Mechanical Behaviour of Curved Composite Beams under Hogging Moment

Waseda University, Department of Civil and Environmental Engineering Member ○ Weiwei Lin Fellow Teruhiko Yoda

1. Introduction

In recent years, steel-concrete composite girders have been widely used for the construction of curved bridges and flyovers for economic and aesthetic reasons. However, curvature of the superstructures leads to combined bending and torsion in the girders, then there is considerable additional complexity associated with their analyses, design and construction compared to that for typical straight bridges. As the increasing demand for curved continuous steel-concrete composite bridges combined with challenges in design and construction, there is a need to make a comprehensive study on the mechanical behaviors of such bridges in order to obtain more efficient design and construction of curved composite girder bridges.

Besides, for continuous steel-concrete composite beams, cracking of the concrete slab in the hogging bending moment region decreases the global stiffness of composite structures and reduces the effect of continuity, thus making the structural behaves highly nonlinear even for low stress levels, then special consideration is necessary. Recently, comprehensive studies on mechanical performance of straight steel-concrete composite beams subjected to hogging moment were performed by the authors[1~3]. On this background, a parametric study for curved composite steel and concrete girders with varying curvatures by using finite element method is performed in this study as an extension study for straight steel-concrete composite girders under hogging moment that presented in previous papers. This paper presents the results obtained from the numerical analysis to study the inelastic behavior of curved composite steel and concrete structures subjected to hogging moment, with the aim of predicting mechanical behavior throughout the range of loading to failure.

2. Model Prototypes

In this study, totally 6 curved composite I-girder numerical models with different curvatures were analyzed. CCB-1, designed as a straight steel-concrete composite beam, was 4600mm in length and was simply supported at a span of 4000mm. The design of this specimen is the same as the specimens used in previous studies[1~3]. The laboratory test was performed on CCB-1, and experimental results including load-deflection relationships and sectional strain distributions were recorded in the test. Test set-up of CCB-1 is shown in **Fig.1**. On the basis of observations in the experiment, the numerical model of CCB-1was built and verified by using test results. Thereafter, numerical models of CCB-2~ CCB-6 were built in the same way while different central angles of 5°, 10°, 15°, 20°, 30° were introduced, and the details were given in **Table 1**. Headed stud shear connectors measuring 22 mm in diameter and 130 mm in height were welded on the top flanges of the steel girders. The total number of shear connectors used was 62 for CCB-1~CCB-6.

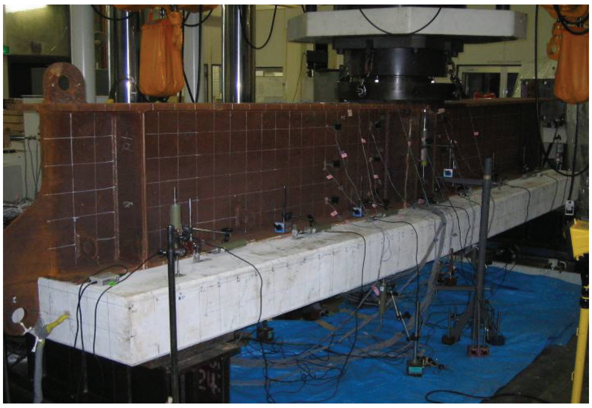


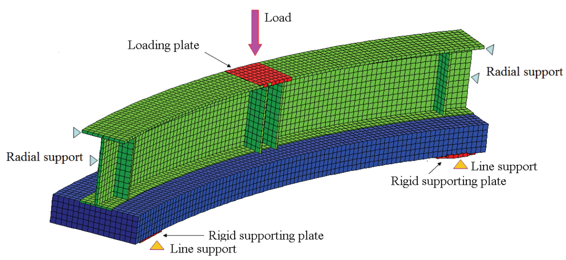
Fig.1 Test set-up of CCB-1 (0°)

Table 1 Details of curved girder models

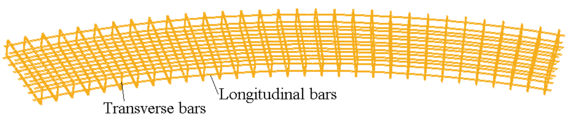
Specimen No	Central angle (°)	Span/Radius	Radius(m)
CCB-1	0	0.000	∞
CCB-2	5	0.087	45.836
CCB-3	10	0.175	22.918
CCB-4	15	0.262	15.279
CCB-5	20	0.349	11.459
CCB-6	30	0.524	7.639

3. Numetical Model Building

The modeling of the test specimen is carried out in three dimensions by using the finite-element method and the *DIANA* software. The modeling for curved composite girder models in this study is conducted in cylindrical coordinate system. Solid elements (eight nodes, with three degrees at each node) were used to simulate the concrete slab, and shell elements (four nodes, with five degrees at each node) were employed to model the steel girder. Re-bar elements (two nodes, with one degree at each node) were used for modeling the reinforcing bars in the concrete slab. Also, in order to account for the slip between concrete slab and longitudinal steel beam, interface elements (eight nodes, with three degrees at each node) were employed. The thickness of the interface element was assumed as zero in the numerical analysis. Finite element model used in this study is shown in **Fig.2**. Considering the continuity of continuous girder, radial (lateral) direction of the two end sections are restrained in order to prevent the lateral deformation at the two ends, as shown in **Fig.2** (a).[1] The material tests for concrete and steel are performed, and the generated data are employed in the finite element analysis. Interface data used in the previous numerical study is also adopted in this study[3].



(a) Curved composite steel-concrete beam model



(b) Modeling of the reinforcing bars

Fig.2 Numerical model of curved composite girder

Keyword: Curved Beam, Composite Beam, Numerical Study, Hogging Moment
Address: 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555 Japan. Tel: 03-5286-2396. E-mail: linweiwei@aoni.waseda.jp

4. Results and Discussion

4.1 Applied load-deflection response

Fig.3 illustrates the load-vertical displacement relationships for all the six curved steel-concrete composite beams (here the straight beam of CCB-1 is treated as the special case of curved beam) measured at the mid-span of each numerical girder model. The results indicate that the curved girder with larger central angles has smaller girder stiffness. The cracking of the concrete slab shows significant influence on the girder stiffness, and the stiffness of the girder with large curvature declines sharply after the initial cracking of the concrete. Thereafter, the girder deflection keeps increasing until the girder yielding, and the corresponding vertical displacements seem similar to each other. The applied load is found to decrease for all cases when the vertical displacement increases to some extent.

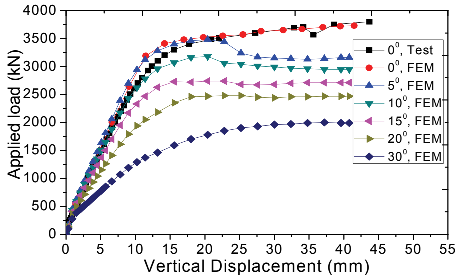


Fig.3 Load-deflection relationship

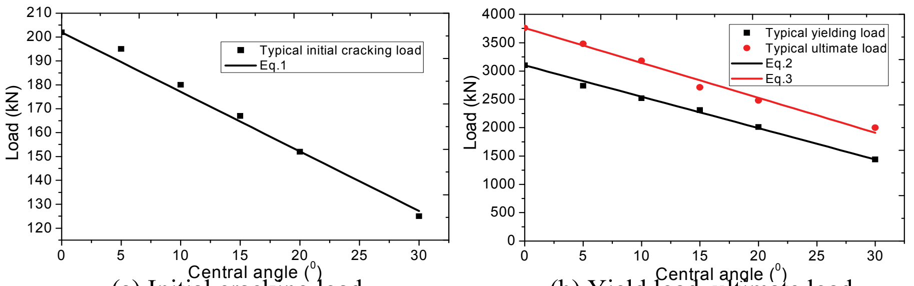
The initial cracking loads, girder yielding loads and ultimate loads of the curved composite girder with typical curvatures are illustrated in the **Fig.4**. These two figures clearly indicate that the load carrying capacities of the curved composite girder show almost linear reduction with the increase of the curvatures. In order to reflect this tendency and suggest a usable prediction method in the engineering practice, reduction equations for initial cracking load, girder yielding load, and ultimate load by using typical results of the straight composite girder are determined initially with regressive least squares algorithm. Finally, the reduction equations are proposed and given in **Eq.1**, **Eq.2** and **Eq.3** as shown below:

$$P_{c,\alpha} = P_c\,(1-\alpha/81) \quad (0°\le\alpha\le30°) \qquad (1)$$

$$P_{y,\alpha} = P_y\,(1-\alpha/56) \quad (0°\le\alpha\le30°) \qquad (2)$$

$$P_{u,\alpha} = P_u\,(1-\alpha/61) \quad (0°\le\alpha\le30°) \qquad (3)$$

where α is the central angle of the curved steel-concrete composite beam, and P_c, P_y, P_u are the initial cracking load, girder yielding load and ultimate load of the straight composite girder, respectively.

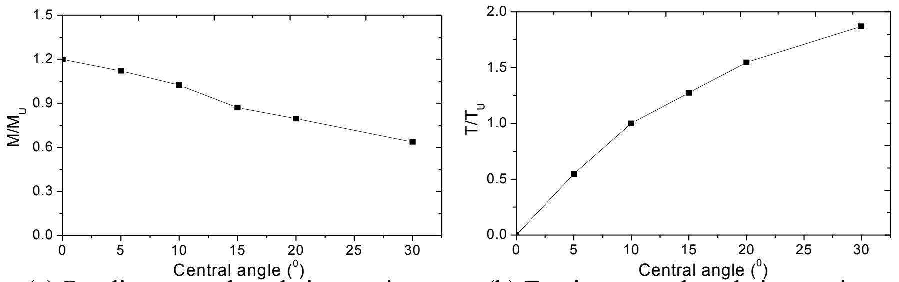


(a) Initial cracking load (b) Yield load, ultimate load

Fig.4 Initial cracking load, Yield load, and Ultimate load- central angle relationships

4.3 Bending-Torsion Interaction

Based on the numerical results, **Fig.5** denotes how the ultimate bending moment and torsion moment change as a function of central angles in curved composite girders. These two figures seem to indicate that, for the curved steel-concrete composite girders, the ultimate bending moment decreases linearly with the central angle increases, and the ultimate torsion moment increases in parabolic pattern with the increment of girder curvature.



(a) Bending-central angle interaction (b) Torsion-central angle interaction

Fig.5 Bending-central angle and Torsion-central angle interaction diagrams

As for the calculation of ultimate torsion moment, there is no standard methods to predict, thus the T/T_U in the present models seems a little bit large, which might be because the ultimate design torsion moment was taken as a very conservative value in this study. In addition, it is to be noted that the present study is only limited to the special loading condition and parameter of central angles, then further study on this aspect is necessary. And finally, referring to the numerical results, the bending-torsion interaction equation based on the numerical results of the present curved composite girder models can be written as follows:

$$\frac{T}{T_u} = -3.71\left(\frac{M}{M_u} - 0.5\right)^2 + 1.91 \qquad (0°\le\alpha\le30°) \qquad (4)$$

5. Conclusions

On the basis of the numerical and experimental results, the initial cracking load, the girder yielding load and the ultimate load of curved composite girders under negative moment decrease linearly as the curvature increases (0≤α≤30°); the reduction equation by using the load carrying capacities of the corresponding straight steel-concrete composite girders are proposed for the curved composite girders under the hogging bending moment. In addition, the simplified hogging bending–torsion interaction equation is proposed to illustrate the bending-torsion interaction relationship for curved steel-concrete composite beams under hogging moment.

6. References

1. Lin, W., Yoda, T., Taniguchi, N., Kasano, H., and He, J. (2013). "Mechanical Performance of Steel-Concrete Composite Beams Subjected to Hogging Moment" Journal of Structural Engineering, ASCE. 140(1), 04013031.
2. Lin, W., Yoda, T., and Taniguchi, N. (2013). "Fatigue Tests on Straight Steel-Concrete Composite Beams Subjected to Hogging Moment." Journal of Constructional Steel Research, Vol. 80. pp. 42-56.
3. Lin, W. and Yoda, T. (2013). "Experimental and Numerical Study on Mechanical Behavior of Composite Girders under Hogging Moment. International Journal of Advanced Steel Construction. Vol. 9, No. 4, pp. 309-333.