ANALYTICAL STUDY ON SEISMIC RETROFITTING METHOD USING CFRP SHEETS FOR STEEL BEAM WITH VARIABLE CROSS-SECTION

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1. INTRODUCTION

For steel structural members such as steel bridge piers and rigid-frame piers, the structural type, wherein cross-sectional dimensions are abruptly changed in the stepped form to minimize the required material and weight, has been widely used. However, under the repeated forces of an earthquake, it is feared that the sufficient seismic-resistant performance of structures cannot be promoted because the cross-sectional change region becomes the starting point for plastic deformation or local buckling. Particularly, in the 1995 Japan–Kobe Earthquake with approximately 6,300 fatalities and more than 150,000 damaged structures and facilities, numerous cases of severe damages of steel bridge piers and rigid-frame bridges were found to originate from the variable cross-sectional regions. Therefore, finding a simple and effective seismic retrofitting method for steel structural members with variable cross-sections to improve their plastic deformation performance is currently an urgent concern. This study is aimed to validate the cyclic loading test results and observed failure behavior of H-section steel beams with an abruptly variable cross-section, retrofitted by a carbon-fiber-reinforced plastic (CFRP) sheet, through nonlinear finite element (FE) analyses.

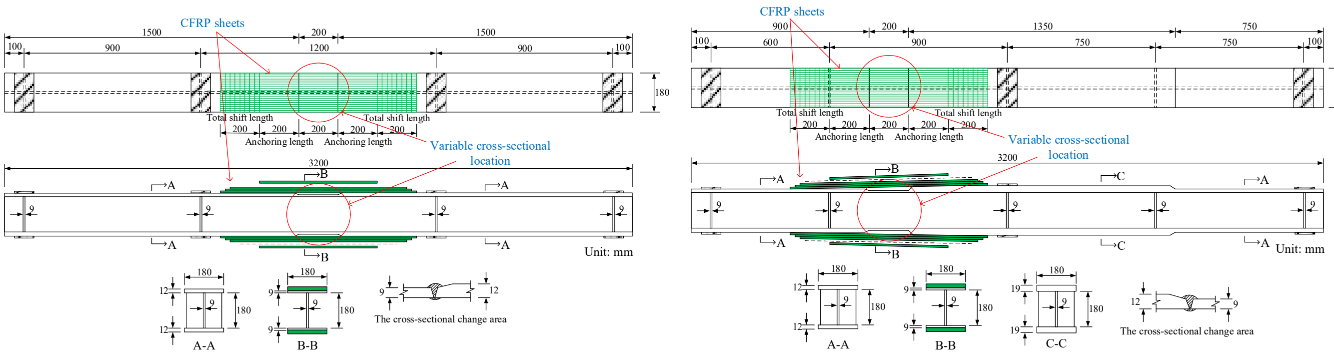
2. FINITE ELEMENT ANALYSIS

2.1 Specimen shape

The dimensional details of the specimens used in the four-point-bending and three-point-bending-shear cyclic loading tests are illustrated in **Fig. 1**. The variable cross-sections were considered to be located on the flanges of the specimens. To avoid the occurrence of local buckling under the elastic stage of the material in the variable cross-sectional areas, the dimensions of these areas were designed with length = 200 mm, width = 180 mm, and thickness = 9 mm. Further, the width–thickness ratio parameter (R) of the variable cross-sectional areas is R = 0.57. The specimens including the four beams with and without the CFRP sheets for bending and bending-shear tests are listed in **Table 1**.

2.2 Analysis model

Fig. 2 shows the mesh shape of the FE analytical model of steel beam bonded to CFRP sheets. In this study, the webs and stiffeners of steel beams were constructed using an eight-node quadrilateral curved shell element (CQ40S). The flanges with the variable cross-sections were modeled using a twenty-node solid brick element (CHX60) with a geometrical shape similar to the actual shapes on the specimens. To reproduce the actual bonding and peeling behaviors of the polyurea putty layer inserted between CFRP sheets and steel beam, this study simulated this putty layer using an eight-node quadrilateral structural interface element (CQ48I). The adhesion layers, which were used to connect the CFRP sheets, were modeled using the solid brick element (CHX60). The CFRP sheets were constructed using the curved shell element (CQ40S).



(a) Retrofitted specimens with bending tests (b) Retrofitted specimens with bending-shear tests

Fig. 1. Specimen shape.

Table 1. Specimen test cases.

Types of loading test	Specimen	Retrofitting method
Bending test	M1	–
	M2	Intermediate-modulus CFRP sheets and polyurea putty
Bending-shear test	MS1	–
	MS2	Intermediate-modulus CFRP sheets and polyurea putty

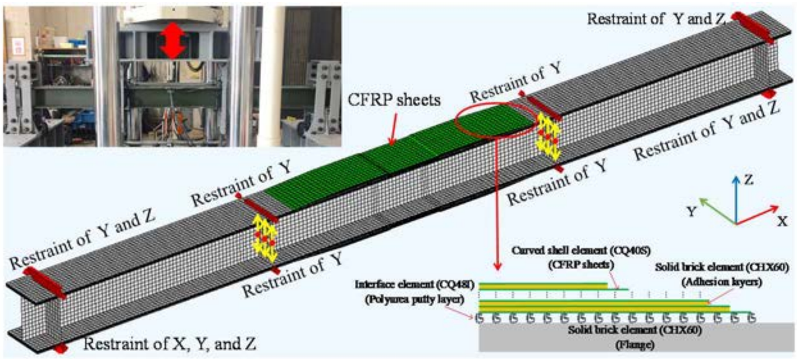


Fig. 2. FE analytical model of H-section steel beam with CFRP sheets.

Keywords: H-section steel beams, Seismic retrofitting method, Cyclic loading tests, CFRP sheets, nonlinear FE analyses
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This study considered the actual cyclic plasticity properties of steel with a modified two-surface model[1)] in the FE analyses. The CFRP sheets were considered as an anisotropic material in the analytical models, with Young's modulus of 4.27×10^5 MPa for the main working direction, and Young's modulus of 2,646 MPa for the orthogonal directions. The material properties of the polyurea putty layer used the nonlinear bond-slip model[2)], which was tested by Pham et al. (2021) through material experiment and FE sensitivity analyses.

2.3 Results and discussion

Fig. 3 illustrates the relationship between the applied load and vertical displacement of nonretrofitted cases M1 and MS1. As shown in **Fig. 3**, with the modified two-surface model as the steel material constitutive rule, the load–displacement hysteresis curve of cases M1 and MS1 in both the analytical and loading test results were almost in agreement. It was understood that the modified two-surface model was established from the actual cyclic measurement data of steel, wherein its yield surface had a coupled translation and changes in size during the plastic deformation, and both the isotropic and kinematic hardening effects were present. The comparison of the load–displacement hysteresis curves between the analytical and loading test results in retrofitted cases M2 and MS2 is shown in **Fig. 4**. From **Fig. 4**, it was confirmed that the trend of the continuous increase in the load-carrying capacities of cases M2 and MS2 after each loading loop in the analytical results completely agreed with the behavior obtained in the loading tests. Further, **Fig. 5** compares the simulated overall deformation and residual deformation of the upper flange of steel beams after the loading test. As shown in **Fig. 5**, the plastic buckling shape of the variable cross-sectional area and the deformation performance of the entire beam in nonretrofitted cases, and no failures in the variable cross-sectional areas and the CFRP sheets of retrofitted cases agreed well with that of the loading test results.

3. CONCLUSIONS

In this study, the load-carrying capacity and failure behavior of H-section steel beams with and without CFRP sheets observed in the cyclic loading tests were accurately reproduced through FE analyses considering the actual cyclic plasticity properties of steel, anisotropic performance of CFRP sheets, and nonlinear bond-slip properties of polyurea putty layer.

REFERENCES

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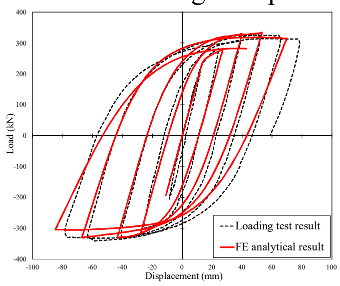
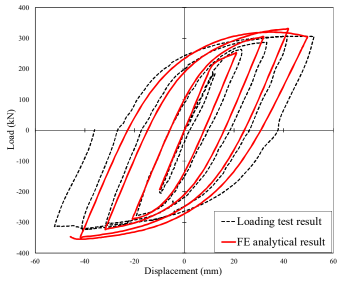
2) Pham, N. V., T. Miyashita, K. Ohgaki, Y. Hidekuma, and T. Harada. 2021. "Repair method and finite element analysis for corroded gusset plate connections bonded to CFRP sheets." *J. Struct. Eng.*, 147(1), 04020310.

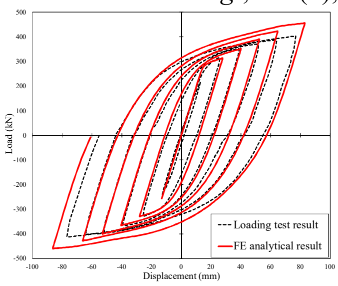


(a) Case M1

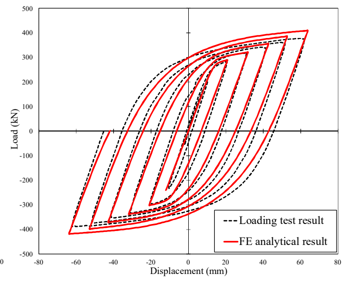


(b) Case MS1

Fig. 3. Load–displacement curves of nonretrofitted cases.



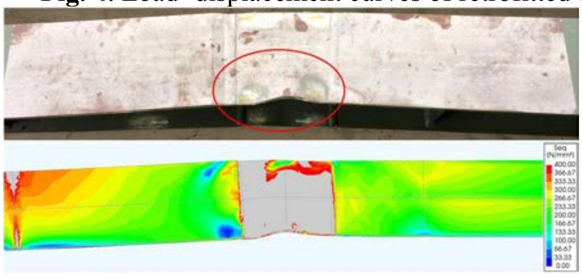
(a) Case M2



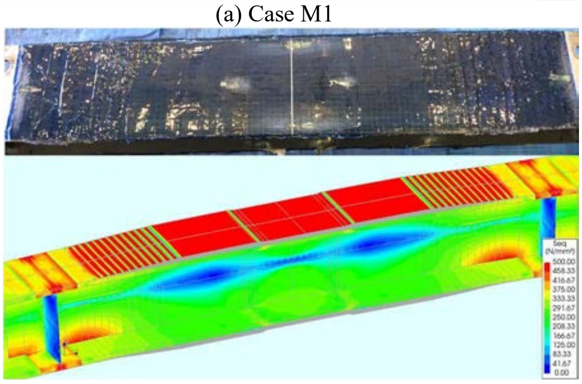
(b) Case MS2

Fig. 4. Load–displacement curves of retrofitted cases.

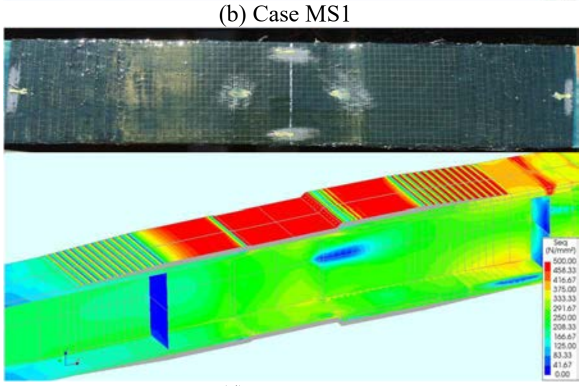
(a) Case M1



(b) Case MS1



(c) Case M2



(d) Case MS2

Fig. 5. Von Mises stress distribution contours and overall deformation of the specimens.