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Moment redistribution of continuous composite I-girders with high strength steel

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ABSTRACT

The continuous composite I-girder bridge should have a sufficient rotational capacity to ensure ductile behavior of the girder and to redistribute the negative bending moment into an adjacent positive bending moment region. However, it is generally known that the ductility of the high strength steel is smaller than that of conventional steel, and application of high strength steel can cause ductility problems in a negative moment region of composite I-girder. In this study, moment redistribution of the continuous composite I-girder with high strength steel was studied through a theoretical and experimental study, where high strength steel with yield and ultimate stress of 690 MPa and 800 MPa, respectively, were considered. The required and available rotation capacity of the continuous composite I-girder with high strength steel was firstly derived based on the plastic analysis and stress-strain curve of high strength steel. A large scale test of the continuous composite I-girder with high strength steel was then conducted to examine the effectiveness of proposed models and to investigate the effect of composite action on the rotational capacity of the negative moment region.

1. INTRODUCTION

The high strength steel has been widely applied to a negative moment region of continuous composite I-girder bridges, and compressive flanges of the girder, as well (Felkel *et al.* 2007). The continuous composite I-girder bridge should have a sufficient rotation capacity to ensure ductile behavior of the girder and to redistribute the negative

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bending moment into an adjacent positive bending moment region, where rotation capacity indicates the inelastic deformation capacity to maintain the strength without significant strength deterioration. When the rotation capacity in the negative moment region is not enough, plastic design based on the moment redistribution concept cannot be applied, and this leads to conservative design of the girder.

Rotation capacity in the negative moment region of an I-girder has been studied by several researchers. Lay & Galambos (1967) proposed an equation to estimate the rotation capacity of beams under moment gradient, considering lateral-torsional buckling and local buckling of the flange and webs. Kemp & Dekker (1991) also suggested an equation to predict the rotation capacity of a I-girder in the negative moment region. Chen & Jia (2008) suggested a method to evaluate the required and moment redistribution of two span continuous composite I-girders. As a result of previous researchers, AASHTO LRFD Appendix B6 (2007) provides an alternative plastic design method for the continuous composite I-girder, considering the moment redistribution concept. However, AASHTO LRFD Appendix B6 (2007) specifies the yield stress limit of 485 MPa to apply this design concept. Further, several researcher pointed out that application of high strength steel could cause ductility problems for I-girder bridges (Felkel *et al.* 2007, Barth *et al.* 2000, Earls *et al.* 2002, Joo *el al.* 2013). Recently, the yield stress of the steel has been increasing dramatically. In South Korea, high strength structural steel named HSB 800 was developed, where yield and ultimate stress of 690 MPa and 800 MPa, respectively.

In this study, moment redistribution of the continuous composite I-girder with high strength steel (HSB 800) was studied through a theoretical and experimental study. The required and available rotation capacity of the continuous girder with high strength steel proposed based on the plastic analysis and stress-strain curve of high strength steel. A large scale test for the continuous composite I-girder with high strength steel was then conducted to examine the effectiveness of proposed models and to investigate the effect of composite action on the rotation capacity of the negative moment region.

2. BACKGROUND THEORY

2.1 Required rotation capacity in negative moment region

In negative moment region of continuous composite I-girder, concrete slab section is subjected to tension. Thus, it is assumed that the negative bending moment is sorely resisted by the steel I-girder and reinforced rebar, neglecting the tensile strength of the concrete slab. The required rotation capacity represents the inelastic deformation that is necessary to ensure full plastic action of the continuous composite I-girder. The required rotation capacity of the negative moment region of the composite I-girder depends on the many parameters such as loading cases, the span ratio of continuous I-girder, and plastic moment and stiffness ratio of positive and negative moment region. The concept of the required rotation capacity of general multi span continuous composite I-girder and numerical examples are discussed in this section.

Firstly, it is assumed that the flexural behavior of composite I-girder follows a bilinear elasto-perfectly plastic moment-curvature response shown in Fig. 1. In Fig. 1, *M* and Φ are the applied moment and curvature of the girder, respectively. Based on this concept, the maximum flexural capacity of the section is limited to plastic moment of the section M_p. Figure 2 (a) and (b) shows the multi span continuous composite girder under arbitrary load, and equivalent single span composite girder, respectively.

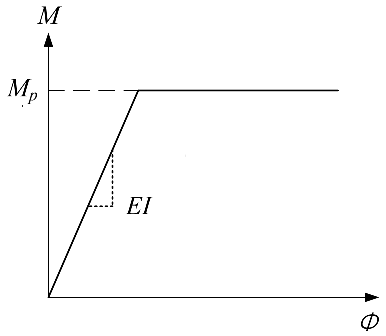


Fig. 1 Simply plasticity model

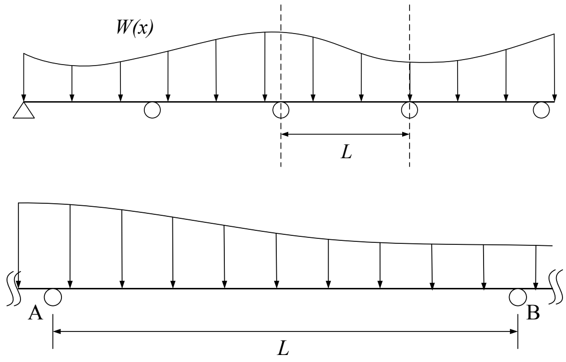


Fig. 2 Multi span continuous composite girder and equivalent single span.

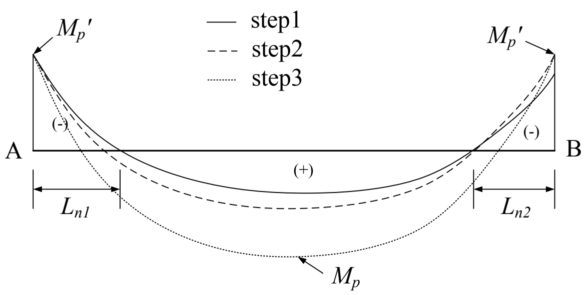


Fig. 3 Moment diagram of Equivalent single span.

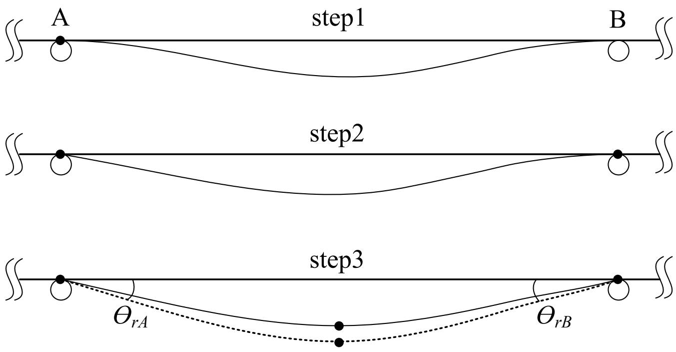


Fig. 4 Plastic hinge propagation with increasing the applied moment.

Let's assume that the negative bending moment is applied at point *A*, and the bending moment at point *A* reaches to M_p' first, where M_p' represent the plastic moment of the section in negative moment region while M_p in Fig. 3 denotes the plastic moment of the positive moment region. Even if the point *A* reaches to M_p', the additional loading can be applied if the rotation capacity of the section is sufficient, since the continuous composite I-girder has several redundant. With increasing the applied loading, the point *B* may reach to M_p', while the moment in point *A* remains M_p' (Refer, step 2 in Fig. 3 and 4). Then, the load can be increased until the plastic hinge is formed at the positive bending moment region, if the rotation capacity of the point *A* and *B* are sufficient (Refer step 3 in Fig. 3 and 4). At this ultimate state (or full plastic state), the rotation at point *A* and *B* (θ_{rA} and θ_{rB}) are defined as the required rotation capacity at point *A* and *B*, respectively.

For the two span continuous composite I-girders with uniform cross section and concentrated loads shown in Fig. 5, the required rotation capacity was evaluated herein. From the Fig. 5, it can be found that the maximum negative bending moment occurs at point *C*. Thus, the first plastic hinge will be formed at point *C* with negative plastic moment M_p'. The applied load corresponding to this state can be obtained as following by neglecting the tensile strength of the concrete slab:

$$P_h = \frac{16M_p'}{3L}. \tag{1}$$

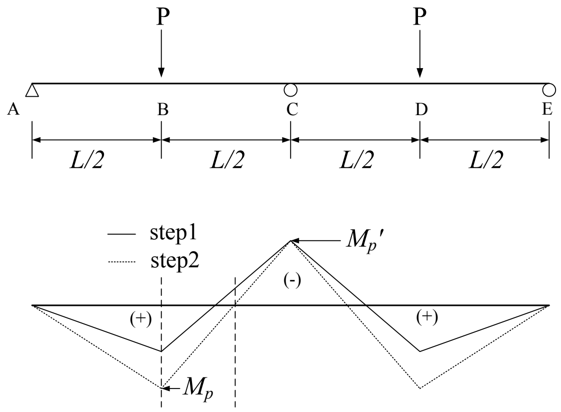


Fig. 5 Two span continuous composite girder with uniform section and concentrated loads.

If the rotational capacity of the composite I-girder in negative bending moment is not sufficient, the failure load is equal to Eq. (1), since the moment redistribution cannot be expected due to brittle behavior in negative bending moment region. On the other hand, if the rotational capacity is sufficient in negative bending moment region, the additional load can be applied to the girder until full plastic state. After forming the plastic hinge at point *C*, *AC* and *CE* span can be assumed as simply supported beam for the additional applied load ΔP. Then, the magnitude of ΔP can be obtained by assuming the Point *B* and *D* reaches to plastic moment M_p. Finally, the ultimate load P_u of the composite I-girder shown in Fig. 5 can be calculated by summing P_h in Eq (1) and ΔP. Thus, P_u is given by

$$P_u = \frac{2M_p(2+\mu)}{L}. \tag{2}$$

In Eq. (2), μ represents the plastic moment ratio, and it is defined as M_p'/M_p.

It should be noted that P_u is only possible when the rotational capacity of the composite I-girder is larger than the required rotational capacity. The required rotational capacity divides into two parts. The first one is the rotation that occurs due to ΔP (It is noted that the rotation at point *C* is equal to zero before the plastic hinge is formed at point *C*), and second part is the rotation that is generated by the plastic deformation from point *B* and *D* reach to M_p to the failure of the girder. In this study, it is assumed that the collapse of the whole girder occurs when the concrete extreme fiber strain is equal to 0.003. Figure 6 shows the curvature distribution of point *B* and *D* when the concrete extreme fiber strain is equal to 0.003. Thus, the rotation that is generated by the plastic deformation can be obtained by calculating the dashed area in Fig. 6.

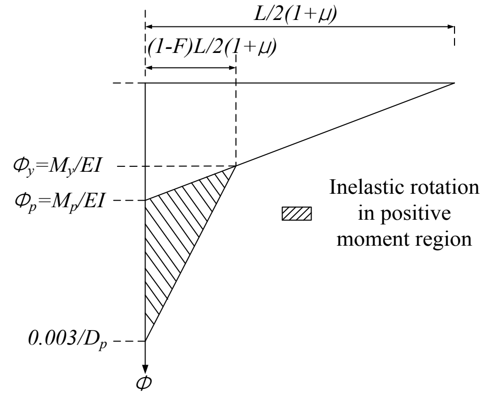


Fig. 6 Curvature distribution in positive moment region at ultimate state

Finally, the required rotation capacity θ_r can be expressed as

$$\theta_r = \frac{LM'_p(6-5\mu)}{16\mu EI} + \left(\frac{0.003}{D_p} - \frac{M_p}{EI}\right)\frac{(1-F)L}{4(1+\mu)} \tag{3}$$

In Eq. (3), the first term and second term represents the the rotation that occurs due to ΔP and by the plastic deformation from point *B* and *D* reach to M_p to the failure of the girder, respectively.

2.2 Available rotation capacity in negative moment region

As mentioned before, the rotational capacity of the section should be larger than the required rotation capacity to ensure ductile behavior, and the rotation capacity of the section is quantified as the available rotation capacity. Figure 7 shows the typical applied moment-rotation relationship of the composite I-girder, where θ_p and θ_u are the rotations of the girder corresponding to M_p (where θ_u is larger than θ_p), and M_m is the maximum moment of the girder. Then, the available rotation capacity θ_a is defined as θ_u - θ_p.

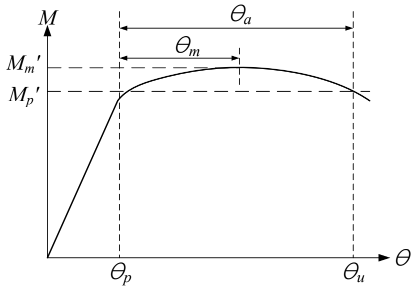


Fig. 7 Typical M-θ relationship.

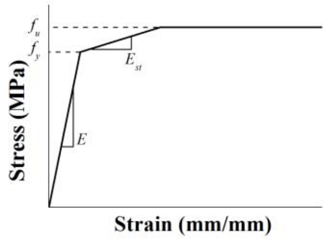


Fig. 8 Typical stress-strain curve for high strength steel.

Joo *et al*. (2013) proposed an equation to estimate the available rotation capacity of the I-girder with high strength steel in the negative moment region, based on a material property of high strength steel shown in Fig. 8. In this study, their approach was adopted to estimate the θ_a of the continuous composite I-girder with high strength steel.

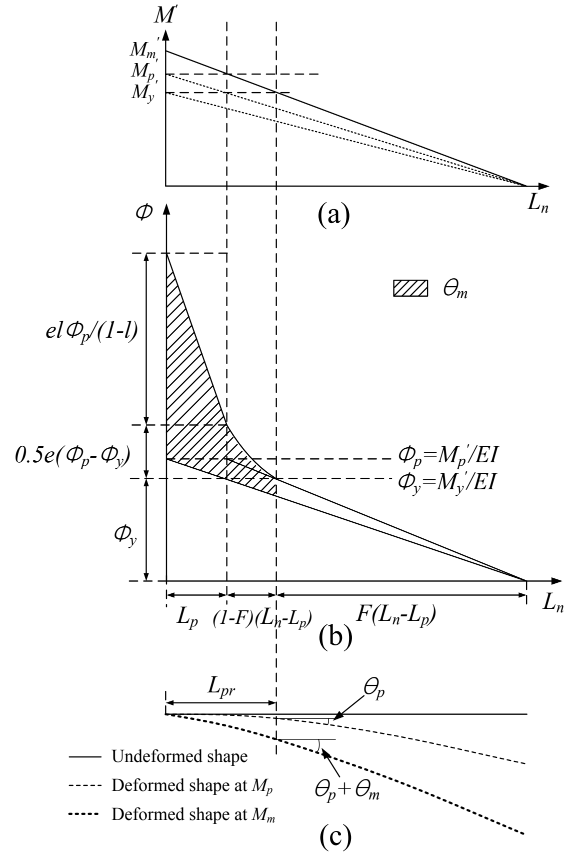


Fig. 9 Bending moment, curvature, and deformed shape in negative bending moment region: (a) moment diagram, (b) curvature distribution, and (c) deformed shapes.

Figures 9 (a), (b) and (C) show the bending moment diagram, curvature distribution and deformed shape in negative bending moment region, respectively. In Fig. 9, L_n is the length of the negative moment region, L_{pr} is the yield length (It is the distance from the internal support to the extreme fiber that is yielded), L_p is the plastic length (It is the distance from the internal support to the point of the cross-section that is fully yielded), and θ_p is the rotation corresponding to elastic limit. θ_m (the rotation corresponding to M_m, Refer Fig. (7)) can be simply obtained the calculating the shade area in Fig. 9 (b), and it is given by

$$\theta_m = \frac{M_p L}{4(1-l)EI}\left[(e-2)(1-F)^2 + 2\left(F(e-eF-2+F)+1\right)l + \left(e+F^2(e+2)\right)l^2 + 2F^2 l^3\right]. \tag{4}$$

In Eq. (4), EI is the flexural stiffness of negative moment region, e is defined as E/E_{st}, where E_{st} is the strain hardening modulus, F is M_y/M_p (where M_y is the yielding moment of the girder), m is defined as M_m/M_p, and l is equal to L_p/L. l is equal to 1-1/m from the geometric relation. The plastic length L_p must first be determined to use Eq. (4). In this study, L_p proposed by Kemp & Dekker (1991) was used.

Usually, θ_a is assumed as twice of θ_m. However, Joo *et al.* (2013) reported that this relationship is not proper for I-girder with high strength steel. They suggested the relationship between θ_m and θ_a based on the results of extensive parametric study, and their result was adopted to calculate θ_a. The relationship between θ_m and θ_a proposed by Joo *et al.* (2013) is given by

$$\theta_a = 1.8809\,\theta_m - 0.0044\ . \tag{5}$$

Finally, Based on the Eqs. (4) and (5), θ_a for the continuous composite I-girder with high strength steel can be obtained.

3. EXPERIMENTAL STUDY

3.1 Test specimen and setup

An experimental study was conducted to examine the validation of the proposed equations for required and available rotation capacity of the continuous composite I-girder with high strength steel. Two span continuous composite I-girder with high strength steel was constructed for the test, as shown in Fig. 10.

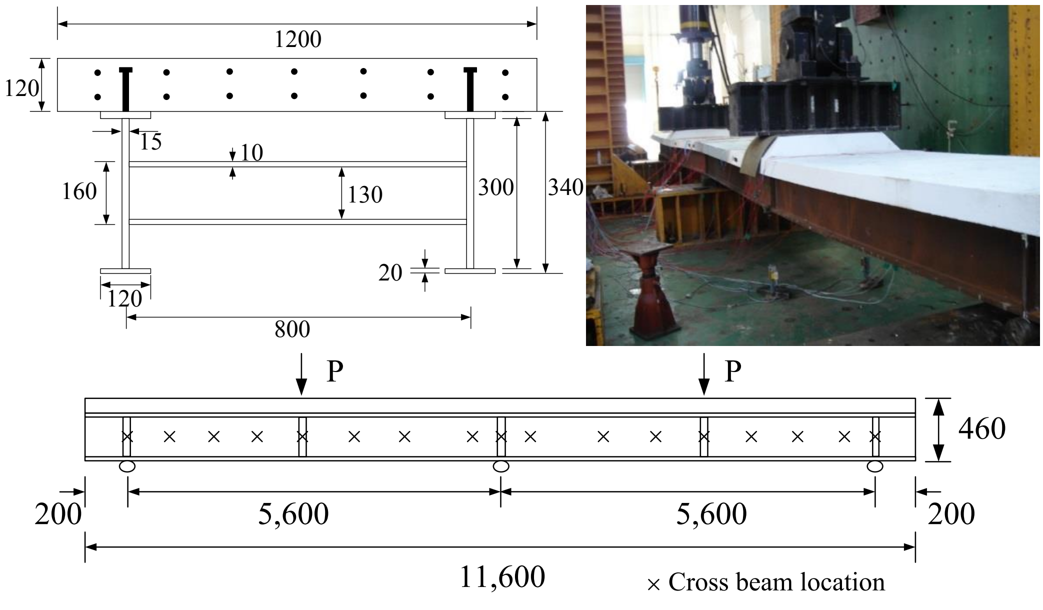


Fig. 10 Schematic view of test setup and dimensions of test specimen.

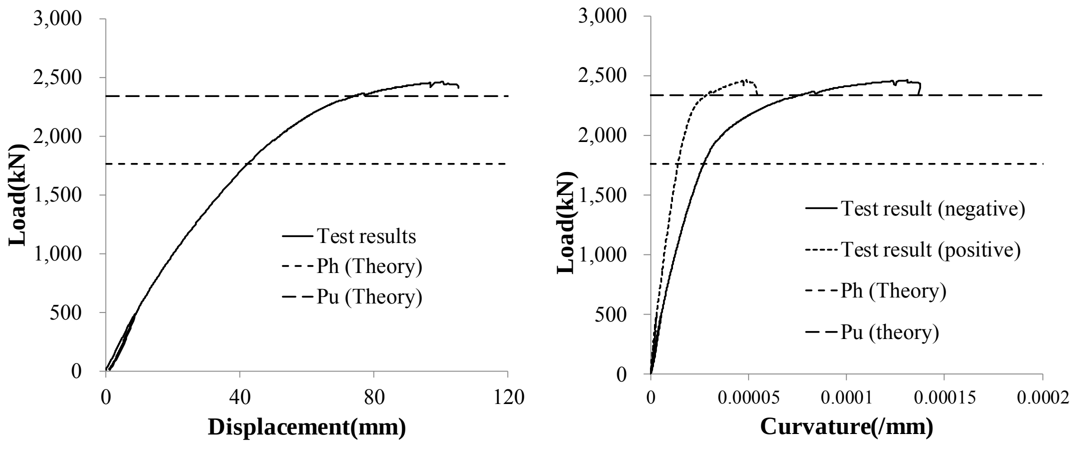
The length of the girder was 11,600 mm, the depth of steel I-girder d was 340 mm, the thickness of the web t_w was 15 mm, the width of the flange b_f was 120 mm, and the thickness of the flange t_f was 20 mm. The specimen was fabricated from HSB800 steel.

From the material test, the yield and ultimate stress of flange were 823.1 MPa and 920.8 MPa, respectively, and the yield and ultimate stress of web were 725.3 MPa and 867.3 MPa, respectively. The two main I-girders were connected by cross beams, and the distance from the center to center of the two main I-girders was 800 mm. In the case of the cross beam, the thickness of the web and flange were both 10 mm. The depth of concrete slab was 120 mm, and the width of concrete slab was 1,200 mm. The compressive strength of concrete slab was 32 MPa from the material test. Concentrated loads were applied at the 1/4 and 3/4 of the span as shown in Fig. 9. The area and yield stress of the reinforcing bar were 549.8 mm^2 and 400 MPa, respectively.

From the proposed equations in section 2, positive plastic moment M_p and negative plastic moment M_p' were 1174.2 kN·m and 926.3 kN·m, respectively. The required and available rotation capacity θ_r and θ_a were 0.01576 and 0.01994 rad, respectively. Thus, full plastic action was expected for the test specimen, since θ_a was larger than θ_r.

3.2 Test results and comparisons

Figures 11(a) and (b) show the comparison of the applied load-displacement relationship and the applied load-curvature relationship, respectively. The displacement shown in *x* axis in Fig. 11(a) was obtained by averaging the displacement at 1/4 and 3/4 of the span. P_h and P_u shown in Figs. 10(a) and (b) were obtained from the proposed equation shown in section 2. From the test results, the discrepancy of P_u between the proposed equations and test was approximately 5.24 %, and test results agree well with the proposed equation. From the Fig. 11(b), it can be found that the stiffness of the applied load-curvature curve in negative bending moment region (Solid line in Fig. 11(b)) was considerably reduced after passing P_h, while the stiffness of the applied load-curvature curve in positive bending moment region significantly reduced near P_u. This imply that the plastic hinge formed near P_h in negative bending moment region, and the failure occurred by formation of the plastic hinge in positive bending moment region, as expected.



(a) (b)

Fig. 11 Comparison of test results with proposed equation: (a) applied load vs. displacement, and (b) applied load vs. curvature.

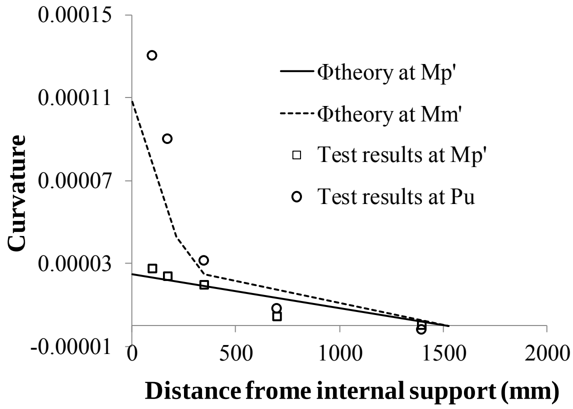


Fig. 12 Comparison of curvature distribution.

The curvature of the test specimen was calculated from the strain data, and the results were compared with the theoretical curvature distribution shown in section 2, as shown in Fig. 12. From the comparison results, it can be seen that the theoretical curvature distribution proposed in this study agree well with test results, and it is suitable to estimate the curvature of the continuous composite I-girder with high strength steel.

4. CONCLUSIONS

This study investigated moment redistribution of the continuous girder with high strength steel through a theoretical and experimental study. The concept of the required rotation capacity of the continuous composite I-girder was discussed, and the required rotational capacity and ultimate load capacity of the two span continuous composite I-girder under concentrated loads were proposed. Further, the available rotational capacity of the continuous composite I-girder with high strength steel was suggested based on the curvature distribution of the section. A large scale test was conducted to examine the validation of the proposed equations. From the test results, it was found that the ultimate load capacity and curvature distribution of the test specimens agrees well with the proposed equations.

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