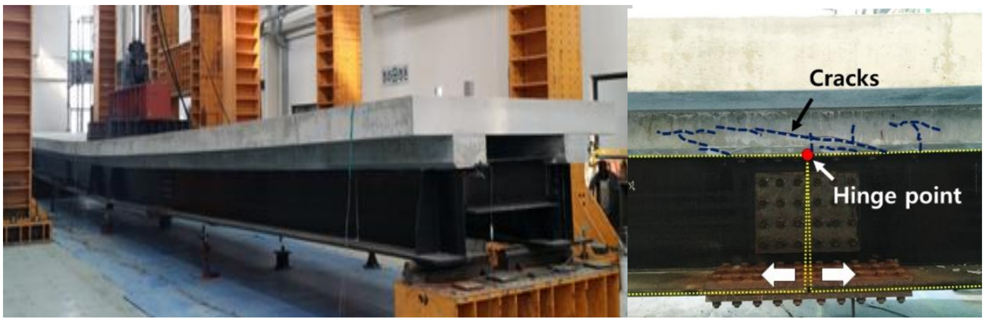


Fig. 10Failure and crack pattern of concrete at bolted connection of girder

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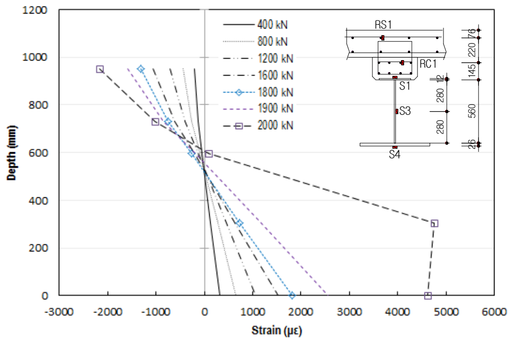

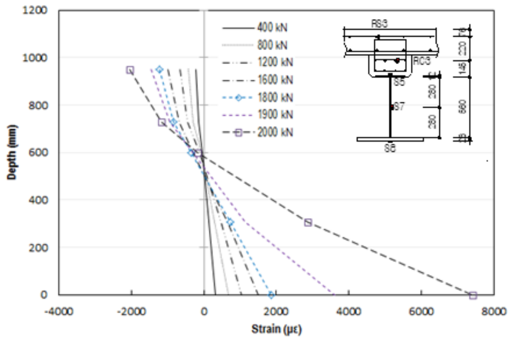

(a) G1 (b) G2

Fig. 11 Change of neutral axis at central section of girder

IV. CONCLUSIONS

This study proposed the hybrid girder combining an 80-MPa high-strength concrete block with an I-shaped steel girder to replace the conventional steel girder used in bridge structures. A simply-supported double girder bridge prototype with span length of 25 m and girder depth of 1 m was designed, fabricated and subjected to flexure test to evaluate the flexural behavior and failure mode of the steel-concrete hybrid girder. The following conclusions can be drawn from the test results.

• A series of forced vibration test conducted on the hybrid girder prior to the bending test revealed that its natural frequency and damping ratio were about 3.515 Hz and 0.569, respectively. This damping ratio is close to 0.5 generally observed in steel girders.

• From the static bending test, the hybrid girder exhibited linear elastic behavior at design load and started to behave nonlinearly with the initiation of the yield of the lower flange of the girder at loading of about 3.1 times the service load.

• The failure of the girder occurred unexpectedly through sudden tensile failure caused by the appearance of a hinge in the upper concrete casing following the gaping of the bolted connection. This pattern did not correspond to that of a normal flexural failure. Nevertheless, the hybrid girder was verified to secure sufficient load bearing capacity since cracking did not develop in the concrete casing until failure and relative slip did practically not occur at the member connection.

V. ACKOWLEDGEMENT

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[1] Jae-Yoon Kang, Jong-Sup Park, Woo-Tai Jung, Moon-SeoungKeum, “Shear Behavior in Indented Concrete Layers with Different Strengths”, Engineering, No.8, pp.423-431. 2016