Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Seismic Performance and Evaluation of Fly-Ash Concrete Columns – Towards resilient and sustainable concrete structures

Sun Yuping[1*], Koyama Tomoyuki[2] and Takeuchi Takashi[1]

[1]*Graduate school of engineering, Kobe University, JAPAN*
[2] *Graduate school of human environment studies, Kyushu University, JAPAN*
[*]*1-1 Rokko-dai, Nada-ku, Kobe city,sun@person.kobe-u.ac.jp, takeuchi_t@person.kobe-u.ac.jp, koyama@arch.kyushu-u.ac.jp*

ABSTRACT

Six concrete columns of about 1/3 scale were fabricated and tested under reversed cyclical lateral loading while under constant axial compression to investigate seismic performance of fly-ash concrete columns. All the test columns were made of concrete with water-to-cement ratio of 65%, and the content of fly-ash in per cubic meter of concrete was 244kg. Among three experimental parameters, the note-worthiest one is the grade of longitudinal rebar. The common normal-strength deformed rebars were placed in three specimens, while the ultra-high-strength rebars with spiral grooves in their surface were used in the other threes, which was aimed at developing a resilient concrete structure. The test results have indicated that utilization of fly-ash and ultra-high-strength rebar is an easy and effective way to materialize the resilient and sustainable concrete structures. An analytical method was also introduced to evaluate the seismic behavior of the columns with ultra-high-strength rebars.

Keywords. Fly-ash concrete, Column, Ultra-high-strength rebar, Spiral groove, Resilience

INTRODUCTION

Since 2000, particularly since human societies have experienced several mega-earthquakes such as 5-12 Sichuan Earthquake in 2008 and 3-11 Eastern Japan Earthquake in 2011, as two key words for the next generation of seismic building structures, sustainability and resilience have gained increasing recognition world-widely.

Utilization of fly ash can trace back to 1950s, and has been in various fields such as cement, concrete, civil engineering, agriculture, forestry, fisheries and construction industry. In Japan, utilization of fly ash in producing cement accounts for about 90% of the total. However, due to economic recession that has continued for a couple of decades, fly ash has seen its limit of utilization in cement field. In order to find new applications of fly ash, Matsufuji et al (Matsufuji, 2001) have recently proposed to mix fly ash in concrete with cement content kept constant and experimentally verified that the compressive strength of concrete increases in correlation to the mixing quantity of fly ash up to 300 l/m^3 even the water-to-cement ratio is kept to be 65%. Furthermore, Koyama et al (Koyama, 2006) and Ito et al (Ito, 2007) have experimentally verified that this kind of utilization of fly ash is very effective in enhancing compressive strength and durability of concrete, respectively. These previous studies imply that the utilization method proposed by Matsufuji et al is a good candidate to reduce environmental load of concrete structure, and hence upgrade their sustainability.

As to seismic capacity, construction industries and societies have paid primary attention to ductility of building structures. Ductile structures usually withstand severe earthquakes by means of absorbing earthquake-induced energy through plastic deformation and tolerable damage of ductile members. As shown in Figure 1, however, while conventional ductile structures can survive major earthquakes, the residual post-earthquake deformation caused by plastic deformation might become so large as to hinder buildings from being immediately reoccupied and easily repaired. Therefore, when designing building structures hit by potential mega-earthquakes, seismic durability should be addressed rather than conventional seismic safety to reduce possible lengthy building closures for repairing or strengthening, thereby saving time, materials, and energy needed for the reopen of the building.

Seismic durability of concrete building structures can be gained through providing stable seismic response and self-centering hysteresis loop to them. Introduction of post-tension stress to unbonded bars placed in concrete columns or walls has recently been proposed and verified to be effective in reducing the permanent post-earthquake deformation and assuring resilience (Panian, 2007). Seismic durability and resilience by post-tensioned members, however, rely primarily upon the stress level of the unbonded post-tensioned bars as well as the mechanical property of concrete. When major ground motions shake buildings, variation in the stress of post-tensioned bars may cause difficulty in reasonable evaluation of the ultimate seismic capacity and resilience. Besides, the axial load level of the peripheral structure members may also become so high as to significantly decrease load-carrying capacity of the concrete at large deformation, and resulting in reduction of resilience of the structure.

Objective of this paper is to provide an experimental and analytical study of an innovative method to achieve sustainable and resilient goals for a concrete structure. This aggressive method doesn’t involve use of complicated post-tension technique, but only utilizes ultra high-strength rebars in fly ash concrete. The point of this method lies in the use of ultra high-strength rebar with spiral groove in its surface. The low bond-resistance of this type of rebar can avoid yielding of the longitudinal rebars and easily and effectively reduce the permanent post-earthquake deformation.

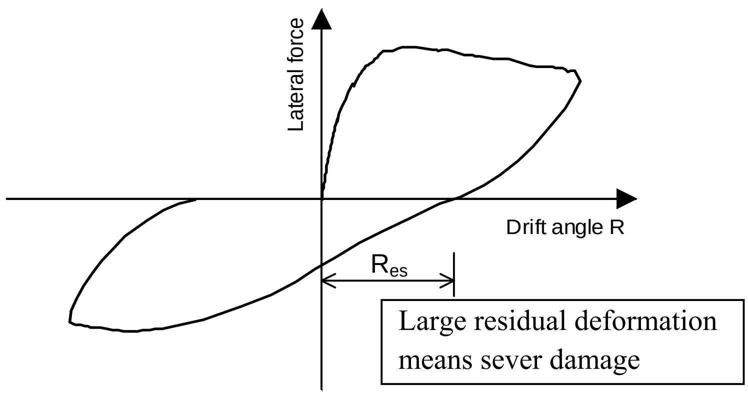


Figure 1. Typical hysteresis loop of ductile concrete structures

OUTLINES OF EXPERIMENT

In order to verify effectiveness of the innovative method in upgrading seismic durability and resilience, six concrete columns of 1/3 scale were fabricated and tested under cyclic reversed lateral force while subjected to constant compression. All the test columns were made of concrete containing large quantity of fly ash. The test columns were divided into two groups according to the grade of longitudinal rebars. The first group of columns adopted normal strength deformed rebar (D13), and the second group of columns used ultra high-strength rebar (SBPDN12.6) with spiral groove in its surface as longitudinal reinforcement. Figure 2 displays the tensile stress-strain relationships of the SBPDN12.6 rebar obtained from five test coupons. Twelve D13 rebars and SBPDN12.6 rebars were placed uniformly along the perimeter of column section with 30mm cover to give an approximate steel ratio of about 2.0%. Table 1 shows outlines of the specimens along with primary test results, and Figure 3 shows reinforcement details and dimensions of the specimens reinforced by SBPDN12.6 rebars.

Each specimen was laterally confined by square hoops (D6) having spacing of 30mm as shown in Figure 2. The transverse reinforcement was designed according to current Japanese design code (AIJ, 2010) to assure each column fail in flexure rather than in brittle shear. The D6 hoop was normal strength bar with yield stress of 438 N/mm^2. The longitudinal D13 rebars in the first group of specimens were anchored at ends by bending into concrete, while SBPDN12.6 rebars in the second group of specimens were anchored at both ends to end steel plates by nuts. According to Funato et al (Funato, 2012), the bond-strengths of D13 rebar and SBPDN12.6 are 15 N/mm^2 and 3 N/mm^2, respectively.

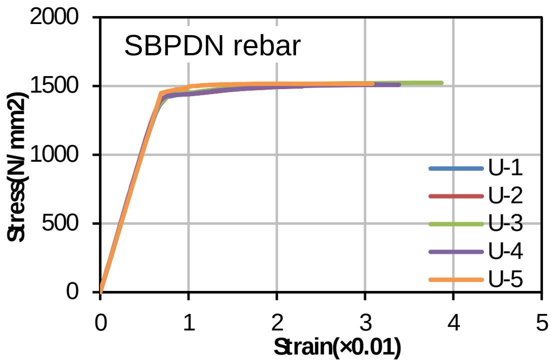


Figure 2. Measured tensile stress-strain relationships of SBPDN12.6 rebar

Table 1. Outlines of specimens and primary test results

Notation		a/D	Rebars grade	Fy (N/mm^2)	Fc (N/mm^2)	Axial load N (kN)	Qexp (kN)	Rexp (0.01rad)
Group No.1	G1-1	2.0	SD345	380	39.8	821	238	1.34
	G1-2	2.5					191	1.05
	G1-3	3.0					155	1.26
Group No.2	G2-1	2.0	SBPDN 1275	1501	29.0	598	261	2.74
	G2-2	2.5					216	3.97
	G2-3	3.0					183	3.98

Note: a/D = shear span ratio, Fy = yield stress of rebar,
Fc = compressive strength of concrete cylinder,
Qexp = measured maximum lateral force, Rexp = drift ratio corresponding to Qexp

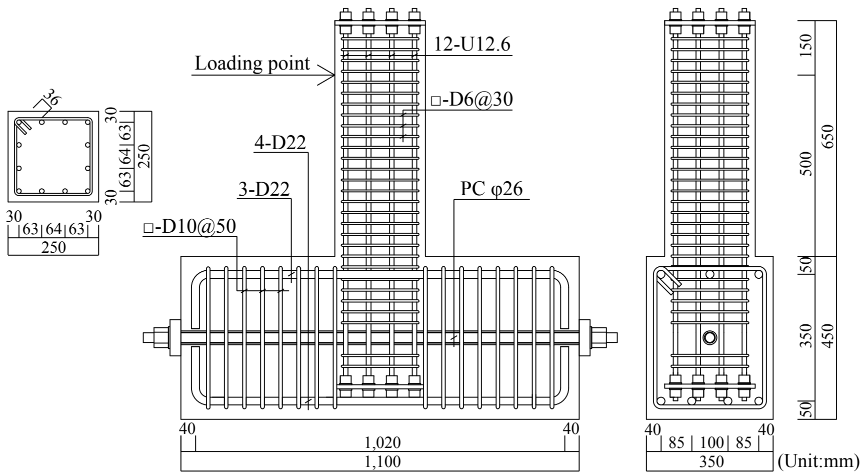


Figure 3. Reinforcement details of specimens with SBPDN12.6 rebars

Concrete was made of ordinary Portland cement with a fixed water-to-cement ratio of 65% The fine powder satisfying requirement of class II in JIS (Japanese Industrial Standard) A 6201 was used as fly ash. Fly ash content, cement content, and water content per unit volume were 244 kg/m^3, 285 kg/m^3, and 185 kg/m^3, respectively. The two groups of specimens were mixed and fabricated by the same mix proportion but with a time interval of about one year. The compressive strengths of concrete cylinder (100mm in diameter) at the stages of testing were shown in Table 1. one can see obvious difference between the concrete strengths of the first group and those of the second group. It can be attributed to shorter mixing time which resulted in the lack of pozzuolanic reaction.

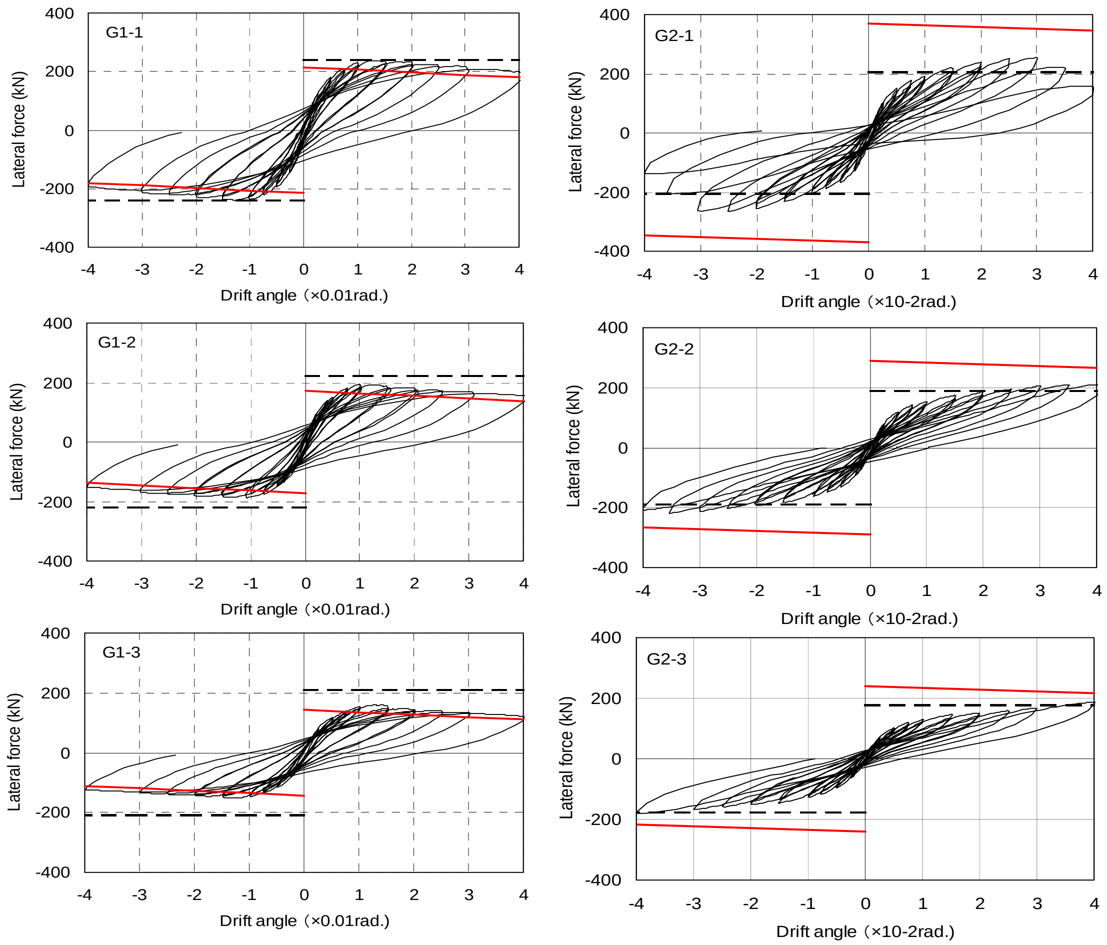
The experimental variable among each group of specimens was shear span ratio, which was 2.0, 2.5, and 3.0. The axial load level, expressed in terms of axial load ratio, was 0.33 for all the specimens, and this value corresponds to the upper limit of axial compression of concrete columns recommended in the AIJ design code (AIJ, 2010). The axial compression was applied to each column via an universal testing machine, and the cyclic lateral force was applied by hydraulic jack of 300kN capacity. The cyclic loading was controlled by drift ratio of column.

To measure strains in longitudinal rebars and hoops, strain gauges were embedded to rebars and hoops located 25mm, 145mm, 265mm, and 410mm away from the end critical section of each column.

EXPERIMENTAL RESULTS AND OBSERVATIONS

Lateral force versus drift ratio relationships. Figure 4 shows the experimentally measured lateral force versus drift ratio relationships of all specimens. The solid and broken straight lines superimposed in Figure 4 represent theoretical ultimate flexural and shear strengths, respectively. The flexural strengths are calculated using the design equation recommended in current design codes (AIJ, 2010), while the ultimate shear strength was obtained using formula proposed by Hirosawa et al (Hirosawa, 1971).

As can be seen from Figure 4, the specimens reinforced with D13 deformed rebars exhibited very ductile seismic response, all reached their respective maximum lateral forces at the drift angle R varying between 0.01rad and 0.015rad. Each specimen also developed its theoretical flexural strength, which means that the design equations recommended for common concrete



(a) specimens with D13 rebars (b) specimens with SBPDN12.6 rebars

Figure 4. Experimental results of lateral force versus drift ratio relationship

members in current design codes are also suitable to the fly ash concrete columns. While the lateral force began to decrease after the peak point, the decrement was very low, and each specimen maintained over 80% of its maximum lateral loading capacity at the drift ratio of 0.04rad.

The specimens with D13 showed spindle hysteresis loops, which implies that mixing large quantity fly ash into concrete have little negative impact on seismic capacity of concrete column. Like common concrete column, the fly ash concrete column have high ductility till large deformation if it satisfies shear-resistant requirement in the design codes. But it should be kept in mind that the high energy-absorption capacity observed in each specimen also leaves large residual drift ratio that might make it very difficult or even impossible to repair or to restore the column to its original position.

On the other hand, the specimens with SBPDN12.6 rebars exhibited very stable seismic response with their lateral resistance constantly increasing till drift ratio of over 0.03rad. the residual post-earthquake deformation was also reduced to one-third of that of columns with D13 rebar. Specimen G2-1 exhibited commencement of decline in lateral resisting force at drift ratio of 0.03rad after reaching its maximum load-carrying capacity and failed in shear in the end. This is mainly because the stable increment in lateral force caused by the increasing moment resisted by the longitudinal rebars that did not yield till the end of test became 20% higher than the theoretical shear strength at R=0.03rad. As compared with specimen G2-1, the specimens G2-2 and G2-3, whose theoretical shear strengths have sufficient margin, exhibited stable increment in lateral resisting force till drift ratio of 0.04rad, and their hysteresis loops also showed significant self centering characteristic with low residual deformation and high resilience.

The above observations mean that utilization of large quantity of fly ash and ultra high-strength rebars with spiral groove in their surfaces is an easy and effective way to materialize sustainable and resilient concrete structures if shear-resisting design of the members follows the current design code for common concrete members. Nevertheless, to apply the proposed sustainable and resilient columns into actual constructions, evaluation method for the ultimate flexure strength needs to be developed. As apparent from Figure 4, the theoretical flexural strength based on conventional plane-remain-plane assumption tends to overestimate the experimental result, which inevitably hinders reasonable design of the proposed columns.

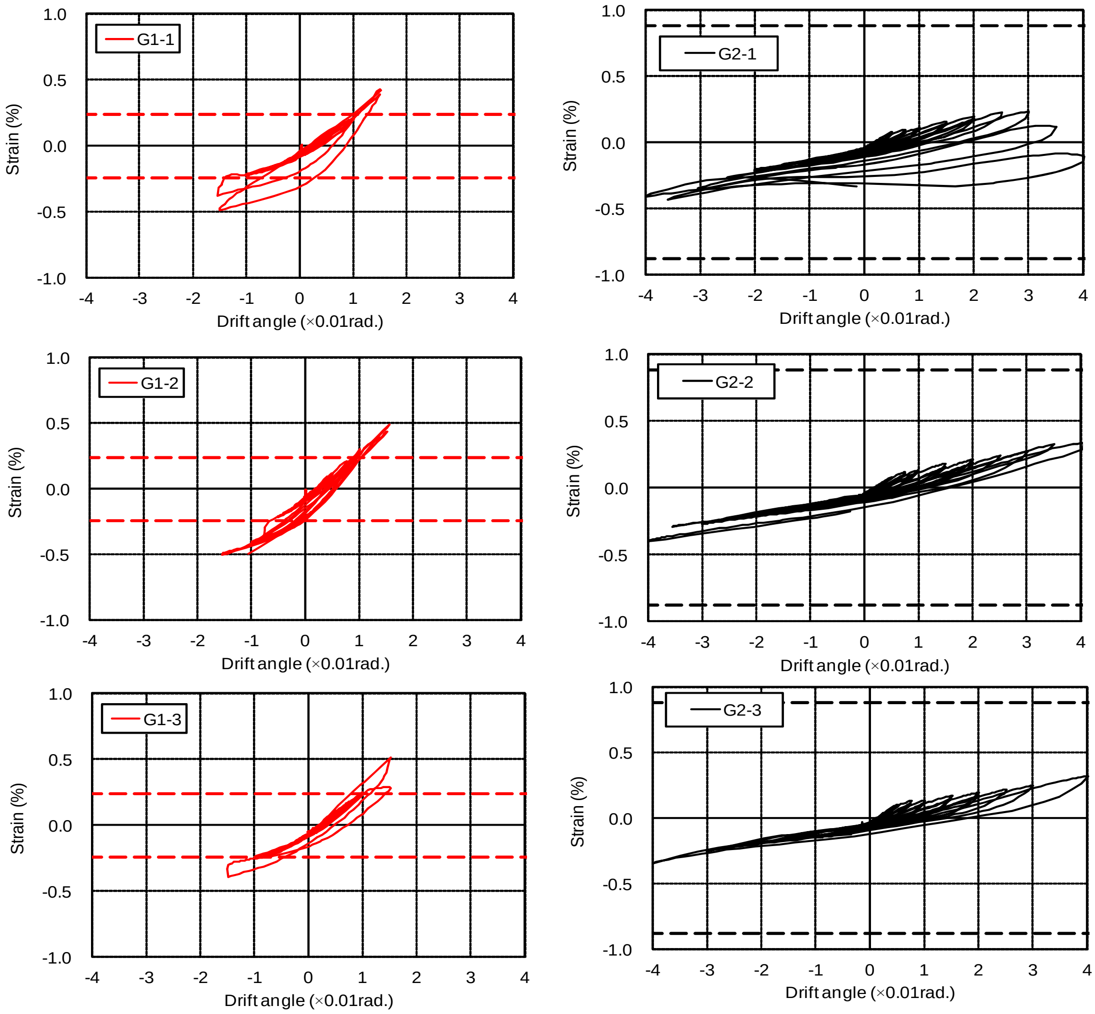
Neither significant splitting crack nor brittle bond failure was observed in the specimens of Group 2 regardless of the high steel strength. The much lower bond strength of SBPDN rebar reduced the interfacial stress transfered between the concrete and the rebar, mitigating occurance risk of splitting crack and/or brittle bond failure.

Longitudinal steel strain versus drift ratio relationships. In order to investigate the mechanism of seismic response shown in Figure 4 for the proposed resilient columns, the measured strains of longitudinal rebars are plotted in Figure 5. The broken horizontal lines superimposed in Figure 5 represent yield strains of D13 steel and SBPDN12.6 rebar. The plotted strains express those measured at the section 145mm away from the end section.

It is obvious from Figure 5 that due to its high bond strength, the measured strains of D13 rebars increased linearly along with increment in drift ratio, reaching and exceeding the yield strain when drift ratio varied between 0.01rad and 0.015rad. The drift ratios where the rebar strains commenced exceeding the yield strain coincide with those measured at the maximum lateral forces. Along with commencement of yielding of the longitudinal rebars, the lateral force began to decline due to inherent property of concrete and the residual drift ratio also increased sharply. This observation implies that avoiding yielding of longitudinal rebars is indispensable to seismic resilience of concrete members.

As compared with the strains of D13 rebars, the measured strains of SBPDN12.6 rebars didn’t reach the yielding strain at the end of test. Till drift ratio R reached 0.005rad, the strains had been increasing linearly along with the drift ratio. After R exceeded 0.005rad, due to its low bond strength, SBPDN12.6 rebars began to slip, and the increment gradient of strains became gentle. Along with stable increase in steel strain, the steel stress and hence the moment resisted by longitudinal rebars increased stably till large deformation. The increment in the moment sustained by SBPDN12.6 rebars could cover decrement in moment capacity due to the more and more significant spalling of cover concrete and the secondary moment caused by axial compression at large deformation.

Residual drift ratio and residual crack width. The residual drift ratio versus drift ratio relationships are shown in Figure 6. As can be seen from Figure 6, before the longitudinal rebars reached yielding, specimens of both groups had nearly the same residual drift ratios. On yielding of longitudinal rebars, the measured residual drift ratios of specimens with D13 rebars commenced diverging from those of specimens with SBPDN12.6 rebars and increased sharply. The residual drift ratio of specimens with SBPDN12.6 rebars increased just at a rate



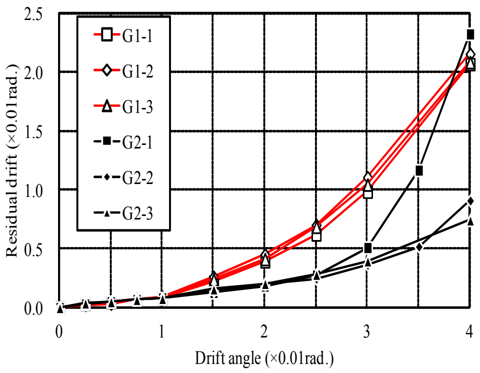
(a) specimens with D13 rebars (b) specimens with SBPDN12.6 rebars

Figure 5. Measured strain of longitudinal rebars versus drift ratio relationships

of about one-tenth of the experienced peak drift ratio till 0.02rad, which corresponds to the safety limit of drift ratio recommended in current Japanese design codes. For specimens whose shear-resisting capacity is reasonably assured, this one-tenth rate of residual drift ratio maintained till R reached 0.03rad, which implies high resilience of the proposed columns.

In order to verify high repairability of the proposed columns, relationships between the experimental residual crack width and the maximum crack width measured at each peak drift ratio are shown in Figure 7. The crack width was measured using crack scale. Since spalling of the concrete cover was so serious that the crack width has lost its practical significance as an index measuring degree of damage, Figure 7 only shows the results till R=0.02rad.

One can see from Figure 7 that the use of SBPDN12.6 rebar can also significantly reduce the residual crack width, and hence upgrade repairability of concrete columns. The measured residual crack width was controlled within 0.2mm, which is only one-fifth of 1.0mm, the limit crack width for repairing recommended in current design code.



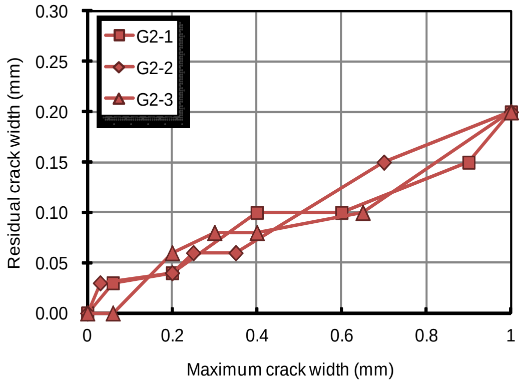
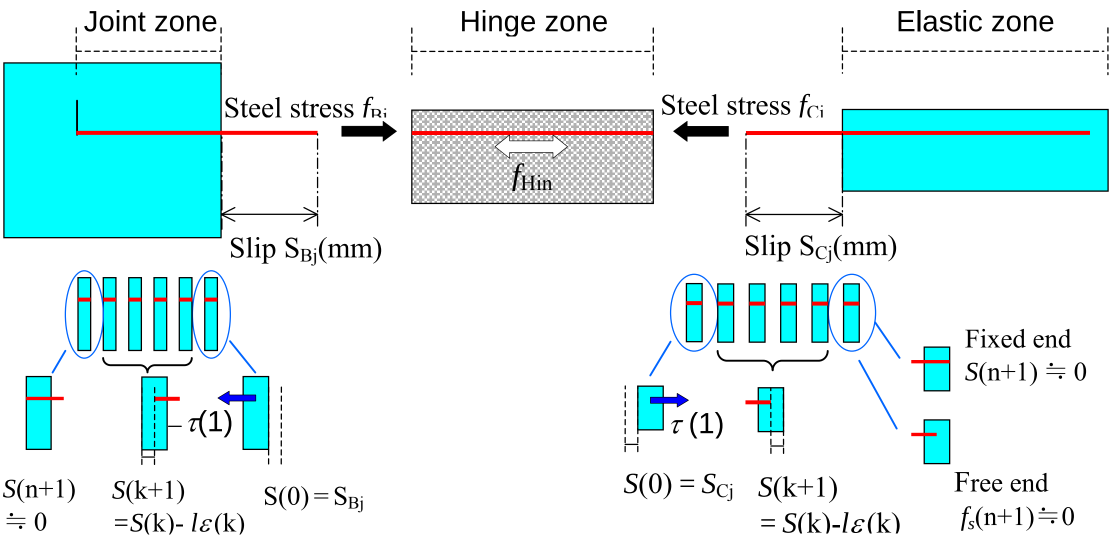


Figure 6 Residual drift ratio

Figure 7 Residual crack width



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

Step 2)
Give an initial stress $F_s(1)$ to the rebar in the first segment. Then calculate the slip at the left side of the k-th segment till k=n.
$\mathbf{S(k+1) = S(k)\text{-}l\varepsilon(k)}$
Where $\varepsilon(k) = f_s^{-1}[F_s(k)\text{-}\tau(k)\, l\pi d/A_s]$

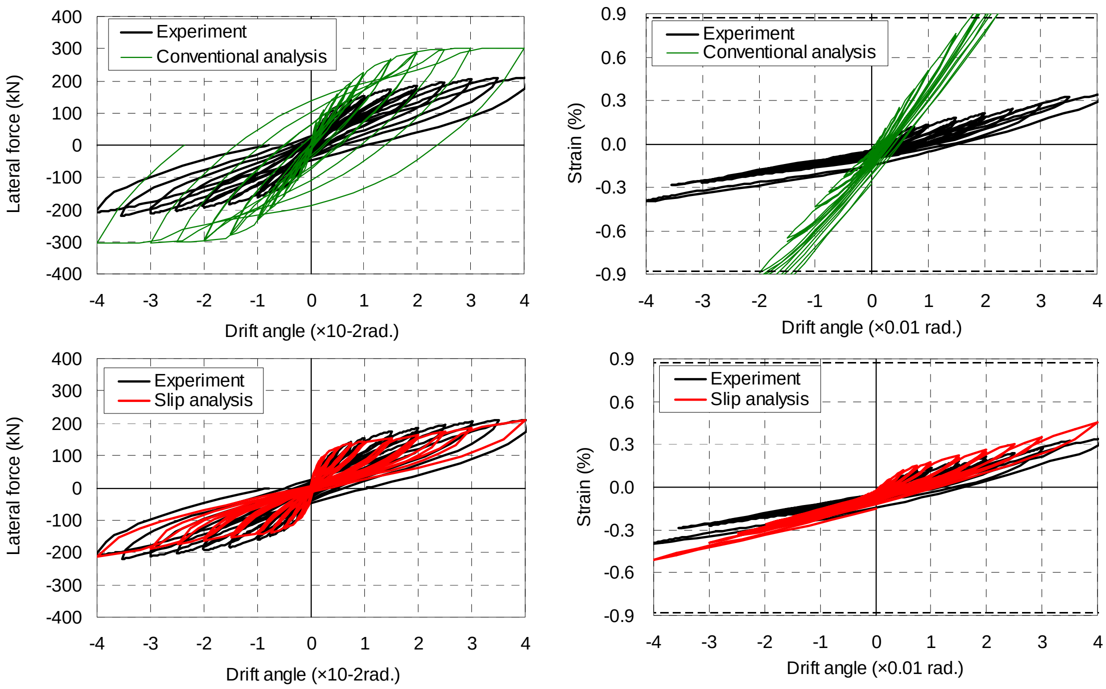
Step 3)
If the boundary condition in the n-th segment is met, the assumed rebar stress $F_s(1)$ is the stress corresponding to the given slip $S(0)$. If not met, assume a new rebar stress $F_s(1)$ and return to step 2).

Notations. S(k), Fs(k), τ(k),ε(k) are the slip, the rebar stress, the bond stress, and the rebar strain in the k-th segment facing to the hinge region, respectively, l is segment length, As and d are the cross area and nominal diameter of the rebar, respectively

Figure 8 Concepts of division of column and iterative procedure for slip effect

EVALUATION OF HYSTERESIS PERFORMANCE

To evaluate hysteresis performance of concrete members made of high-strength steel with low bond-strength such as SBPDN12.6 rebar, the first author and his colleague have proposed an integrated analyticalal method (Sun, 2006). In addition to the confinement effect by transverse steel, this method can take slip of rebar into consideration. When using this method to analyze cyclic behavior of the proposed resilient columns, the following



(a) hysteresis loop (b) strain of SBPDN12.6 rebar

Figure 9 Example of comparison between the theoretical and test results

assumptions are made; 1) concrete does not resist tensile stress, 2) only the concrete plane remains plane after bending, 3) lateral displacement of the column is mainly due to the flexural rotation concentrated in the plastic hinge region with a length of 1.0D (D is the section depth), 4) strain and stress of the rebar are uniformly distributed within the plastic hinge region, and 5) bond-strengths of D13 rebar and SBPDN12.6 rebar are taken as 15 N/mm^2 and 3 N/mm^2, respectively.

To consider effect of rebar's slip, the column is divided along its axis into three regions; they are joint region, plastic hinge region, and elastic region. Figure 8 shows the division of column and the iterative procedures to evaluate the effect of rebar's slip on the steel strain and stress. Details of the proposed method can be found elsewhere (Sun, 2006).

The theoretical hysteresis loop is compared with the measured result of the proposed resilient column in Figure 9. Figure 9 only shows comparison of specimen G2-2 since the other two columns of the second group have the same comparison results. For comparison, the analyticalal hysteresis loop based on conventional flexural analysis is also shown in Figure 9. In addition, to further verify accuracy and reliability of the proposed analyticalal method, the theoretical strain of SBPDN12.6 rebar is compared with the test result in Figure 9 as well.

It is obvious from Figure 9 that the conventional flexural analysis tends to overestimate the test results by 50%-60% as one had seen in Figure 4. The discrepancy can be attributed to ignorance of effect of the rebar's slip in the conventional analysis as shown in Figure 9(b). The analyticalal steel strain based on whole plane-remain-plane assumption has overestimated the experimental result since drift ratio R exceeded 0.005rad.

On the other hand, the theoretical predictions based on the author's method exhibit very close agreement with the measured hysteresis loop in aspects of the shape of hysteresis loop, increasing tendency in lateral load resistance along with increment of displacement, ultimate load-carrying capacity, and the residual drift ratio. The same agreement can also be observed between the theoretical strain of rebar and the experimental result. These observations imply that the analytical method proposed by the authors can give accurate and reliable predictions.

CONCLUSIONS

An innovative approach to materialize sustainable and resilient concrete structures is presented in this paper. This approach only utilizes large quantity of fly ash and ultra high-strength rebar with low bond resistance, and does not involve any complicated technology. Based on the experimental and analyticalal studies described in this paper, the following conclusions can be drawn:

1) Utilization of ultra high-strength rebars with spiral groove in its surface is an easy and effective method to make resilient concrete structures. Columns with this kind of rebars exhibit very stable response till large deformation with very low residual deformation. Neither significant splitting crack nor bond failure occurred in spite of the high steel strength due to the low bond strength.
2) The hysteresis performance of resilient columns can be accurately evaluated using the analyticalal method presented in this paper, which clears theoretical obstacle to practice of this resilient columns.
3) The fly ash concrete member with common deformed rebars can be reasonably designed by the design formulas for normal concrete recommended in current design codes.

ACKNOWLEDGEMENTS

This study was partially supported by Visiting Scholar Foundation of Key Laboratory of New Technology for Construction of Cities in Mountain Area in Chongqing University, China. The SBPDN12.6 rebars were provided by Neturen Co. Ltd. These kind support and assistance are greatly appreciated.

REFERENCES

Matsufuji, Y. et. al. (2001). "Mix proportion principle of concrete containing large quantity of coal ash with constant cement content." *Concrete Research and Technology,* Japan Concrete Institute 12-2, pp. 51-60. (in Japanese)

Koyama, T. et. al. (2006) . "Strength development of concrete containing large quantity of by-products with constant cement content, *Proceedings of the Japan Concrete Institute* 29-1, pp. 231-236 (in Japanese)

Ito, K. et. al. (2007) . "Carbonation of Concrete using Fly Ash by Long-term Exposure Test." *Journal of Architecture and Urban Design, Kyushu University* 12, pp.115-1206

Panian, L. et. al. (2007) . "Post-tensioned concrete walls for seismic resistance." *PTI Journal,* July, V.29, 10, pp.39-45

AIJ(2010). "Standard for Structural Calculation of Reinforced Concrete Structures." *Japanese Institute of Architecture*, Maruzen, Tokyo

Funato, Y. et. al. (2012). "Modeling and application of bond stress versus slip relationship of ultra high-strength rebar with spiral groove in its surface." *Proceedings of the Japan Concrete Institute* 34-2, pp. 157-162 (in Japanese)

Hirosawa, M. et. al.(1971). "Strength and ductility of concrete members subjected to axial force." *Proceedings of the AIJ Annual Conference*, pp. 829-830 (in Japanese)

Sun, Y. et. al. (2006). "analyticalal Study of Cyclic Response of Concrete Members Made of High-Strength Materials." *Proceedings of the 8th U.S. NCEE,* San Francisco, USA, Paper No. 1581