Investigation on Seismic Behavior of CFRP Retrofitted Reinforced Concrete Column with Partial Deterioration: Experimental and Numerical

Z. M. Wu, D. X. Hou, and W. Dong

***Abstract*—Due to frost damage or insufficient vibration during construction, partial deterioration of reinforced concrete (RC) columns commonly exist in practical engineering, which would weaken the seismic behaviors of the structure. The work of strength is needed for the RC columns with deterioration. Thus, in this paper, the seismic behavior of CFRP retrofitted reinforced concrete column with partial deterioration was investigated by numerical and experimental approaches. Firstly, a numerical model was proposed to analyze seismic behavior of partially deteriorated RC columns and CFRP retrofitting columns. Then, the experiment with six specimens was carried out to validate the numerical results. It is found that the proposed numerical model can be used to analysis the seismic behaviors of CFRP retrofitted reinforced concrete column with partial deterioration.**

***Index Terms*—Numerical analysis, partially deteriorated, CFRP, seismic behavior**

I. Introduction

Many factors such as freezing, and insufficient vibration during construction may deteriorate the strength of concrete. In most cases, partial deterioration is more common in practical engineering, which might weaken the seismic behaviors of the whole columns. Thus, it is necessary to strengthen these partially deteriorated RC columns. Carbon Fiber Reinforced Polymers (CFRP) sheets is widely used to retrofit RC columns in practice

Many researchers have examined the seismic behaviors of RC columns retrofitted with CFRP. For example, Colomb et al. studied the seismic behaviors of RC short columns retrofitted with CFRP sheets [1]. The research indicated that the seismic behaviors of RC columns are improved significantly. Ye et al. also studied the seismic behaviors of short column with CFRP, and proposed a method to calculate the amount of required CFRP sheets [2] . Rechart *et al.*, vstudied the seismic behaviors of CFRP retrofitted RC long columns with circular sections [3]. The results showed that the retrofitting function of CFRP is related to the axial load of column, the amount of CFRP, and the inner reinforcements.

However, most available literatures mainly focused on CFRP retrofitting RC columns with intact strength, few researches focused on the partially deteriorated RC columns. Wei et al. examined the axial and eccentric compressive behaviors of CFRP retrofitting partially deteriorated RC columns [4]-[6]. Nevertheless, Wei *et al.*, has not investigated the seismic behaviors of CFRP retrofit partially deteriorated columns.

The objective of this paper is to investigate the seismic performances of flexure-dominant partially deteriorated RC columns and try to retrofit the partially deteriorated columns with CFRP. The finite element analysis of the seismic behaviors of partially deteriorated RC columns and CFRP retrofitting specimens was carried out using software ABAQUS. The validity of finite element model was then verified by the results from laboratory tests of six specimens. There is a good agreement between experimental and numerical results.

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II. Finite Element Analysis

A. Modeling of Specimens

Finite element analysis was conducted with software ABAQUS [7]. The simulated specimens include six columns with different intact strength f_{in} and deteriorated strength f_w, retrofitted with different thickness CFRP t_{cfrp}. The specimens have the same height *L,* diameter *D,* and axial load ratio $N/(f_{in}A)$. All the deteriorated range *R* of columns was spread from the foot of the columns up to the height of 250mm above the foot of the columns. The details of the numerical models were shown in Table I and Fig. 1.

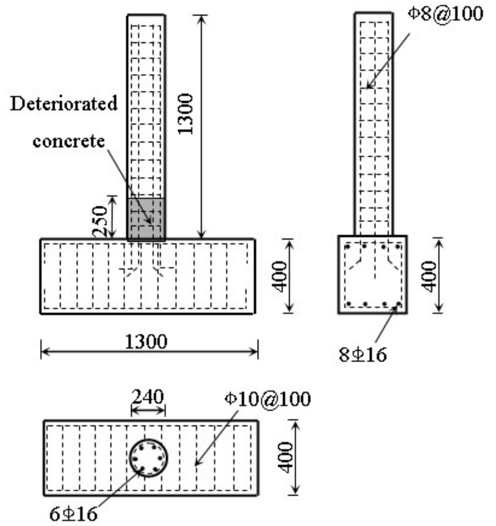

Fig. 1. Notation of geometrical parameters of specimens

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TABLE I: GEOMETRICAL AND MATERIAL PARAMETERS OF PECIMENS

Specimen	D (mm)	L (mm)	R (mm)	f_{in} (MPa)	f_w (MPa)	$N/(f_{in}A)$	t_{cfrp} (mm)
DB50	240	1300	-	52	-	0.1	-
BR200	240	1300	0-250	52	22	0.1	0
BR300	240	1300	0-250	52	31	0.1	0
BR301	240	1300	0-250	52	31	0.1	0.167
BR302	240	1300	0-250	52	31	0.1	0.334
BR203	240	1300	0-250	52	22	0.1	0.501

A. Boundary Conditions and Load Application

The stub of column was restrained against all degrees of freedom. The displacement of stub in the x-axis direction was also restrained during loading. The top and lateral loading plates were tied on the top of columns to prevent local crashing of concrete. Firstly, the axial compressive load was applied on the loading plate. Then the laterally circular load was applied on the lateral loading plate. The reinforced bars were embedded into the concrete, and the slippage between them was neglected. The boundary conditions and load application of specimen was shown in Fig. 2.

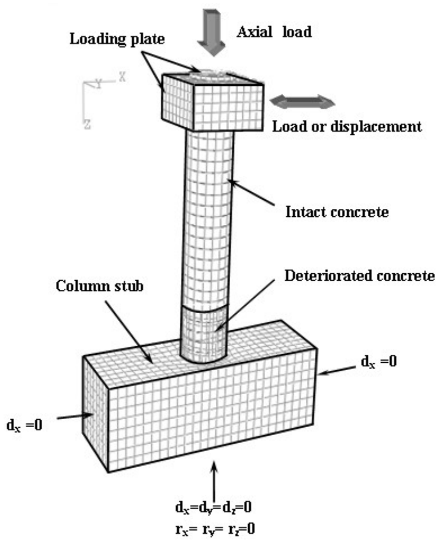


Fig. 2. FE model of specimen

B. Element Type and Mesh

An eight nodes 3-D solid element (C3D8R) was used to model concrete. The longitudinal and transverse steel bars were simulated by truss element (T3D2). The structured meshing technique was used for meshing. The maximum dimension of aggregate was 20mm, thus 50mm and 35mm were selected as the size of concrete and reinforcement grid, respectively.

C. Modeling of Material Properties

The damaged plasticity concrete model defined in Standard ABAQUS is used in the analysis. The yield function was developed by Lublinear [8], and modified by Jeeho [9]. The unaxial stress-strain relationship of compressive and tension behaviors are required. Attard [10] model was adopted as the compressive constitutive law of concrete in this study as shown in Fig. 3. The model of Mark [11] was selected as the compressive damage model; the damage was presented by means of damage ratio variation during transverse loading, as shown in Fig. 4. The tension strength of concrete f_t is equal to 0.3 $f_c^{\ 2/3}$ according to the CEO-FIB2010 [12]. Shah's model [13] was used as tensile behavior of concrete. The tension behavior was shown in Fig. 5.

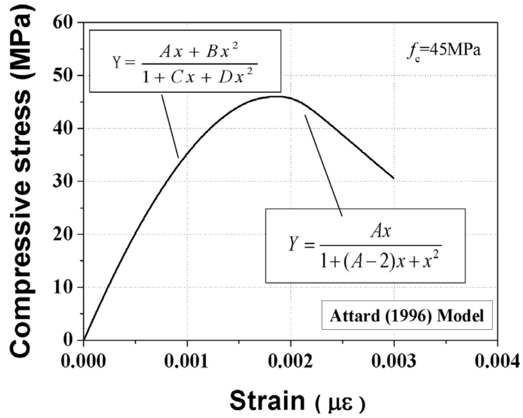


Fig. 3. Compressive model of concrete

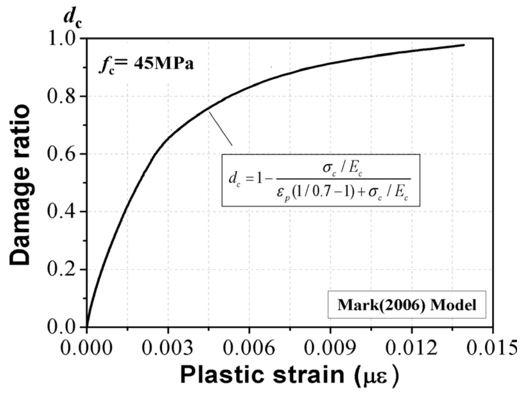


Fig. 4. Compressive damage model of concrete

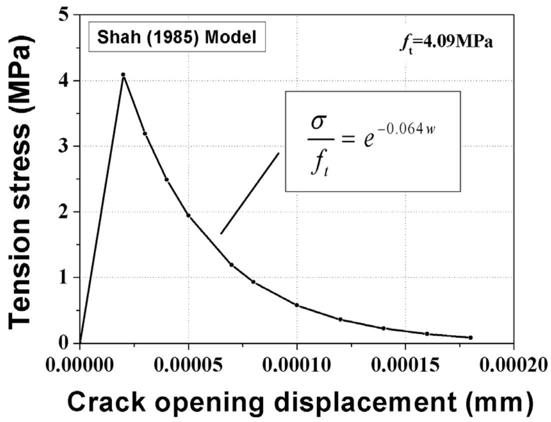


Fig. 5. Tension model of concrete

The steel bar was assumed as a hardening elastic-plastic material. The stress-strain curve used in the numerical analysis is shown in Fig.6. The yield strength of deformed steel bar and plain bar is 360MPa and 290MPa, respectively, the ultimate strength of which is 580MPa and 420MPa, and the elastic modulus of which is 206GPa and 210GPa. The hardening modulus was considered as one percent of the elastic modulus.

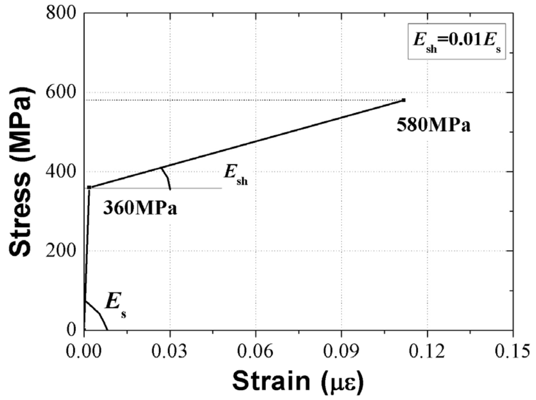


Fig. 6. Hardening elastic-plastic of steel bar

CFRP sheets were defined as an orthotropic elastic lamina in ABAQUS. The following parameters were required in finite element analysis: The elastic modulus in tensile direction E_{cfrp}, Poisson's ratio v_{cfrp} and ultimate stress f_{cfrp} were 235GPa, 0.25 and 3400MPa, respectively, all of which were obtained from coupon test. Reduced integration quadrilateral membrane element with four nodes (M3D4R) was used to define CFRP. The slippage between CFRP and concrete was ignored, and the CFRP material was tie to the concrete.

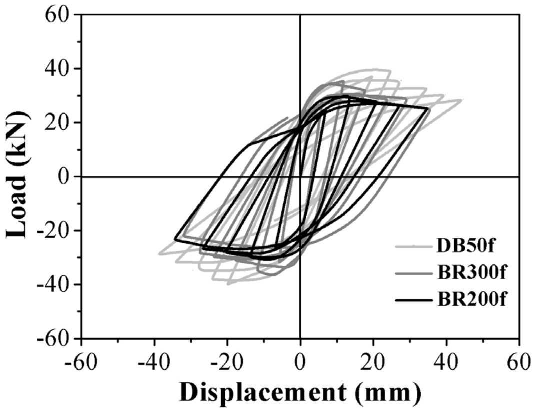


Fig. 7. Predicted hysteretic loops of deteriorated and control column

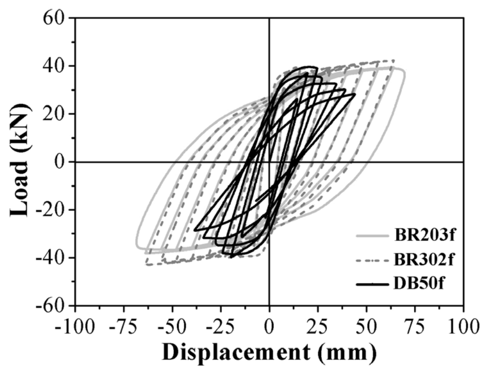


Fig. 8. Predicted hysteretic loops of retrofitted and control column

D. Numerical Results

The numerical results showed in Fig. 7, which indicated that when the deteriorated segment locates at the foot of the column, the seismic behaviors of RC columns are weakened seriously. The influence of the deteriorated segment on the seismic behaviors is related to the deteriorated strength. The retrofitting effect of wrapped CFRP was shown in Fig. 8, which indicated that the bearing capacity of deteriorated column with deteriorated strength 22MPa can almost reach to the one of the control column after retrofitting 3 layers CFRP, and the deteriorated column with deteriorated strength 31MPa requires 2 layers CFRP.

III. Experimental Verifications

The FE model described above has been validated against the test results carried out in the laboratory. A total of six flexure-dominant specimens, including two partially deteriorated columns, three retrofitted deteriorated columns and one reference column, were tested. The details of test specimens are corresponding to the numerically simulated specimens, which were shown in Table I.

A. Experiment

The experimental instruments were shown in Fig. 9. Each column was placed in an existing frame with a 200t hydraulic actuator. The column stubs were fastened to the rigid floor with four high-strength rods to prevent slip and overturning under large lateral loads. The actuator with a 200t load cell was mounted vertically onto the frame to apply the vertical axial load. Another two 30t horizontal hydraulic actuators with load cells were used to apply lateral reversal load. All instruments were connected to IMC data acquisition system for data selection. Before yield of the longitudinal bars, the horizontal load was applied in accordance to the load control mode, and the displacement control mode was adopted after yielding of longitudinal bar.

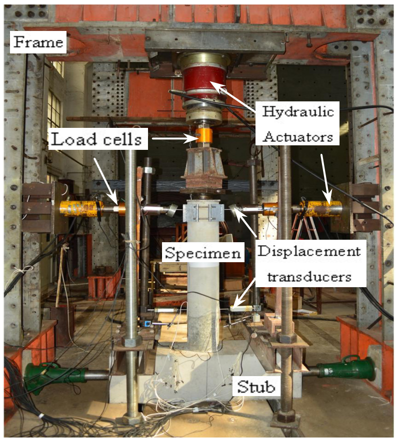
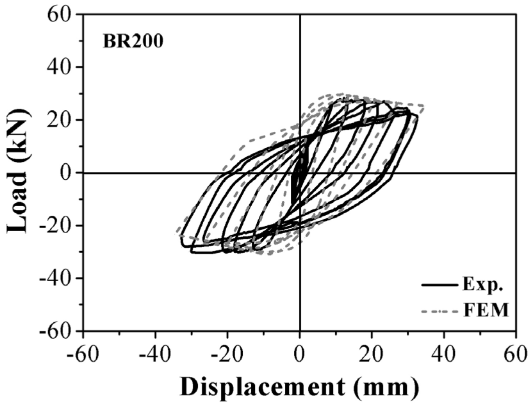


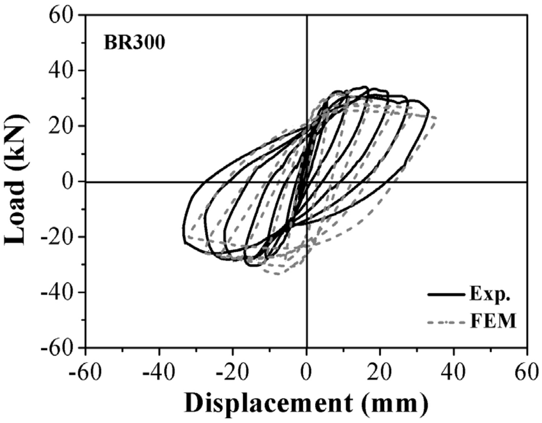
Fig. 9. Experimental instrument

B. Verifications of Proposed FE Model

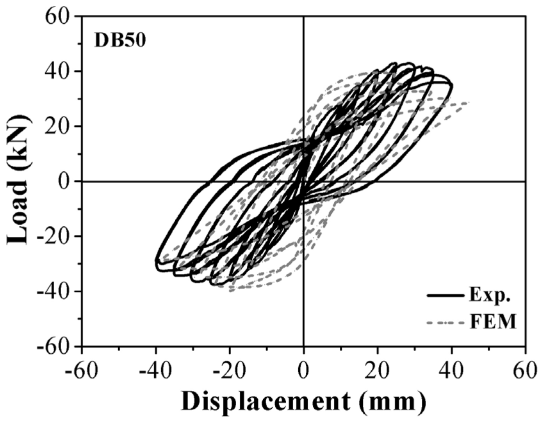
The hysteretic loops were shown in Fig.10 (a)-(e). It is clearly visible that the experimental results have a good agreement with the FEA results. The bearing capacities of experimental and analytical results were shown in Table 2. Owing to the ignoring of slippage between concrete and reinforcement bars, the displacements of the partially deteriorated columns in FEM analysis are slight smaller than the test result. The experimentally hysteretic loops present the same regularity to the ones obtained from finite element analysis, which indicates the proposed FE model is valid to predict the seismic behaviors of partially deteriorated columns, and the effectiveness of externally wrapped CFRP on retrofitting partially deteriorated columns.



(a)



(b)



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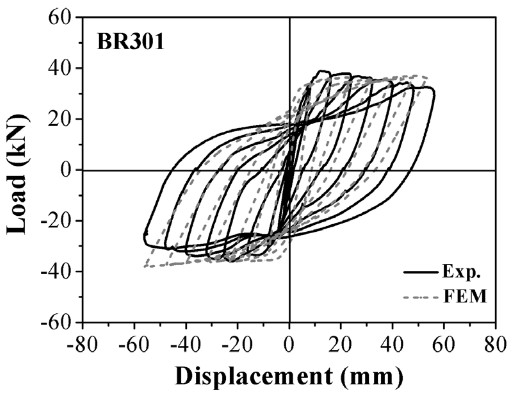

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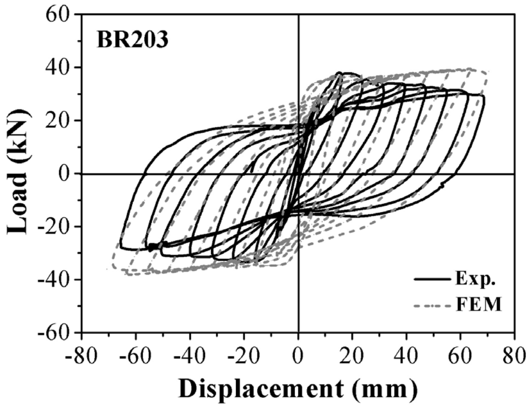

(e)

Fig. 10. Hysteretic loops of experimental and FEA results

TABLE II: TEST AND FEA RESULTS

Specimen	N_{exp} (kN)	N_{FEM} (kN)	$\frac{\lvert N_{exp} - N_{FEM} \rvert}{N_{exp}} \times 100\%$
DB50	42.6	39.2	7.9%
BR200	29.8	30.1	10.0%
BR203	39.1	39.8	1.8%
BR300	35.6	34.4	3.4%
BR301	38.9	37.2	4.3%
BR302	41.0	41.6	1.5%

IV. CONCLUSION

According to the analytically and experimentally research results, the following conclusions are obtained:

1) 3-D finite element model can predict the seismic behaviors of partially deteriorated columns and the effect of externally wrapped CFRP.
2) When the deteriorated segment locates at the foot of the columns, the partial deterioration can weaken the seismic behaviors of the whole columns.
3) Wrapping CFRP is an effective method to recover the seismic behaviors of the partially deteriorated column.

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