EARTHQUAKE-RESISTING PROPERTIES OF CONFINED HIGH-STRENGTH CONCRETE FRAMES

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ABSTRACT :

Objective of this paper is to present experimental information about the seismic properties of confined HSC moment-resisting frames with emphasis placed on effect of the steel strength on the overall performance in term of capacity curve, the damage degree, and the residual deformation of frames..

Eight test frames of about 1/3 scale were fabricated and tested under reversed cyclical lateral force while subjected to constant axial compression. All of the specimens were made of ultra HSC having compressive strength of 90MPa, and the columns of each frame were confined by square steel tubes while the beam was confined by high-strength hoops. Square steel tube was used to confine HSC columns in lieu of common hoops because of its following advantages: 1) to provide strong confinement to HSC easily, 2) to confine the whole column section so that one can expect enhancement not only of ductility but also of ultimate load-carrying capacity. Longitudinal reinforcement in the columns of each specimen comprised of twelve D10 deformed bars distributed uniformly along the perimeter of concrete section to give a steel ratio of 2.14%. Variables among the test are: 1) wall thickness of steel tube, 2) axial load level, and 3) yield strength of longitudinal steels.

From the experimental work described in this paper, the following conclusions can be drawn: 1) When columns were confined by square steel tubes having B/t=64 and B/t=112, HSC frames with fc =90 MPa exhibited very ductile seismic response under axial load with axial load ratio of 0.5 and 0.3, respectively. 2) Use of high-strength steel (HSS) with yield strength of 900MPa can not only increase the ultimate load-carrying capacity, but also enhance the deformation capacity of HSC frames. In addition to the enhancement effect in strength and ductility, the high-strength steel can greatly mitigate the damage of frames that usually become serious as the ductility becomes large. 3) As compared with HSC frame with normal-strength longitudinal rebars, the HSC frames with HSS exhibit much less residual deformation, implying that the frames with HSS can be easily and economically repaired after hit by serious earthquake.

KEYWORDS: Confined concrete, Steel tube confinement, High-strength concrete, High-strength steel, Moment-resisting frame, Residual deformation

1. INTRODUCTION

High-strength materials, particularly high–strength concrete (HSC), have found increasing use in building structures due to the following advantages; 1) to reduce the structural member size and decrease the weight of structures and hence the seismic loading, 2) to enable construction of taller concrete buildings, 3) to create more usable space and enable more flexible design, and 4) to upgrade durability of concrete buildings.

In the earthquake-prone regions, however, inherent brittle failure mode of HSC may impede its application to construction. To promote the use of HSC in these regions, methods are desirable to effectively prevent the HSC members and structures from brittle failure mode induced by strong earthquake. Confinement of concrete by transverse steels has been widely and long known to be effective in improving ductility of concrete. Traditionally, structure engineers have utilized spirals or hoops to confine concrete beams and columns. Nevertheless, as the concrete strength becomes higher, the necessary amount of spirals or hoops also becomes larger. Therefore. use of large amount of transverse hoops may not only worsen placement of the concrete, but also form a stiff "steel wall" between the confined core and the unconfined shell of concrete member, which tends to push the concrete shell out prematurely. From this viewpoint, a new and more reliable confinement method is required for HSC structures.

Authors have recently proposed a new confinement method for the HSC [Fukuhara et al, 2004]. In this new confinement method, the steel tubes are used as lateral confiner of concrete in lieu of conventional transverse hoops. Confinement by steel tube has several advantages over confinement by traditional hoops in that; 1) it is easy to provide confining pressure strong enough to improve ductility of HSC without hindering placement of concrete, 2) it provides confinement effect to the whole concrete section including the concrete cover, and 3) the steel tube can work as form for concrete columns.

In addition to the improvement in ductility of HSC, one more important issue needs to be addressed about the reparability of concrete buildings from the viewpoint of protection of property value. Traditionally, a structure that shows large energy-dissipation capacity has been considered to be good in terms of earthquake-resistance. However, large energy-dissipation involves large residual deformation and serious damage in structural elements or members. Therefore, development of HSC structure with sufficient ductility and permissible residual deformation is desirable.

Objectives of this paper is to investigate effect of the use of ultra high-strength steel on the residual deformation of HSC moment frame, and to provide fundamental information on the seismic properties of concrete frame made of high-strength concrete and ultra high-strength steel simultaneously.

2. EXPERIMENTAL PROGRAM

2.1. Specimen

A total of eight 1/3 scale one-story and one-span concrete frames were fabricated to simulate the lowest story of high-rise concrete buildings. All of these frames were made of tube-confined columns and hoop-confined beam and were designed so that they would exhibit ideal beam sideway mechanism. Figure 1 shows details of the specimens.

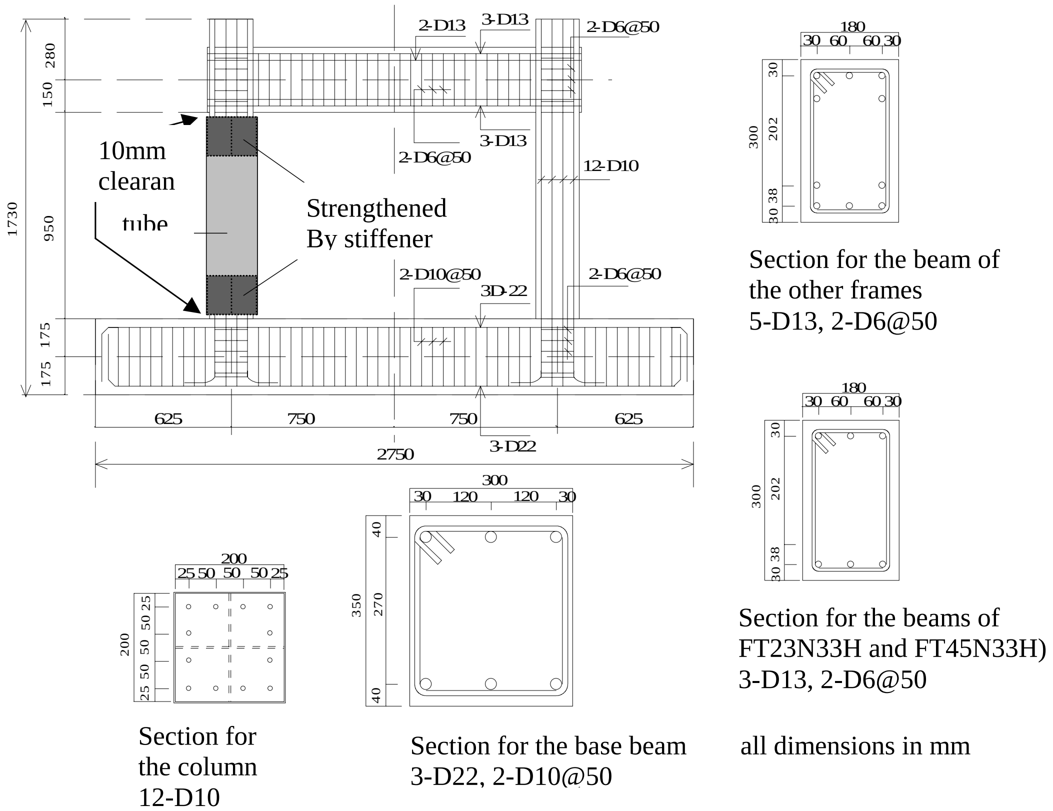

Figure 1 Details of the test frame

Table 2.1 Outlines of the Test Frames

Notation	f_c' (N/mm^2)	F_{cy} (N/mm^2)	F_{cu} (N/mm^2)	F_{By} (N/mm^2)	F_{Bu} (N/mm^2)	Axial load (kN)	Axial load ratio η	t (mm)
FT23N33	83.6	347	493	395	497	2207	0.33	2.3
FT45N33	82.5					2178	0.33	4.5
FT45N50	82.1					3284	0.5	4.5
FT60N50	82.9					3316	0.5	6.0
FT23N33H	88.8	997	1170	915	1106	2344	0.33	2.3
FT45N33H	89.4					2376	0.33	4.5
FT45N50H	89.3	906	1041	894	1022	3572	0.5	4.5
FT60N50H	89.3					3568	0.5	6.0

Note: f_c' = Strength of concrete cylinder (100x200mm) at the stage of testing
F_{cy} and F_{cu} = Yield and ultimate tensile strength of the longitudinal reinforcement in columns
F_{By} and F_{Bu} = Yield and ultimate tensile strength of the longitudinal reinforcement in beams
t = thickness of the steel tube used to confine columns

As one can see from Figure 1, concrete columns in each frame were confined by square steel tube having inner width of 200mm, while the beam of each was confined by conventional transverse hoops. Confinement by common hoops was applied to beam mainly because it generally doesn't subject to large axial compression and needs little confinement if the beam is designed to fail in flexure.

Longitudinal rebars in each column consist of twelve D10 (SD345 or KSS785) deformed bars uniformly distributed around the perimeter to give a steel ratio of 2.14%. Five D13 (SD390 or KSS785) deformed bars compose the tensile rebars in the beams of six frames to give a tensile steel ratio of 1.34%, which is larger than the upper limit recommended for concrete beam in the AIJ standards [2], while only three D13 (KSS785) were provided in the beams of the specimens FT23N33H and FT45N33H as listed in Table 2.1. Beam in each frame was confined by D6 (SD295) deformed bar having spacing of 50mm to give a transverse steel ratio of 0.67%. The SD295 deformed bar had a yield stress of 307MPa.

Square steel tubes used to confine columns were made in laboratory of Kyushu University by at first bending steel plate with target thickness into channel-shape, and then welding two of them. To enhance confinement effectiveness of the square steel tube, inner cross-type stiffeners were welded to the steel tube of at both bottom and upper ends of each column with length of 250mm. The inner stiffeners were made of steel plates with the same thickness and mechanical properties as those of the perimeter plates. The plates with thickness of 2.3mm, 4.5mm, and 6.0mm have yield strength of 279MPa, 286MPa, and 263MPa, respectively.

Ready-mixed concrete with targeted compressive strength of 80 MPa was used to fabricate all of the eight frames. Common Portland cement and coarse aggregate with maximum size of 13 mm were used to make the HSC. The standard cylinder strength at testing stage for each specimen is given in Table 1 along with the calculated ultimate moments.

Variables among the tests were the thickness of steel tube, with inner stiffeners or without, and the level of compressive load applied to the columns. Thickness of the steel tube, expressed in terms of ratio of outside width B to thickness t, i.e. B/t ratio, had values of 89, 46, and 35, while the axial load level expressed in term of axial load ratio η (=P/(A_g f_c'), where P is the applied axial load, A is the gross area of column section, and f_c' is the concrete cylinder strength) was 0.33 and 0.50. The axial load ratio of 0.33 corresponds to the upper limit for common normal-strength concrete columns recommended by the AIJ standard [AIJ, 1999], and η=0.5 was designed to investigate to what axial compression level the steel tube confinement can stand.

2.2 Test set-up and measurements

Figure 2 shows test apparatus. This test set-up was used to apply reversed cyclic lateral load while the test frame was subjected to constant axial compression applied through a universal testing machine having capacity of 5000kN. Cyclic loading was a displacement-controlled type, and the inter-story drift ratio R (=inter-story drift divided by the height 1100mm) was adopted to control loading process. The designed loading program is shown in Figure 3.

Four displacement transducers were divided into two pairs to measure lateral deformation of the right column and the left column, respectively; and the average value of both columns' lateral displacements was taken as the inter-story drift of test frame. Apparently, difference of the measured right and left columns' lateral displacement gives the average axial deformation of the beam.

In addition to the lateral displacement, the axial deformation of the right and the left columns were also measured using another four displacement transducers, each two of which measured one column's axial deformation. For each test frame, a total of 83 strain gages were embedded to measure the strains of the longitudinal rebars and the surface strains of the steel tube.

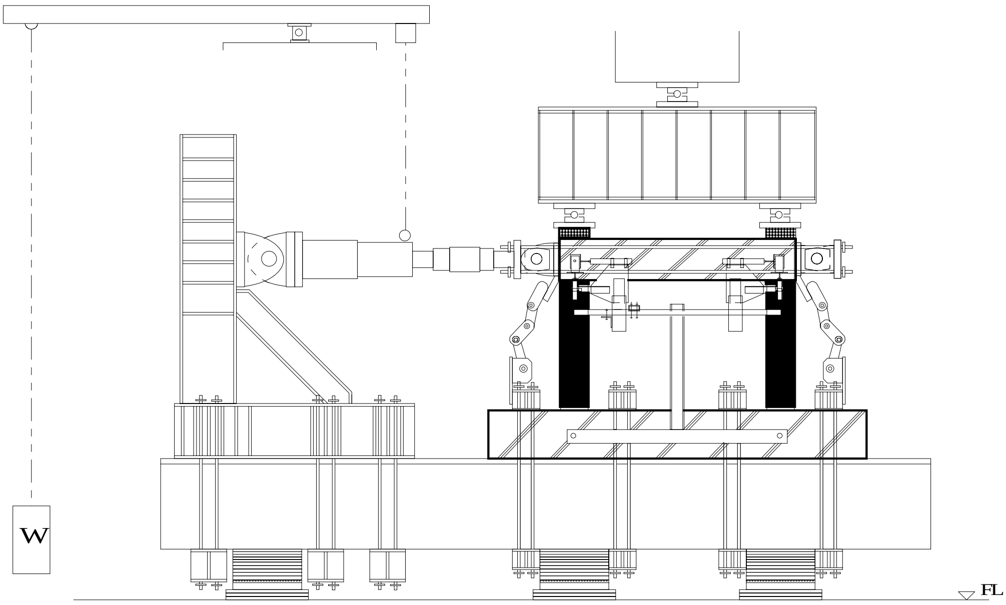

Figure 2 Test apparatus

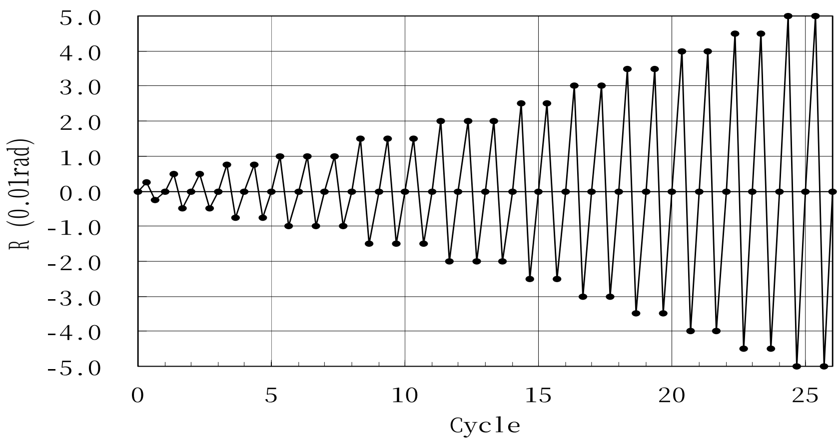

Figure 3 Loading program

3. OBSERVED BEHAVIOR AND EXPERIMENTAL RESULTS

3.1 Observed behavior

All of the test frames exhibited identical beam sideway mechanism as shown in Photos 1 and 2 . It can be seen from

Photo 1 Frame with Normal-Strength Rebars

Photo 2 Frame with Ultra High-Strength Rebars

Table 2 Primary Measured Results and Calculated Results

Notation	V_{max} (kN)	R_{max} (0.01rad)	V_{co} (kN)	V_{cn} (kN)	$\frac{V_{max}}{V_{co}}$	$\frac{V_{max}}{V_{cn}}$
FT23N33	377.1	1.16	344.4	322.3	1.10	1.17
FT45N33	377.5	1.16	355.5	328.3	1.06	1.15
FT45N50	422.0	1.19	386.7	345.9	1.09	1.22
FT60N50	411.4	1.23	404.9	370.1	1.02	1.11
FT23N33H	413.8	2.53	437.4	422.3	0.95	0.98
FT45N33H	462.9	2.05	494.3	440.9	0.94	1.05
FT45N50H	535.9	2.48	597.5	530.6	0.90	1.01
FT60N50H	575.7	2.49	670.8	558.9	0.86	1.03

Note: V_{max} = the measured maximum lateral load
R_{max} = the inter-story drift ratio at the V_{max}
V_{c0} = the calculated lateral load capacity ignoring effects of P-Δ and slip of rebar [Sun, 2004]
V_{cN} = the calculated lateral load capacity considering effects of P-Δ and slip of rebar[Sun, 2006]

Photos 1 and 2 that the plastic hinge zones had developed at both ends of beam and the bottom end of columns as designed. Visible expansion of steel tube plate was observed at the bottom of both columns, while the steel tube strains measured at the top of columns was very little.

It is noteworthy that damages observed in the frames where ultra high-strength longitudinal reinforcements were adopted are much less than those observed in the frames made of normal-strength longitudinal rebars, while both kinds of frames had been laterally deformed to the same level of deformation. This observation implies that use of ultra high-strength longitudinal rebars can simply reduce the seismic damage of the concrete frame.

The measured maximum lateral forces are listed in Table 2 along with the calculated results, and Details of the calculation method for the ultimate lateral load-carrying capacity of the frames can be found elsewhere [Sun et al, 2004]. As apparent from Table 2, for the frames made of normal-strength longitudinal rebars, conventional calculation method proposed by Sun et al [Sun et al, 2004] could predict the experimental results fairly well. On the other hand, this method tends to overestimate ultimate load capacity for frames with ultra high-strength rebars. This is mainly because the method by Sun et al [Sun et al, 2004] doesn’t consider effects of the P-Δ moment at large deformation and the slippage of high-strength steel. To solve this problem, the authors have recently proposed a new method that can consider these effects [Sun et al, 2006]. From Table 2 one can see that this new method do evaluate the ultimate capacity of confined HSC frame very well.

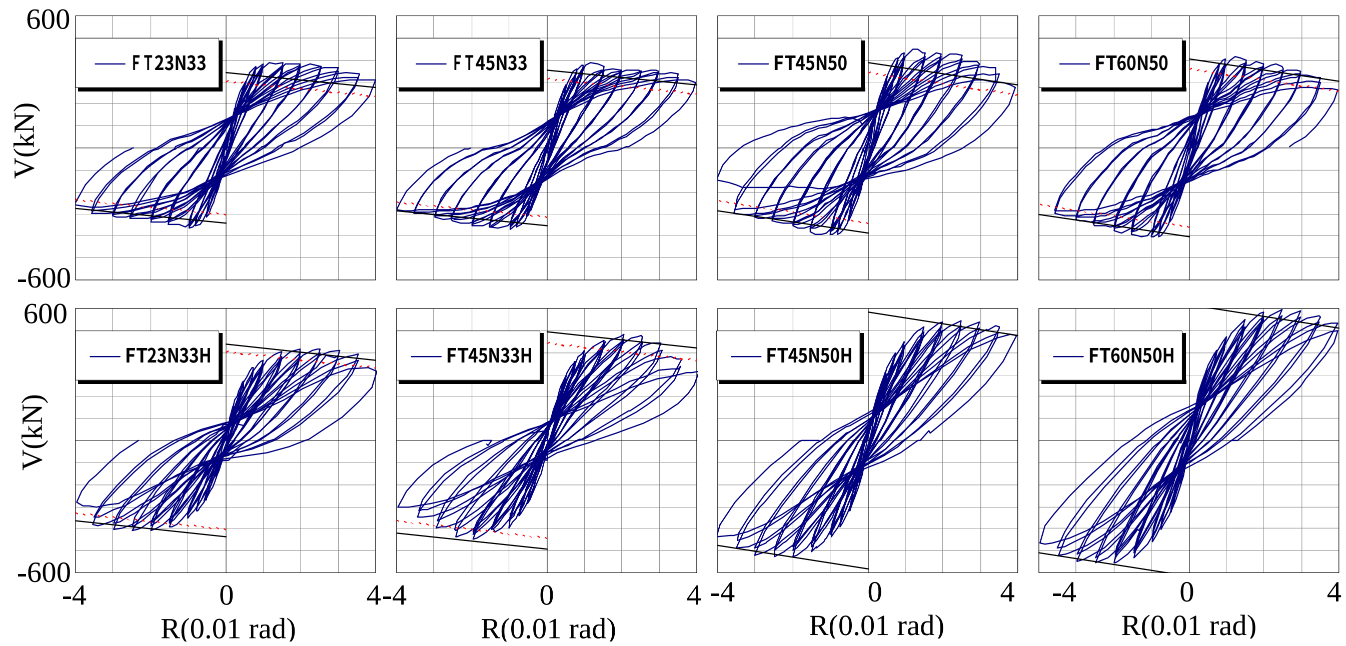

Figure 4 The measured lateral load V versus inter-story drift ratio R relationships

3.2 Experimental Results and Discussions

Figure 4 shows experimental results of the lateral load V versus inter-story drift ratio R relationships. The solid and dotted lines superimposed in the V-R hysteretic loops represent the calculated mechanism lines. The solid line was obtained by assuming that the beam sustain half of the measured maximum lateral load by compression, and the dotted line was based on assumption that the beam doesn't carry any axial load.

As compared with the frames made of normal-strength rebars, the frames made of ultra high-strength rebars indicate larger deformation capacity in addition to higher ultimate load capacity. The ultimate deformation where the frame reaches maximum load-carrying capacity exhibits much larger value, and this phenomenon becomes more obvious as the axial compression becomes higher. These observations mean that use of the ultra high-strength steel as rebars of HSC frame may significantly enhance the ductility of frame.

Figure 5 compares the axial elongation of beam of the frames with normal-strength rebars with that of the frames with ultra high-strength rebars, while effect of the steel strength on the residual deformation, energy absorption capacity, and equivalent viscous damping coefficient of confined HRC frames are plotted in Figures 6, 7, and 8, respectively.

As obvious from Figure 5, the higher the strength of rebar, the smaller the axial elongation of the beam, which implies that use of ultra high-strength longitudinal reinforcement is effective in reducing the difference of lateral deformation in adjacent columns, hence decrease damage in concrete beam.

Figure 6 indicates that the residual deformation of frames can be significantly and simply reduced by use of ultra high-strength rebars. On the other hand, it should be noted from Figure 7 that use of high-strength rebar does reduce the energy absorption capacity greatly, resulting in much lower equivalent viscous damping coefficient as shown in Figure 8. The equivalent viscous damping coefficient for the frames with high-strength steel as rebars varies between 4.8% and 8.7% until story drift ratio R reaches 0.02rad. These observations, in fact, means that the use of ultra high-strength steel enable design of concrete frame with large ductility and controllable residual deformation simultaneously. Therefore, inserting energy absorption devices such as low-yield stress steel plate damper and friction-type steel damper into the confined high-strength concrete frame may enable construction of concrete buildings that have sufficient earthquake-resistant capacity and be subtly damaged by strong earthquake. In other words, the really durable concrete building can be realized.

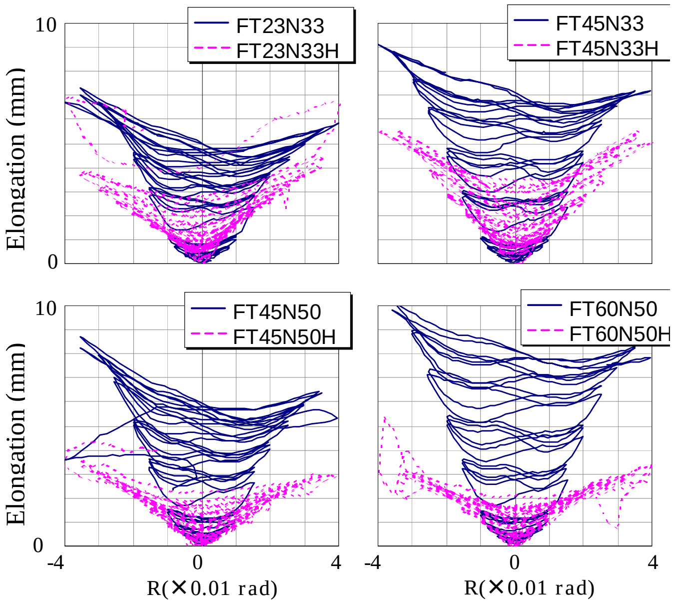

Figure 5 Comparison of elongation in beams

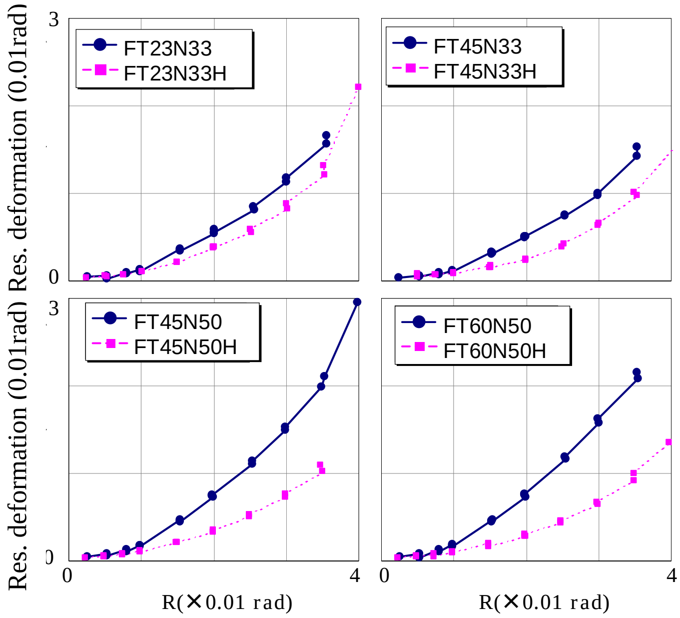

Figure 6 Comparison of residual deformation

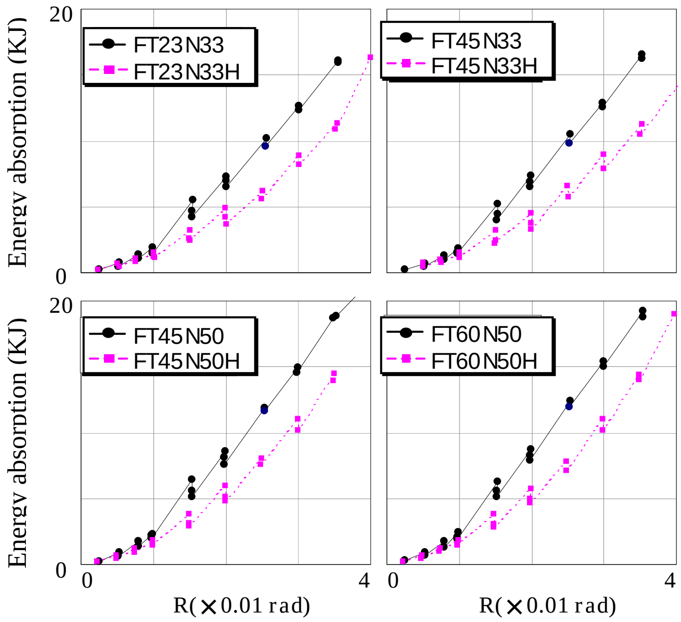

Figure 7 Comparison of energy absorption

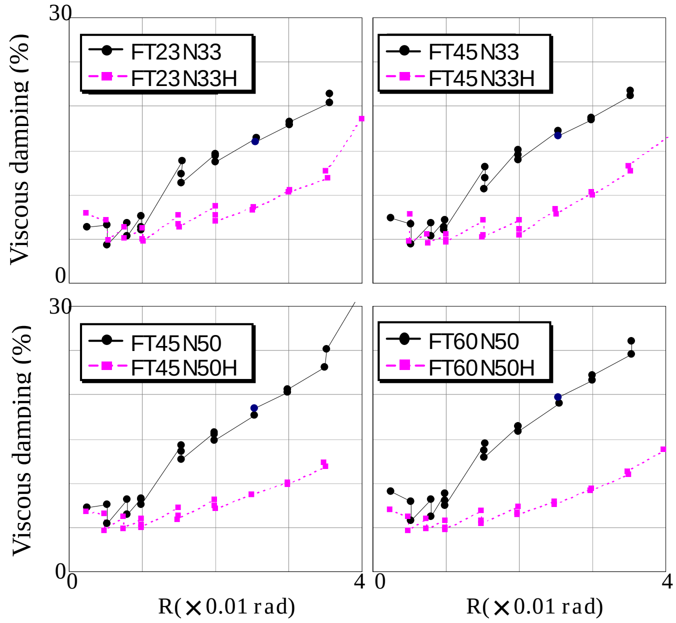

Figure 8 Comparison of viscous damping

4. CONCLUDING REMARKS

Eight 1/3 scale HSC frames were made and tested under reversed cyclic lateral load to investigate effect of confinement by steel tube and use of high-strength steel as rebars in beam and column on seismic capacity of confined HSC frame. From the experimental results reported in this paper, the following conclusions are reached.

1) Confinement of HSC column by steel tube that is strengthened with inner cross-type stiffeners can ensure high seismic performance to HSC moment-resisting frames. When strengthened with inner stiffener, confinement by the thin steel tube with B/t ratio of 89 enabled the HSC frame under high axial compression to behave in a very stable manner up to large deformation.
2) Use of ultra high-strength longitudinal reinforcements is very effective in reducing the residual deformation of structural members, hence greatly mitigating seismic damage of confined HSC frame.
3) The ultimate lateral load-carrying capacity of confined HSC frames can be accurately evaluated using the method proposed by the authors [Sun et al, 2006].

4) Confinement by steel tube and use of high-strength steel in HSC frame is a simple and effective method that enables construction of concrete buildings with high ductility and low damage, really durable concrete building.

REFERENCES

Architectural Institute of Japan (1999). AIJ Standards for Structural Calculation of Steel Reinforced Concrete Structures

Fukuhara, T. and Sun, Y. (2004). Behavior of HSC Moment-Resisting Frames Under Seismic Loading. *Proceedings of the 13th Word Conference on Earthquake Engineering*, Paper No. 3172 (12pages), Vancouver, Canada

Sun, Y. et al. (2006). Analytical Study of Cyclic Response of Concrete Members Made of High-Strength Materials. Proceedings of the 8th National Conference on Earthquake Engineering, Paper No. 1581 (10 pages), San Francisco, USA