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Elasto-plastic impact response analysis of RC beams flexurally strengthened with externally bonded FRP sheet

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Abstract

FRP sheet bonding methods have been proposed for upgrading the impact-resistant capacities y of the RC beams and the applicability was experimentally investigated. However, to establish a rational strengthening method for RC beams, not only experimental but also numerical studies should be considered. From this point of view, in order to establish a numerical analysis method for appropriately evaluating the impact-resistant behaviours of the beams flexurally strengthened with FRP sheet, 3D elasto-plastic impact response analysis for the beams under impact loading was conducted varying constitutive model for concrete: the Karagozian & Case Concrete model (KCC); the Continuous Surface Cap model (CSC); and a proposed model by the authors. The applicability of these models was investigated comparing with the experimental results. The results obtained from this study are as follows: 1) the mid-span deflection of unstrengthened RC beams can be properly predicted applying either model; 2) the deflection for the RC beams strengthened with FRP sheet can be appropriately simulated by applying the proposed model; and 3) crack patterns of the RC beams can be more appropriately evaluated by applying the proposed model.

Keywords: FRP sheet, RC beam, impact response analysis, FEM, constitutive model of concrete, flexural strengthening

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Introduction

In Japan, many reinforced concrete (RC) galleries have been constructed over the highways to protect the transportation networks from falling rocks. However, impact energy of the rocks tends to be increased due to aged deterioration of the slopes along the roads and recent unusual weather. Therefore, it is necessary to upgrade the impact-resistant capacities of the structures. Fibre reinforced polymer (FRP) sheet bonding method may have a potential to resolve this issue. The authors have experimentally investigated the applicability of this method by conducting drop-weight impact loading tests of the RC beams. However, to establish a rational method, not only experimental but also numerical studies may be considered.

From this point of view, in order to establish a numerical analysis method for appropriately evaluating the impact-resistant behaviours of the RC beams flexurally strengthened with FRP sheet, 3D elasto-plastic impact response analysis for the RC beams under impact loading was conducted varying constitutive models for concrete: Karagozian & Case Concrete model (KCC) [1]; Continuous Surface Cap model (CSC) [2]; and a proposed model[3] by the authors. The applicability of these models was investigated comparing with the experimental results. Here, the LS-DYNA code was used for these numerical analyses.

Experimental Overview

The RC beams used in this study have a rectangular cross section of 250 × 200 mm (height × width) and a clear-span length of 3.0 m. Aramid FRP (AFRP) sheet was bonded to the tension side-surface of the beams leaving 50 mm between the supporting point and the end of the sheet. Mass per unit, elastic modulus, and ultimate elongation of AFRP sheet are 830 g/m^2, 118 GPa, and 1.75 %, respectively, in which these values were nominal ones. Two deformed rebars with φ = 19 mm diameter were placed in the upper and lower fibres, respectively, and were welded to the steel plates of t = 9 mm thickness at the ends of the beam to save the anchor length. Stirrups of φ = 10 mm diameter were arranged every 100 mm.

Drop-weight impact test was conducted by dropping the weight from a prescribed height H = 2.5 m onto the mid-span of the beam using the impact test apparatus. The weight was made of a solid steel cylinder with installed a load cell and mass of the drop weight was 300 kg. The beams were placed on the supports equipped with load cells for measuring the reaction forces and were tightened at the ends using steel cross beams to prevent lifting off. The supporting jigs were able to rotate freely while restrain horizontal movement of the beam. Here, time histories of the impact force, the reaction force, and the mid-span deflection were measured. After each test, the residual deflection was measured and crack patterns observed on the side-surface of the beam were sketched.

Overview of Numerical Analysis

One quarter of each RC beam was three-dimensionally modelled considering biaxial symmetry with respect to the mid-span cross section and the central surface in the width direction of the beam. Figure 1 shows the mesh geometry of the beam strengthened with AFRP sheet as one example. In this model, concrete, axial rebar, and the AFRP sheet were divided using eight node solid elements and stirrup was divided using beam elements. AFRP sheet, axial rebar, and stirrup were assumed to be perfectly bonded to concrete in this analysis. Element length of the concrete in the axial direction is assumed to be 25 mm long basically. The drop weight was also precisely divided using solid elements following the actual shape.

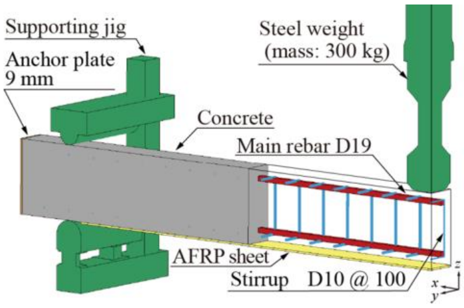
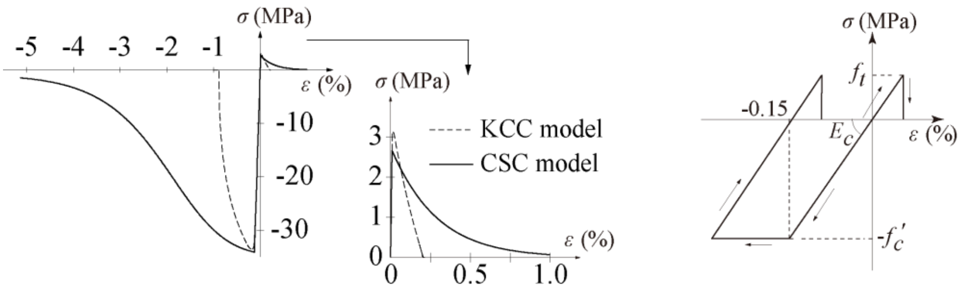


Figure 1: FE model



(a) KCC and CSC model

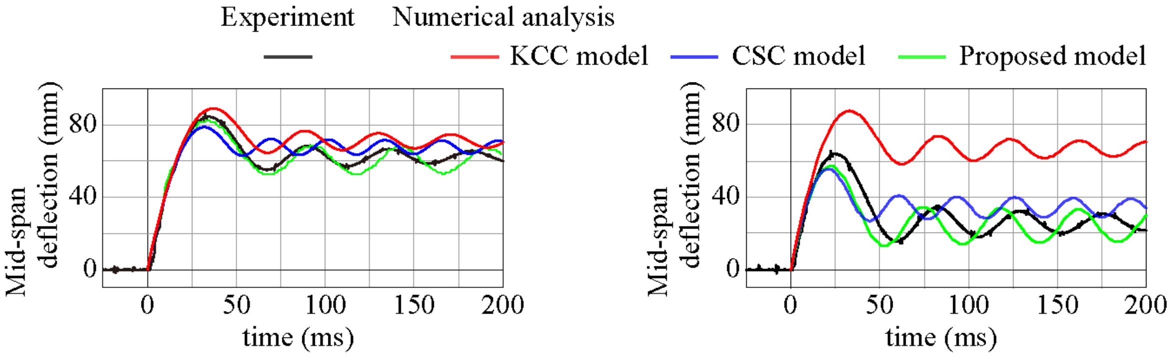
(b) Proposed model

Figure 2: constitutive models for concrete

Many concrete models have been installed into the LS-DYNA code, for example, KCC model [1] and CSC model [2]. However, the applicability of these models to numerical analysis for RC beams strengthened with FRP material under impact loading has not been sufficiently investigated yet. In this study, the authors investigated the applicability of KCC, CSC, and a proposed model [3]. These stress-strain relationships are shown in Fig. 2. Even though KCC and CSC models have functions of tension and compression softening, the softening gradients are different between two models as shown in Fig. 2(a). However, the proposed model shown in Fig. 2(b) is assumed that, in the compression region: (1) yield stress was equal to the compressive strength f'_c; (2) yield strain was set as 1500 μ strains; (3) yielding of concrete follows the Drucker-Prager's yield criterion; in the tension region, (4) tensile stress was cut off after reaching tensile strength of concrete; and (5) a fictitious tensile strength was introduced based on the G_f concept [3]. The tensile strength was evaluated using negative pressure. Compressive strength f'_c of concrete was 33.7 MPa, which is obtained from the material test at commencement of the experiment.

Comparison of Numerical and Experimental Results

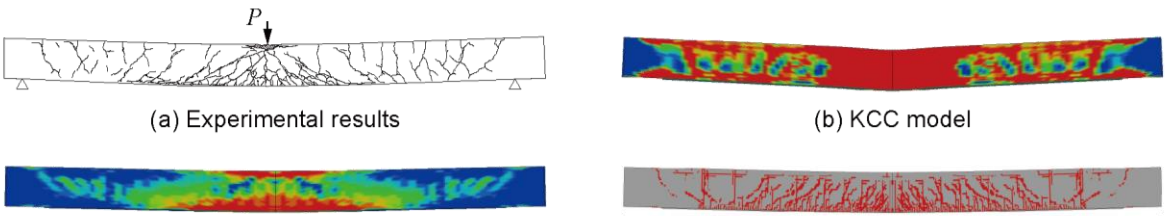
Figure 3 shows comparisons of the time histories of the mid-span deflection in the cases of unstrengthened and strengthened RC beams between experimental and numerical results in which three constitutive models for concrete are considered. From this figure, it is observed that in the case of unstrengthened RC beam, the mid-span deflection can be properly evaluated applying either model. On the other hand, in the case of strengthened RC beam with AFRP sheet, the deflection can be adequately simulated for the experimental results by applying the proposed model here. Figure 4 shows comparisons of the crack patterns on the side-surface of the strengthened RC beam between experimental and



(a) unstrengthened RC beam

(b) Strengthened RC beam

Figure 3: Mid-span deflection of unstrengthened and strengthened RC beams



(a) Experimental results

(b) KCC model

(c) CSC model

(d) Proposed model

Figure 4: Crack patterns for strengthened RC beams on side-surface

numerical results obtained from three constitutive models. From these figures, it is seen that crack patterns including flexural and diagonal ones obtained from the numerical analysis applying the proposed model were good agreement with the experimental results. This implies that the strengthening effects of the AFRP sheet on impact-resistant capacities of the RC beams can be properly evaluated by applying the proposed model.

CONCLUSIONS

1) In the case of unstrengthened RC beams, the mid-span deflection can be properly predicted applying each constitute model: KCC; CSC; and proposed model;
2) in the case of the RC beams strengthened with AFRP sheet, the deflection can be appropriately simulated by applying the proposed model; and
3) the crack patterns of the RC beams can be more appropriately evaluated by applying the proposed model than the other KCC and CSC models.

Reference

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