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SEISMIC BEHAVIOR AND ASSESSMENT OF CONCRETE WALLS REINFORCED BY CFRP BARS

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Abstract

Experimental investigation and numerical analysis on seismic behavior of concrete walls reinforced by carbon fiber reinforced polymer (CFRP) bars are conducted in this paper. Due to high corrosion-resistance, high tensile strength and long linear-elastic stress-strain property, CFRP bars are utilized as longitudinal reinforcing bars in the boundary elements of concrete walls for the purpose of stable lateral-resistant capacity and small residual deformation, both of which have been taken as the main indices measuring the so-called drift-hardening capability of concrete components, including beams, columns and walls.

Three full-scale concrete walls reinforced by eight CFRP bars (12mm in diameter) in each boundary element of wall panel were fabricated and tested under reversed cyclic lateral loading while subjected to constant axial load. All specimens had the identical geometry with the shear span ratio of 2.0, and the wall panels were 2360mm high by 1280mm long and 200mm thick. The main experimental variable was the axial load level, which was represented in terms of axial load ratio ranging from 0.17 to 0.33.

Test results have shown that the axial load level significantly influence the seismic response and drift-hardening capability of concrete walls reinforced by CFRP rebars. Under the axial load ratio of 0.17, which corresponds to the axial load level sustained by an about fourteen-story building, the wall exhibited high drift-hardening capability until the drift level of 2.0%. The residual drift and flexural crack of this wall were effectively reduced to only 14% and 23%, respectively, of those measured at the corresponding peak drift (unloading drift) levels. With the increment of axial load ratio, the drift-hardening capability of the walls reinforced by CFRP rebars tended to decrease to 1.2% drift due to the crushing of concrete shell under high compressive stress as well as the rupture of CFPR rebars. The residual drifts after unloading from 1.5% drift of the walls under higher axial load ratio than 0.26, however, were still less than 0.5%, indicating a repairable probability of 98%.

Parallel to the experimental work, a numerical analytical method to assess hysteretic behaviors of concrete walls reinforced by CFRP bars is also proposed. The numerical analytical method is based on the so-called finite spring method (FSM) to take the effect of bond slip of CFRP bars into consideration. The analytical results by the proposed method agreed very well with the test results until the drift where concrete commenced crushing and/or the CFRP rebars began rupturing.

Keywords: concrete wall; CFRP bar; seismic behavior; drift-hardening capability; residual deformation

1. Introduction

There have been more and more substantial loss and properties damages to human societies caused by mega-earthquakes in recent years. The seismic intensity of these mega-earthquakes much exceeds the anticipated level specified by the design codes. Buildings located in earthquake-prone zones may lose functions with large permanent deformation and then couldn't be immediately reoccupied and easily repaired even not collapse after experiencing earthquakes. For lifeline engineering structures, such as power station, hospital, etc., it is more significant to come into service rapidly after earthquakes for saving lives. Nowadays the adequate resistant capacity to potential mega-earthquakes and low residual post-earthquake deformation, which is the so-called drift-hardening capability, are two key properties for seismic structures [1].

Shear walls are seismic resistant members widely used in building structures. Conventional concrete shear walls are designed for the purpose of ductility, which can absorb earthquake-induced energy through plastic deformation and tolerable damage. The design concept of ductility has played the leading role in most seismic design codes worldwide; however, the large residual deformation of conventional concrete walls might become too large to recover function immediately. A novel shear walls with the drift-hardening capability need be proposed to solve these problems mentioned above.

One of the methods to work out issues caused by conventional concrete walls is the use of high strength reinforcing materials for enhancing the walls with resilience [2]. Carbon fiber reinforced polymer (CFRP) bars are composite materials with properties of high corrosion-resistance, high tensile strength and complete linear-elastic stress-strain property, which can be utilized in lieu of steel bars partly or completely in concrete structures to enhance the performance. Besides, CFRP bars have light weight and high strength, which can effectively reduce the weight of concrete structures with reasonable seismic resistance [3].

Objective of this paper is to propose an experimental and analytical study of an innovative method to achieve stable lateral-resistant capacity and small residual deformation for concrete walls. To achieve above mentioned purposes, three full-scale CFRP reinforcing concrete walls were fabricated and tested under cyclic reversed lateral loading while subjected to constant compression. CFRP bars are placed in boundary elements of concrete walls, where the stress and strain of reinforcing bar are much large, as longitudinal reinforcing materials to develop its performance benefits. An analytical method, which can take effect of the slippage of CFRP bars into account, was also introduced to evaluate the hysteresis performance of the proposed walls. Validity and accuracy of the proposed method will be verified through comparing the analytical results with the experimental ones.

2. Experimental program

2.1 Details of test walls

In order to investigate seismic behavior of concrete walls reinforced by CFRP bars, three concrete walls of full-scale with CFRP bars as longitudinal reinforcing materials in boundary elements were fabricated and tested. All specimens had the identical geometry and reinforcement details as shown in Fig.1. The wall panels were 2360mm high by 1280mm long and 200mm thick with a loading beam at the top and the lateral loading point was at the height of 2560mm form the upper surface of foundation beam. The shear span ratio was 2.0, which was widely adapted in concrete wall designing.

Eight CFRP bars (12mm in diameter) were placed in each boundary element and confined by rectangular stirrups (plain steel rebars with 6mm in diameter) having spacing of 50mm. Web reinforcements in wall panels consisted of two layers of deformed steel rebars (8mm in diameter). The vertical web reinforcing rebars were distributed uniformly along the depth of wall panel section. While the horizontal web rebars had spacing of 70mm along the height of wall panel. It should be mentioned that the horizontal web reinforcing rebars were enhanced having spacing of 50mm below the height of 600mm.

Both ends of CFRP bar were anchored to 10 mm-thick steel plates to which the steel sleeve (330mm long) housing each CFRP bar with high-strength and non-contract grouting material was welded for the purpose of avoiding slippage and ensuring the maximum performance of CFRP bars. The main experimental variable was the axial load level represented as axial load ratios of 0.17, 0.26 and 0.33. Specimen numbers of CFRPRW1, CFRPRW2 and CFRPRW3 represented three test walls under axial load ratios of 0.17, 0.26 and 0.33, respectively.

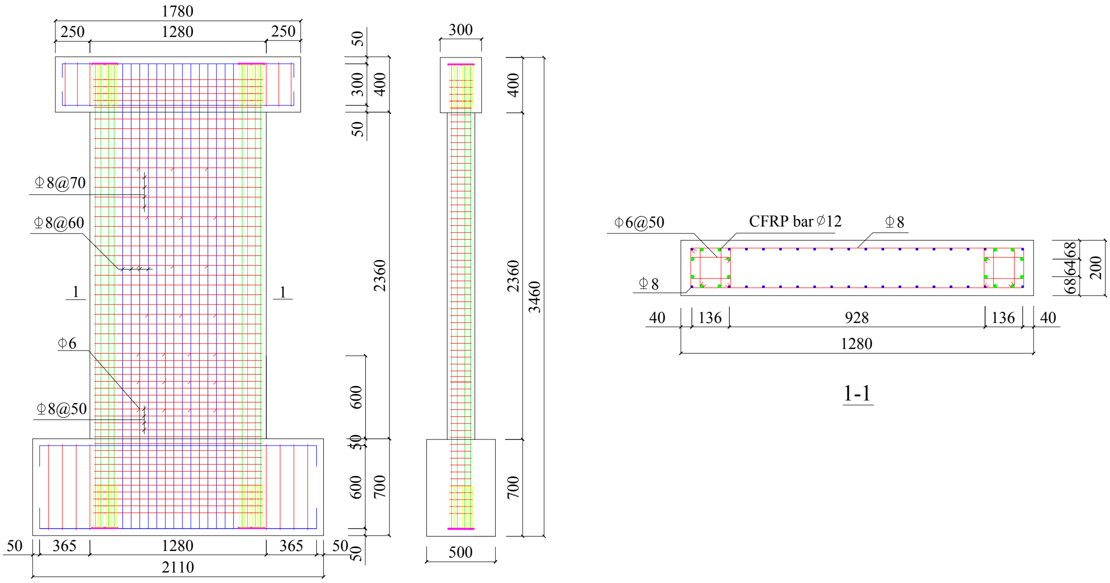


Fig. 1 – Dimensions and reinforcement details of test shear walls

2.2 Material properties

Table 1 shows mechanical properties of reinforcing bars used. HPB300 is used to refer to plain steel bars utilized as rectangular stirrups in boundary elements. HRB335 means deformed steel bars constituting web reinforcements in wall panel. It can be seen that the CFRP bar had high tensile strength of 2310.3 MPa and always exhibited the linear elastic property until failure with ultimate tensile strength. So there was not yield stage in the tensile test of CFRP bars.

Ready-mixed concrete was used to cast the test walls and its cubic (150mm length) strength, f_{cu}, was 57.2MPa.

Table 1 –Mechanical properties of the reinforcing bars

Bars	**Diameter/mm**	**Yield strength/MPa**	**Ultimate strength/MPa**	**Yield strain/με**	**Elongation/%**	**Modulus/MPa**
HPB300	6	414.8	529.4	1860	19.4	2.23×10^5
HRB335	8	361.3	502.6	1599	19.2	2.26×10^5
CFRP bar	12	-	2310.3	-	-	1.43×10^5

2.3 Loading apparatus and measurements

Specimens were tested under reversed cyclic lateral loading and constant axial load applied by the loading apparatus shown in Fig. 2. A MTS servo-controlled hydraulic actor with maximum capacity of 2500kN was used to apply cyclically reversed lateral load. The axial load was provided by two hydraulic jacks, each of them had the maximum capacity of 2000kN. There was a sliding mechanism between vertical hydraulic jacks and reaction steel beam for the purpose of making hydraulic jacks move with the loading beam of specimen, which could make sure the loading points keep constant during the quasi-static test. Besides, the value of axial load could be adjusted automatically in real time by the hydraulic oil pump during the whole test. Both the two points of axil loading setup mentioned above gave a guarantee to the constant axial load, which was significant in the quasi-static test of seismic structural member.

Fig. 2 – Loading apparatus

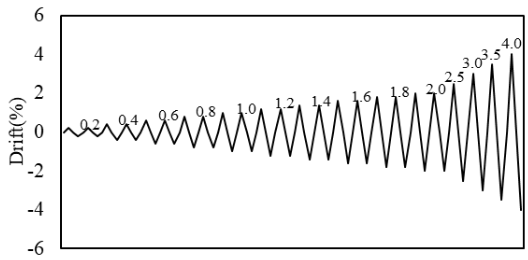


Fig. 3 – Loading program

The lateral loading was controlled by drift ratio defined as the ratio of lateral displacement at the lateral loading point to the shear span (2560mm) of each tested wall. Fig.3 shows the loading program. Two cycles were applied at each level of lateral displacement with increments of 0.2% up to 2.0%, after which one cycle was applied at the drift ratios of 2.5%, 3.0% and 3.5%, respectively.

Apart from the lateral displacement at the whole height of 2560mm were measured and recorded, the measurements of lateral and vertical displacements at different positions along the height of wall were conducted by seven pairs of displacement transducers (DTs). Besides, strains of longitudinal steel bars, CFRP bars, stirrups and transverse steel bars were also measured by strain gages at different specific locations. Fig.4 indicates the location of strain gages and DTs.

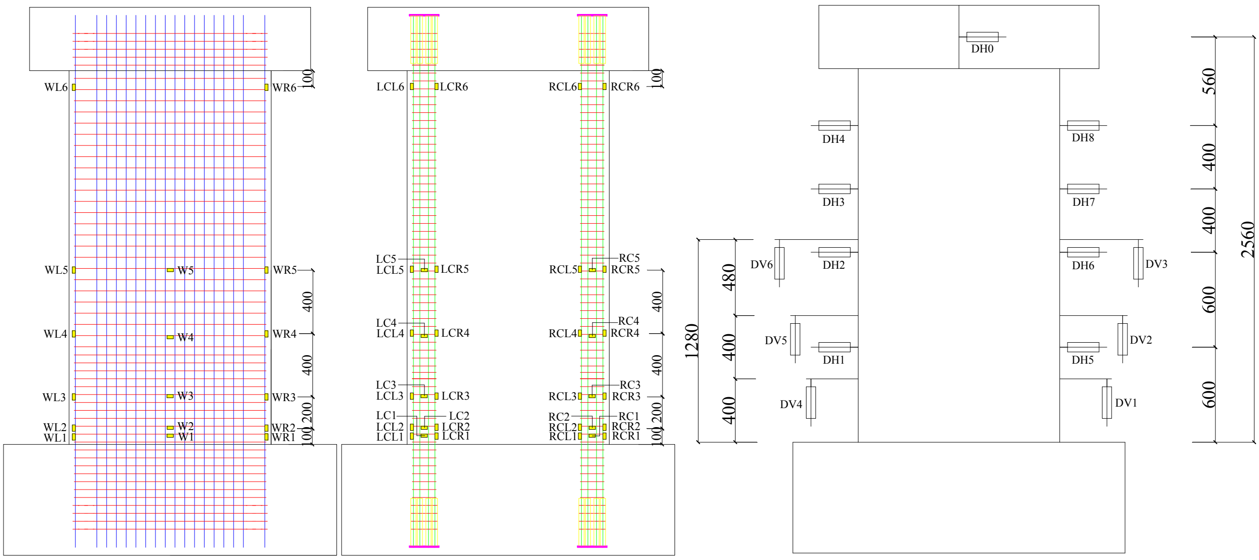


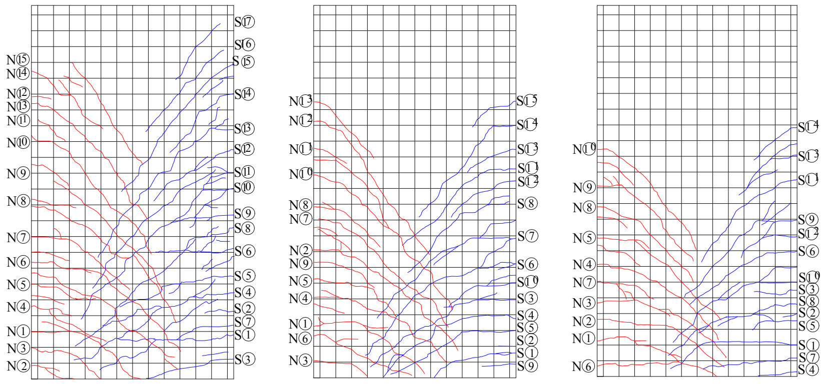
Fig. 4 – Location of strain gages and DTs

3. Experimental results and discussions

3.1 Cracks and damages of specimens

Fig.5 and Fig.6 show cracks and damages, respectively, of all specimens. It can be observed that all tested walls exhibited similar cracking and damaging mode regardless of the axial load level. Firstly, concrete wall façade commenced flexural cracking under the lateral loading. Under increased lateral displacement, flexural cracking continued to propagate and were accompanied with shear cracking meanwhile the longitudinal deformed steel rebar began to yield. Cover concrete spalling was observed as loading continued, after which specimens reached peak lateral load. At the end of test, concrete walls lost seismic resistance because of the concrete crushing and/or CFRP bars rupturing.

The effects of axial load level on cracks and damages are obvious. The crack propagation was restrained with the lower height of cracking as increasing the axial load ratio. Concrete crushing also became more serious at the high axial load level.



(a)CFRPRW1 (b)CFRPRW2 (c)CFRPRW3

Fig. 5 – Cracks observed during the whole test

(a)CFRPRW1 (b)CFRPRW2 (c)CFRPRW3

Fig. 6 – Photos of walls taken after testing

3.2 Measured lateral force versus drift relationships

Fig.7 shows the measured lateral force versus drift relationships of three specimens. The solid circles superimposed in Fig.7 represent the rupture of CFRP bar commencing. As can be seen from Fig.7, Specimen

CFRPRW1 and specimen CFRPRW2, subjected to axial load ratios of 0.17 and 0.26, exhibited stable lateral resistance even at the large drift ratio beyond 2.0% revealing the drift-hardening capability. The lateral capacity of specimen CFRPRW3 also represented drift-hardening capability till 1.2% drift, after which a decline was observed due to the crushing of concrete shell under high axial load ratio of 0.33 as well as the rupture of CFRP bars. All specimens had the so-called origin-pointing hysteretic loops, which mean that the lateral force-drift curve approached toward origin at unloading stage indicating low residual drift.

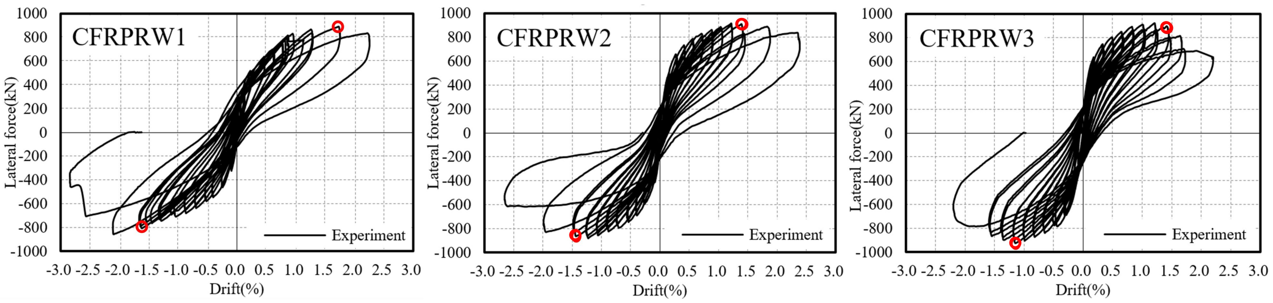


Fig. 7 – Measured lateral force-drift responses of test walls

3.3 Envelop curves of specimens

The peak lateral load at the first cycle of each drift level and the corresponding drift relationships called envelop curves were drawn in Fig.8. It should be mentioned that data that lateral load declined to below the value of 85% maximum lateral load was removed according to the Specification for Seismic Test of Buildings of China (JGJ/T 101-2015) [4].

As one can see from Fig.8, the maximum lateral load increased as increasing the axial load ratio, while the corresponding drift and the ultimate drift showed the opposite tendency. Specimen CFRPRW2 and CFRPRW3 experienced larger maximum lateral load with increments of 2.9% and 5.7%, respectively, compared to specimen CFRPRW1. As for the effects of axial load on deformation capacity of specimens, specimen CFRPRW1 had the reasonable ultimate drift, which was similar with specimen CFRPRW2 while 35.6% larger than specimen CFRPRW3.

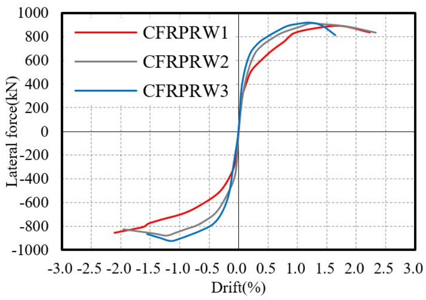


Fig. 8 –Measured envelope curves

3.4 Residual deformation and residual crack width

Fig.9 represents residual drifts unloading from different drifts of specimens. Specimen CFRPRW1 only had 0.17% residual drift even unloading from 1.92% drift, experiencing the 86% recovery of deformation after seismic loading. Specimen CFRPRW2 and CFRPRW3 also exhibited high deformation recovery levels, which could reach 89% and 86%, respectively, after unloading from the maximum drift. As also can be seen that, the residual drifts after unloading from 1.5% drift of the walls even under the high axial load ratio up to 0.33 were still less than 0.5%, indicating a repairable probability of 98%[5].

Maximum and residual crack widths were measured at the peak lateral drift and unloading drift, respectively, of each loading drift level as shown in Fig.10. The property of high recovery after seismic loading similar to deformation recovering can also be seen on cracks. The flexural crack of specimen CFRPRW1 was effectively reduced to only 23% of that measured at the corresponding peak drift level. Specimens remained well crack recovering capability though increasing axial load ratio higher than 0.17.

The above experimental results imply that placing CFRP bars in boundary elements of concrete walls can achieve the seismic resilient goals of stable lateral-resistant capacity and small residual deformation even up to large deformation and axial load level. It should be mentioned that the deformation limit of CFRP reinforcing wall with high axial load must be strictly controlled for the purpose of sufficient drift-hardening capability.

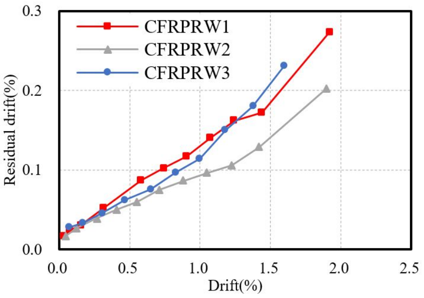


Fig. 9 – Residual drifts

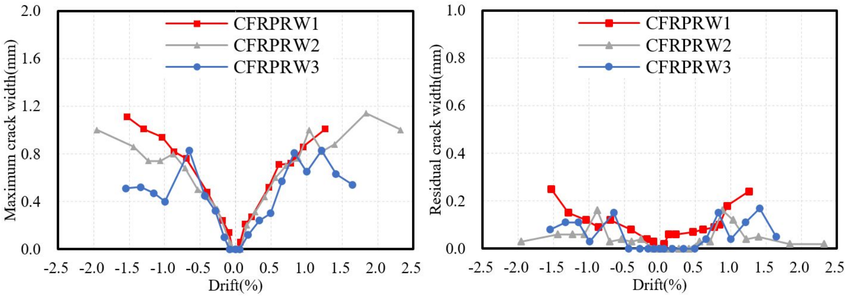


Fig. 10 – Maximum and residual crack widths

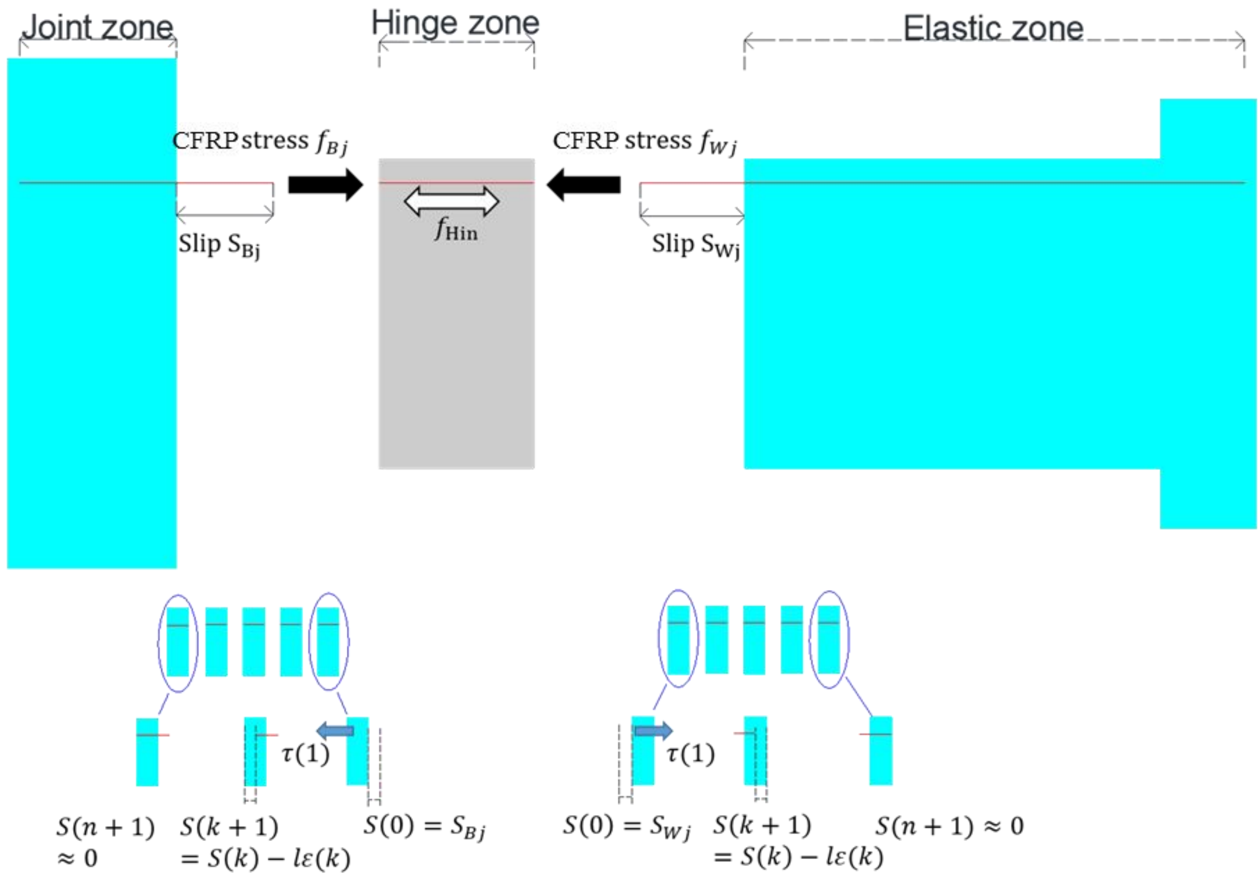
4. Numerical analytical method to assess hysteretic behaviors of suggested walls

Parallel to the experimental program, a numerical analytical method to evaluate hysteresis performance of concrete walls reinforced by CFRP bars is also proposed. As mentioned in the previous section, CFRP bars having the properties of high tensile strength and complete linear-elasticity is different from the steel bar, which is a kind of elastic-plastic material. Because the plastic stage, steel bars can exhibit large plastic deformation under high tensile loading. So the whole section of steel bars reinforcing wall can be assumed to remain plane and the rebar's slip can be ignored during analytical procedure. While as for CFRP bars without large plastic deformation, the slippage of CFRP bars in concrete is inevitable. The traditional analytical method based on plane-remain-plane assumption to assess common steel bars reinforcing concrete walls can't provide reasonable predication of the walls reinforced by CFRP bars, and a new method utilized for the suggested walls is necessary.

4.1 Basic assumptions and analysis procedures

The proposed numerical analytical method is based on the so-called finite spring method (FSM) to take the effect of bond slip of CFRP bars into consideration. There are several assumptions made in this method: 1) concrete does not resist tensile stress, 2) only the concrete plane remains plane after bending, 3) strain and stress of the CFRP bar are uniformly distributed within the plastic hinge region, 4) lateral deformation of the wall is mainly due to the flexural rotation concentrated in the plastic hinge region.

Based on these assumptions, the wall is divided along its height into three regions; they are joint region, plastic hinge region, and elastic region to take effect of CFRP bar's slip into consideration. The divisions of wall and analysis procedures are shown in Fig. 11. This numerical analytical method to assess hysteresis behaviors come to be executable by using an iterative procedure, whose principle was introduced in detail elsewhere [6].



Step 1

Assign S_{Bj} to $S(0)$, which is the slip at the right side of the first segment. $S(0)=S_{Bj}$. And calculate the bond stress $\tau(1)$ from the slip model [7].

Step 2

Give an initial stress $F_s(1)$ to the bar in the first segment. Then calculate the slip at the left side of The k-th segment till k=n. $S(k+1) = S(k) - l\varepsilon(k)$ Where $\varepsilon(k) = f_s^{-1}[F_s(k) - \tau(k) l\pi d / A_s]$

Step 3

If the boundary condition in the n-th segment is met, the assumed CFRP bar stress $F_s(1)$ is the stress corresponding to the given slip $S(0)$. If not met, assume a new CFRP bar stress $F_s(1)$ and return to step 2.

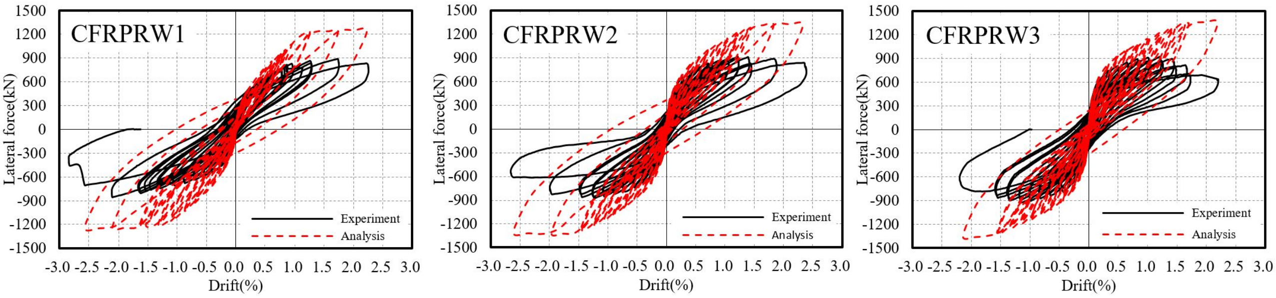
Notations. $S(k)$, $F_s(k)$, $\tau(k)$, $\varepsilon(k)$ are the slip, the CFRP bar stress, the bond stress, and the CFRP bar strain in the k-th segment facing to the hinge region, respectively, l is the segment length, A_s and d are the cross area and nominal diameter of the CFRP bar, respectively.

Fig. 11 – Concepts of division of wall and iterative procedure for slip effect

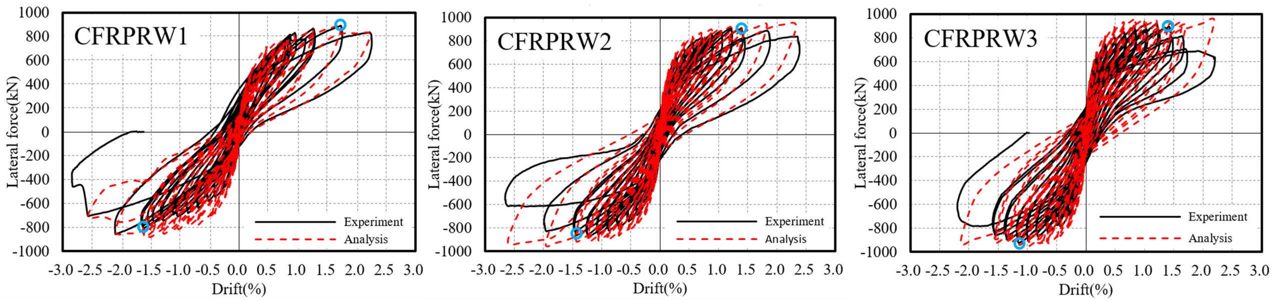
4.2 Comparison between measured and analytical results

Fig. 12 compares the analytical hysteresis loops with experimental results. Two analytical results corresponding to whether or not bond-slip of CFRP bars is taken into consideration are plotted the Fig. 12 to verity the necessity of considering the effect of this factor which has been discussed in the previous section. It can be seen in Fig.12 (a) that the calculated lateral load for each specimen was overestimated with ignorance of bond-slip of CFRP bars. There is approximate 40%-50% overestimation in the ultimate lateral resistant capacities using the conventional analysis method based on the whole plane-remain-plane assumption without consideration of the CFRP bar's slippage.

The calculated results of hysteresis loops by the proposed analytical considering bond-slip of CFRP bars are shown in Fig. 12(b), in which solid circles superimposed mean that CFRP bars began to rupture. One can see from Fig. 12(b) that the theoretical predictions for all specimens using the numerical analytical method proposed by authors agreed very well with the test results till about 1.5% drift level where CFRP bars began rupturing.

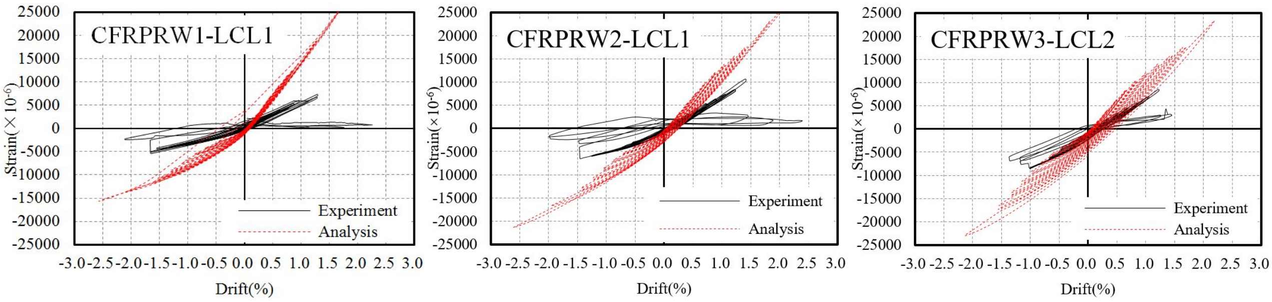


(a) Ignorance of bond-slip of CFRP bars

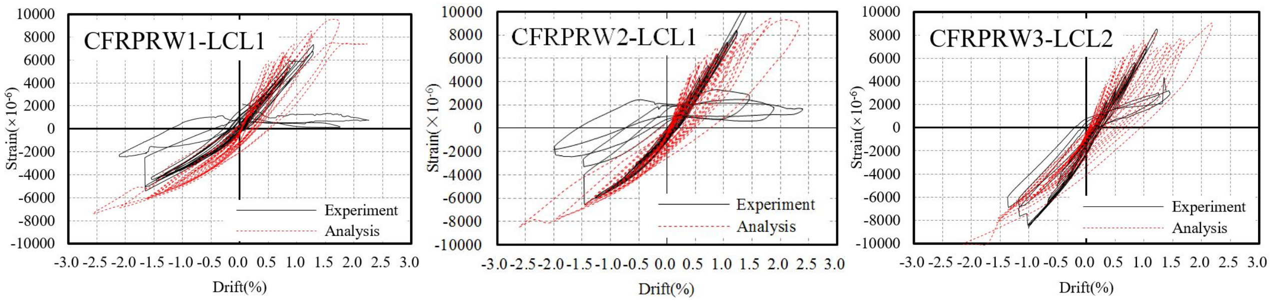


(b) Consideration of bond-slip of CFRP bars

Fig. 12 – Comparison between measured and analytical hysteretic curves



(a) Ignorance of bond-slip of CFRP bars



(b) Consideration of bond-slip of CFRP bars

Fig. 13 – Comparison between measured and analytical strains of CFRP bars

Fig. 13 presents the comparison between measured CFRP bar's strain and analytical results using two numerical analytical methods. The overestimation of CFRP bar's strain can account to the discrepancy of predicting hysteresis loops by the traditional analytical method. The plastic hinge region of wall, especially edge zone, experienced large deformation. CFRP bars placed in that area greatly deformed with cracking concrete during the analytical procedure ignoring the slippage of CFRP bar, which is verified in Fig. 13(a). The strains increased sharply and reached much larger values than the experimental results, which results in larger stress of CFRP bars and lateral resistance of specimen because of the properties of completely linear-elasticity and ultra-tensile strength hold by CFPR bars. While the proposed analytical method can take the slippage of CFRP bars into consideration to eliminate the overestimation in CFRP bar's strain and lateral load of wall. As is presented in Fig. 13(b), analytical results exhibited well agreement with the measured strains of CFRP bars increasing the drift to 1.5%. After that, under the increment of drift, CFRP bars began rupturing in the test with no increase in strain.

The calculated results predicated using the proposed analytical method imply that the CFRP bars exhibited capability without rupturing till the end of test, which was verified in the CFRP bar's strain-drift relationship. That phenomenon can account for the inaccuracy of specimens' hysteresis loops at the drift level above 1.5%, which can be taken as the available drift limit of the proposed numerical analytical method.

5. Conclusions

Three full-scale concrete walls reinforced by CFRP bars in edge zone were fabricated and tested under reversed cyclic lateral load while subjected to axial load for the purpose of proposing a novel seismic concrete member with drift-hardening capability. The seismic behavior and assessment of this CFRP reinforcing wall were studied through both experimental and analytical methods in this paper and the following conclusions can be drawn:

1) Placing CFRP bars in boundary element contributes stable lateral resistance and little residual deformation to concrete wall up to 1.5% drift even under a high axial load ratio of 0.33.

2) The axial load level significantly influences the seismic behavior. The higher the axial load ratio, the lower the drift level up to which the CFRP reinforcing wall can exhibit stable drift-hardening capability. The "maximum drift-hardening drift" decreased from 2.0% to 1.2% as increasing the axial load ratio from 0.17 to 0.33.

3) The proposed numerical analytical method considering the slippage of CFRP bar can give a reasonable predication of the hysteretic behaviors of CFRP reinforcing walls until the drift where concrete commenced crushing and/or the CFRP bars began rupturing.

6. Acknowledgements

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