Seismic performance of FRP-strengthened RC joints by applying bond effects of concrete-FRP interface

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ABSTRACT

In this research, using the nonlinear finite element method, a numerical study has been performed on the seismic behavior of the deficient RC beam-column joints (with non-seismic detailing), and the seismic rehabilitation of these joints by using FRP composite laminates. At first, based on previous experimental studies, a series of RC joint specimen were considered to verification the proposed numerical model. These series of specimens include six RC interior joint specimens with non-seismic detailing and retrofitted with FRP laminates under cyclic loading. Comparison between the load-displacement curves obtained from numerical model with corresponding experimental data show that the proposed model is capable to high accurately predict the response of RC joints under cyclic loading. Then, based on the verified model, the performance of two dimensional (2-D) deficient and strengthened exterior RC joint, three dimensional (3-D) interior and exterior RC joints with considering the effect of slab and beam perpendicular to the plane of frame and also strengthening of (3-D) RC joints with focusing on the behavior of the FRP to concrete interface is evaluated. It was observed that the failure mode of the retrofitted RC exterior specimens, unlike the deficient specimens, is the formation of the plastic hinge in the beam section. In addition, it is seen that the slab and the lateral beam have a significant effect on the performance of deficient joints, which can increase the resistance of the 3-D specimens by more than 20%; also, in 3D strengthened joints, the possibility debonding of FRP laminates from concrete is higher than the 2-D model.

KEYWORDS

RC beam-column joints, Nonlinear finite element, FRP laminate, cyclic loading, bond effects FRP-Concrete interface

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1. Introduction

Although the buildings designed according to the current seismic codes have the necessary details to withstand energy imposed on the structure by earthquake ground motion, but existing reinforced concrete (RC) structures designed and built according to the old regulations do not have the necessary seismic detailing. Accordingly, in recent years, to deal with possible future risks, various researches have been conducted to increase the performance level of existing RC structures. Some of these techniques for retrofitting the beam–column joints include epoxy injection repair, steel jacketing, concrete jacketing, addition of external fiber reinforced polymeric (FRP) laminates. Due to the significant advantages of FRPs such as corrosion resistance, low thermal conductivity, lightness and high resistance to weight ratio, as well as simpler implementation steps than other improvement methods, it is used as a suitable material to improve the behavior of elements in the RC frames.

2. Methodology

In this research, according to the various limitations of experimental studies, a three-dimensional (3-D) non-linear finite element model considering the tension and compression softening of concrete material, failure modes of FRP composite sheets and debonding of concrete and FRP interfaces using ABAQUS finite element program is presented.

The concrete damaged plasticity (CDP) model has been used to simulate the nonlinear behavior of concrete including the descending branch of the stress-strain curve. This model uses of the yield function of Lubliner et. al. (1989) [1], with the modifications proposed by Lee and Fenves (1998) [2] to account for different evolution of strength under tension and compression.

To define the uniaxial compression behavior of concrete, the relationship presented by Saenz (1964) [3] is used. This constitutive equation is defined as:

$$\sigma_c = \frac{E_0 \varepsilon_c}{1 + (R + R_E - 2)\left(\frac{\varepsilon_c}{\varepsilon_0}\right) - (2R - 1)\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2 + R\left(\frac{\varepsilon_c}{\varepsilon_0}\right)^3} \quad (1)$$

In addition, a suitable and simple stiffening model proposed by Bischoff and Paixao (2004) [4] is used to simulate the tensile behavior of concrete. That is:

$$\sigma_t = f_{cr} e^{-800(\varepsilon_t - \varepsilon_{cr})} \quad (2)$$

To modeling of the steel reinforcements, the bi-linear stress-strain relationship with a combined isotropic-kinematic hardening model was assigned.

To connect the longitudinal rebars with the adjacent concrete and to define the bond-slip behavior, the connector elements with only the degree of axial freedom have been used. The relationships presented in CEB-FIB Model Code/2010 [5] were used for this purpose.

The Lamina linear elastic element is used to model FRP composites (orthotropic elasticity) in plane stress. Also, to modeling the failure of composite sheets, the Hashin criteria [6] have been used by considering four failure criteria including the tensile failure of fibers, the compressive failure of fibers, the tensile failure of the matrix and the compressive failure of the matrix.

To define debonding behavior of FRP-to-concrete interfaces, a surface-based adhesive behavior model has been used. Surface-based cohesive behavior can be used to model the delamination at interfaces directly in terms of traction versus separation.

In this study, concrete is modeled as 3-D solid continuum element with eight nodes and three degrees of freedom at each node, called C3D8R. A truss element called T3D2 was used to model steel reinforcement bars.

3. Discussion and Results

3.1. Model verification

In order to validate the finite element model presented in this paper, the data obtained from the experimental test program performed by Allam et al. [7] are used. Six interior RC beam-column joints were selected for this purpose, including two deficient specimens without seismic detailing designed based on ACI318-63 [8], one specimen designed in accordance to the current ACI318-14 code [9] and three deficient specimens retrofitted with different types of FRP composite laminates.

The results of cyclic analysis of the RC specimens modeled by the proposed numerical model were compared with the corresponding experimental results by load-displacement response diagrams. For instance, the cyclic response from the numerical analysis and the experimental test for the RS-SC specimen (specimen rehabilitated with high-strength carbon/epoxy FRP) is shown in Figure 1. As can be seen, the numerical model accurately predicts the maximum value of the specimen capacity, the corresponding displacements and the subsequent resistance deterioration in both the push and pull phases.

3.2. Parametric studies

In this section, first, the behavior of exterior beam-column joints with structural characteristics similar to interior joints without seismic details and also retrofitted

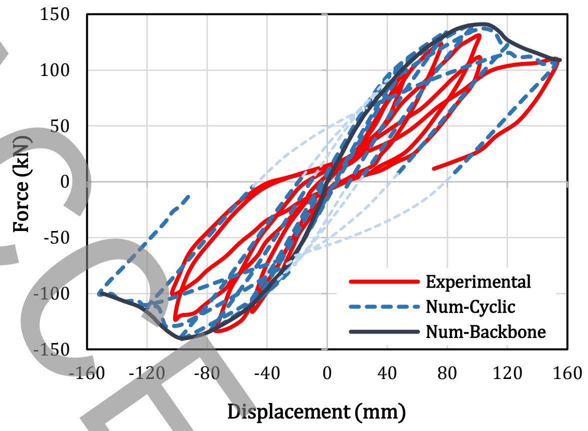

Figure 1. Comparison of the cyclic response of numerical analysis with experimental test for RS-SC specimen

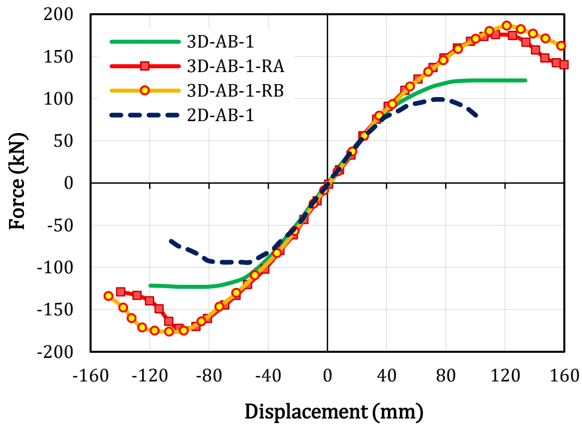

Figure 2. Comparison of the cyclic response of numerical analysis with experimental test for RS-SC specimen

with FRP sheets was evaluated. Then, according to the three-dimensional performance of the frames in the face of lateral loading, the effect of slab and orthogonal beam on the performance of diffident interior and exterior specimens was studied. Figure 2 is a column chart in which the maximum resistances of the interior joint specimens for 2-D and 3-D modeling approaches are compared. In the next section, the practical three-dimensional patterns for strengthening of deficient RC joints by FRP sheets with and without additional wrapped sheets were investigated. For instance, Figure 3 shows the backbone curve obtained from the cyclic analysis of retrofitted interior 3-D joint specimens for comparison with the response of deficient 3-D and 2-D joint specimens. As can be seen, strengthening the specimen has a significant effect on improving the performance of the interior RC joint.

4. Conclusion

Verification results showed that the proposed finite element model can accurately predict the various failure mechanisms of retrofitted RC concrete joints.

In parametric studies it was found that retrofitting 3-D joints using FRP sheets with a similar pattern of 2-D joints has a greater effect on the performance of deficient interior joints than exterior joints.

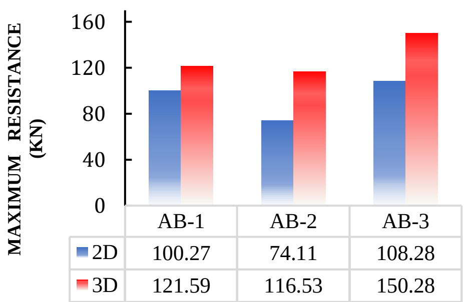

Figure 2. Comparison of maximum resistance in 2D and 3D modeling

In addition, it was seen that the possibility of debonding of FRP sheets from substrate concrete in the 3-D model is higher than the 2-D model due to one-sided connection and wrapped FRP sheet attached to the beam and column increases the bond resistance of the FRP laminates.

5. References

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