Analytical assessment of RC beam-column connections strengthened with CFRP sheets

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ABSTRACT

Past experiences from recent earthquakes indicate that shear failures of beam-column connections were one of the main reasons causing significant damages and collapses of RC structures subjected to earthquake loadings. Many researchers and engineers have conducted to propose an effective way to improve the joint shear strength of RC connections. This paper presents an analytical model for the RC exterior beam-column joints strengthened with CFRP sheets. In the analytical model, the effect of shear behavior of the RC beam-column joint, bond slip of the beam longitudinal reinforcements and CFRP sheets were considered and incorporated into the non-linear structural analysis program. Final analytical results were compared with those from the experiment of eight exterior RC beam-column specimens. The analytical results showed that the developed connection model is very useful to investigate the hysteretic joint behavior and overall load-displacement response of the RC beam-column connections strengthened with CFRP sheets.

1. INTRODUCTION

The observations from recent earthquakes shows that deficiency of seismic detail in the joint area (ex. inadequate transverse reinforcements, weak column/strong beam design, etc.) resulted in joint shear failures and non-ductile performance of reinforced concrete frames. Due to the significant contribution of the seismic performance of the RC moment frames, several techniques to improve joint shear strength have been developed and applied in beam-column joints. These techniques include the use of concrete jackets, bolted steel plates and jacketing with corrugate steel sheet. One of the effective ways is to use CFRP (carbon fiber reinforced polymer) materials. The CFRP materials have several advantages over other materials: they have high strength and stiffness to weight ratio, excellent fatigue behavior and corrosion resistance, they are lightweight and can be easily applied to concrete surfaces.

This paper proposed an analytical model of an exterior RC beam-column joint strengthened with CFRP laminates. The inelastic behaviors such as joint shear behavior, bond slip behavior of the beam longitudinal reinforcements, plastic hinge in the beam and the effect of CFRP sheets were incorporated into the non-linear structural analysis program, DRAIN-2DX(Foutch and Shi, 1997). This program is able to simulate the strength degradation, stiffness degradation and pinching effect. The analytical results then was compared with those from experiment of eight RC exterior beam-column joint specimens.

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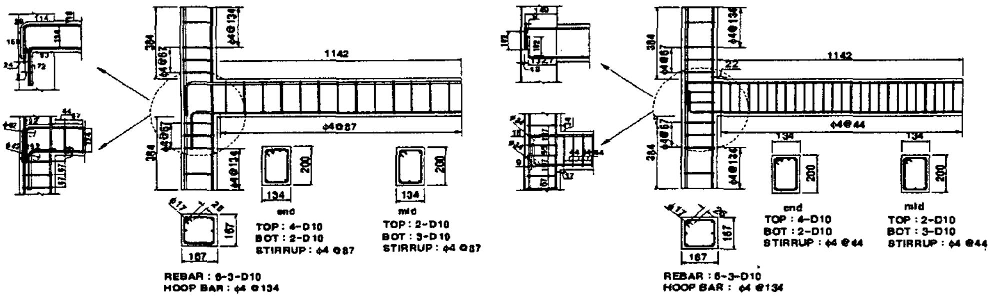
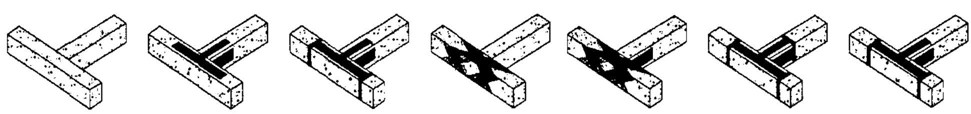


a. Non-seismic detail (NS) b. Seismic detail (SD)

Fig. 1 Details of the reinforcements of the test specimens



a. NS-01 & SD-1 b. RNS-1 c. RNS-2 d. RNS-3 e. RNS-4 f. RNS-5 g. RNS-6

Fig. 2 Description of test specimens

2. SPECIMENS FOR TEST

A total of eight 1/3-scale specimens were designed and tested. The specimen NS-01 (Fig. 1a) was designed based on the non-seismic detailing which is commonly used in Korea (without confinement reinforcement in beam-column joint region and relatively large stirrup spacings of the beam). On the other hand, the specimen SD-01 (Fig. 1b) was designed based on the seismic requirements of the ACI 318 Code (with confinement reinforcement in beam-column joint region and restively small stirrups spacing of the beam). Six remaining specimens, which have non-seismic detail of reinforcements, were developed with different ways of wrapping CFRP for the joints (using T-shape, L-shape, X-shape of CFRP sheets and strips). Fig. 2 shows graphically how the CFRP sheets were applied to the beam-column specimens. It was aimed to investigate the effective ways of using CFRP sheets to improve the shear strength of the joints. The properties of concrete, steel reinforcements and CFRP materials can be found elsewhere (Kim Min ect, 2006).

3. PROPOSED CONNECTION MODEL

The RC beam-column joints strengthened with CFRP sheets were modeled using DRAIN-2DX program (Fig. 3). Each (upper and lower) column was modeled using Element 02 to account for axial force and moment interaction. The beam was modeled using Element 02 for the elastic part. To explicitly simulate the bond slip of the longitudinal beam reinforcements and plastic hinge rotation near the end of the beam, two nonlinear rotational springs were modeled using Element 10. Fig. 4 shows the hysteretic behavior of Element 10. The input parameters for the bond slip spring was determined based on the formulation proposed by Morita and Kaku (1984). The shear behavior in the joint was modeled by three nonlinear rotational springs from Element 10. The input data for the shear behavior was calculated based on the analytical result using the modified compression field theory (MCFT) developed by Vecchio and Collins (1986). Element 10 was also used to model CFRF sheets with input parameters calculated based on the static equilibriums of the joint. The parameters

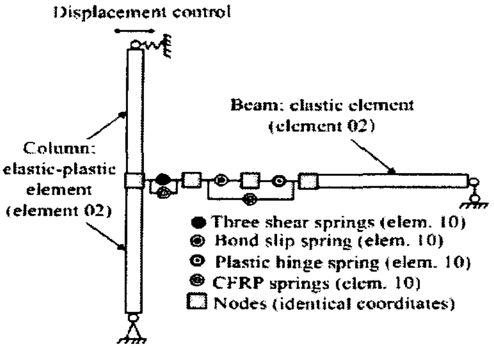


Fig 3. Specimen model

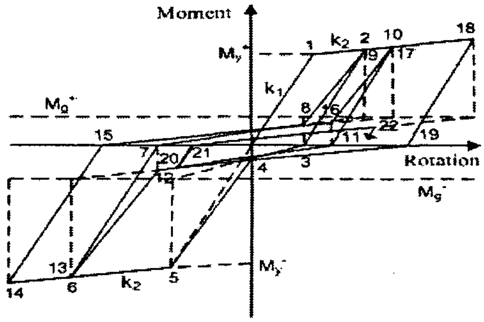


Fig 4. Element 10 developed by Foutch & Shi (1997)

were calculated based on the wrapping of CFRP sheets, orientation and location of CFRP sheets and with or without strips.

4. THE ANALYTICAL RESULT

The maximum lateral loads obtained from analysis were compared with those obtained from the experiment, as shown in Table 1. The comparison shows that the analytical models provide a good estimation for the RC joints with CFRP sheets. The highest difference in positive side was of 6.7% and in negative side was of 12%.

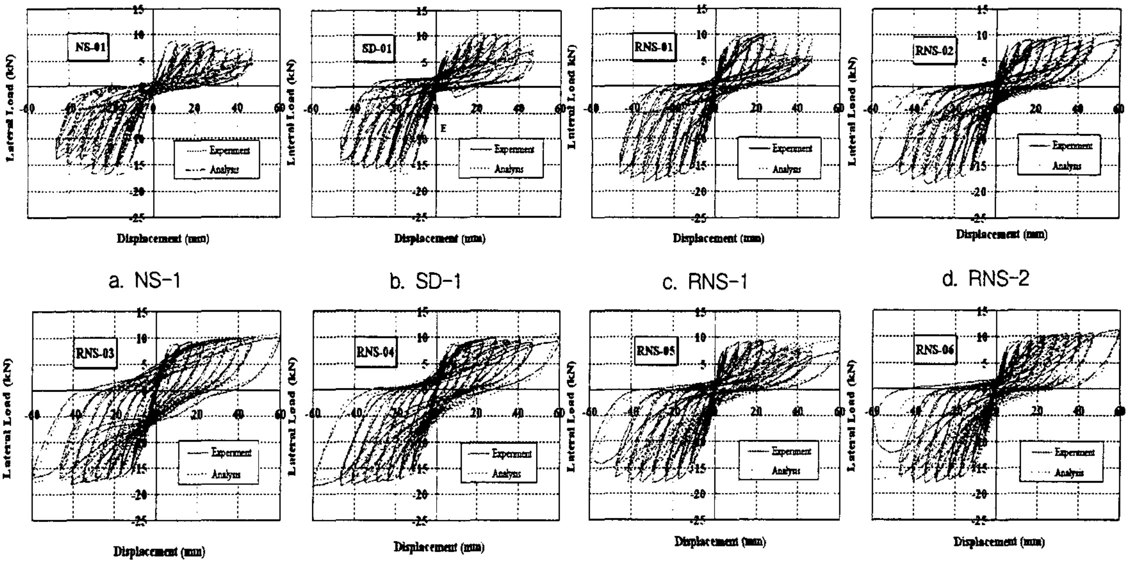
Fig. 5 presents the analytical and experimental relationships between the lateral load and displacement of specimens during the loading history. Generally, the hysteretic behavior calculated from the analytical model fairly similar to those from the experiment. Although the proposed model cannot accurately simulate the real behaviors such as the delamination of CFRP sheet and actual effect of strips, the hysteretic behaviors calculated from the analytical model are very close to the results obtained from the experiment. It is believed that the proposed analytical model would be a simple but very effective tool to evaluate the seismic performance of the CFRP-strengthened beam-column joints.

5. CONCLUSIONS

An analytical model was presented to investigate the seismic behavior of CFRP-strengthened RC exterior beam-column connections subjected cyclic loadings. The effect of joint shear, bond slip, and CFRP sheets were incorporated in the analytical model. The proposed model provides useful information on the shear capacity of CFRP-strengthened beam-column joints in terms of the quantity

Table 1. The maximum lateral loads from analytical and experimental results (kN)

Specimen		NS-01	SD-01	RNS-1	RNS-2	RNS-3	RNS-4	RNS-5	RNS-6
Positive side	Experiment	8.54	10.42	10.10	9.87	10.02	9.90	9.52	11.3
	Analysis	8.77	10.15	9.69	10.52	10.4	10.51	9.39	10.54
	Difference (%)	2.7	2.7	4.7	6.6	3.8	6.2	1.4	6.7
Negative side	Experiment	16.77	15.6	18.42	18.6	18.46	18.57	18.02	18.1
	Analysis	16.99	16.9	16.71	16.97	17.58	17.4	15.86	17.42
	Difference (%)	1.3	7.7	9.3	8.8	4.8	6.8	12	3.8



a. NS-1 b. SD-1 c. RNS-1 d. RNS-2

e. RNS-3 f. RNS-4 g. RNS-5 h. RNS-6

Fig 5. Comparison between analytical and experimental results

and configuration of the CRFP sheets. The analytical results calculated from the model indicate that even low quantities of CFRP materials may provide significant increase of the shear capacity of the joints, which is critical to achieve the good seismic performances. The predictions of the shear strength provided by the analytical models were found in good agreement with eight experimental results, thus adding confidence to the validity of the proposed model.

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