SEISMIC BEHAVIOR OF R/C SHORT COLUMNS CONFINED LATERALLY BY A STEEL SQUARE TUBE

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SUMMARY

A large number of brittle shear failures in reinforced concrete (R/C) short columns have been reported during recent destructive earthquakes in Japan and other earthquake countries. While, it is also widely accepted that the ultimate shear strength carried by an R/C short column with conventional hoops and/or spirals does not increase remarkably even if considerable amount of transverse reinforcement is provided in the R/C short column section. On the contrary, other experimental studies by authors and other researchers have demonstrated that, if the R/C short column is confined by a steel tube with adequate tube-thickness, then brittle shear failure can be prevented and the short column can develop its ultimate flexural capacity with excellent deformation capacity [Kumamoto and Yoshimura (1997 and 1999), Yoshimura (1988, 1991 and 1998b)]. In addition, it has been also demonstrated that the diagonal (X-shape) reinforcements provided within the R/C short column and/or beam members can improve the poor seismic behavior such as brittle shear failure and pinching phenomenon of lateral-load versus story-drift hysteresis loops [Park and Pauley (1975), Yamamoto and Minami (1990), Yoshimura (1992, 1996, 1997, 1998a)]. Herein, new aseismic element using diagonally reinforced concrete short column confined laterally by a steel square tube is proposed. In order to investigate the seismic behavior of diagonally reinforced concrete columns, experimental studies were conducted by using the thirty-three different specimens. Among them, diagonally reinforced concrete short columns confined laterally by a steel square tube could develop the high strength and initial (or elastic) stiffness, large ductility and energy absorption capacity.

INTRODUCTION

Even after the world's first seismic building code was established in Japan in 1924, a large number of earthquake damage to building structures and/or structural elements have been reported during destructive earthquakes in Japan and other earthquake countries. Among these, brittle shear failures in R/C short columns caused by the 1968 Tokachi-oki earthquake are one of the highlights in earthquake damage being observed in modern R/C building structures. In order to prevent the structural damages such as brittle shear failures and to design more seismic buildings with adequate earthquake resistance and deformation capacity, seismic design provisions in the old Japanese Building Standard Law (BSL), which was firstly established in 1950, was drastically revised in 1981, and the current seismic design method has been effective since then. On the contrary, a large number of R/C building structures which were designed in accordance with the design provisions of the old BSL are still existing throughout the country, and it is noted that many of those buildings were severely damaged during the 1995 Hyogoken-Nanbu earthquake. Based on the lessons obtained from these severe structural damage to the existing building structures designed by the old design codes and standards, a new Building Code for Promotion of Seismic Strengthening of the Existing Building Structures was established on 25th of December in 1995. In accordance with the provisions of this Code, seismic safety of the large scale existing buildings for both public

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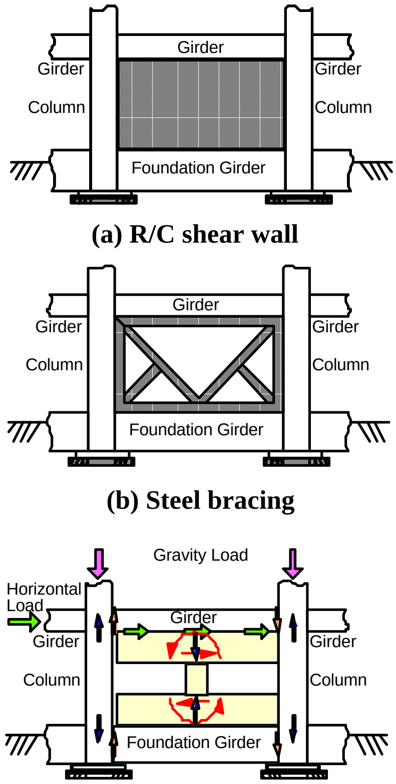
and private uses must be investigated against coming big earthquakes, and seismic strengthening should be required if the building does not have an adequate seismic resistance and/or deformation capacity. According to a guideline for seismic strengthening design of the existing R/C building structures [Japan Association for Building Disaster Prevention (1990)], only R/C shear walls and steel bracings shown in Figures 1(a) and 1(b) are recommended to use as the antiseismic elements for existing buildings because of being accepted widely as the earthquake resisting elements for moment-resisting space frames in Japan. By means of these aseismic elements, however, it is difficult to control or provide all of the effective conditions required for earthquake resistant design such as high stiffness and strength, large ductility and energy absorption capacity simultaneously. Herein, more practical aseismic elements are proposed by using diagonally reinforced concrete short columns confined laterally by a steel tube. Figure 1(c) represents the proposed aseismic element composed of a diagonally reinforced concrete short column, top- and bottom-girders. It is understood from Figure 1(c) that, by using the proposed seismic elements, adequate window openings can be provided even after being strengthened. This is one of the big difference from the case of using the R/C shear walls and/or steel bracings as the seismic strengthening elements into ordinary R/C moment resisting frames. By means of this proposed aseismic elements, top- and bottom girders are connected firmly to the adjacent exiting R/C beam- and column-members, and the short columns are intended to resist lateral earthquake forces mainly by the shear and flexural moments induced in the short columns during an earthquake.

It is widely accepted that an R/C short column with conventional hoops and/or spirals is difficult to prevent the brittle shear failure mode. However, other experimental studies had demonstrated that, if the R/C short column is confined by a steel square tube with adequate tube-thickness, then brittle shear failure can be prevented and the short column can develop its ultimate flexural moment capacity [Kumamoto and Yoshimura (1997), Yoshimura (1988, 1991 and 1998b)]. In addition, the evaluating method for ultimate lateral strength of a confined R/C short column which is determined by flexural, shear and bond deterioration failure mode had been proposed by authors [Kumamoto and Yoshimura (1999)]. However those confined R/C short columns with ordinary main parallel longitudinal reinforcing bars (Re-bars) showed poor energy absorption capacity due to pinching caused by bond deterioration between main longitudinal Re-bars and their surrounding concrete inside the steel tube. While, diagonal (X-shape) reinforcements provided into R/C members have been proposed for improving seismic behavior of R/C members [Park and Pauley (1975), Yamamoto and Minami (1990), Yoshimura (1992, 1996, 1997, 1998a)]. Main objective of present study is to investigate the seismic behavior of diagonally reinforced concrete short columns confined laterally by a steel square tube.



(a) R/C shear wall

(b) Steel bracing

(c) Proposed aseismic element

Figure 1: Aseismic elements

SPECIMENS

Reinforcing details, size and shape of typical specimens are shown in Figure 2, and all the thirty-three specimens are listed in Table 1 together with the material properties used for each specimen. All the specimens are composed of a short column with 15cm x 15cm cross-section, and top- and bottom-girders. In case of specimens with lateral confinements by steel square tube, 5mm clearances are provided on top and bottom of the steel square tube so as that the steel tube does not carry the longitudinal stress but only carry the transverse stresses during lateral loading reversals. All the specimens are classified into two test groups according to the difference in the experimental objective. Since main objective of the present study is to develop an effective lateral-load resistant element composed of an R/C short column which is intended to place within the plane enclosed by the existing beam and column members, the short column are not basically subjected to any axial (or vertical) loads. Herein, the First Group Specimens are to investigate the effects of concrete strength, number of Re-

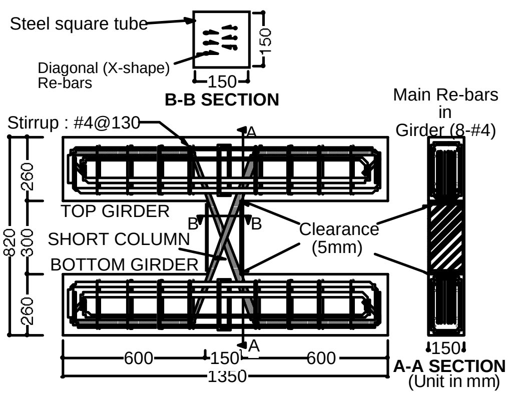


Figure 2: Size and shape of test specimen

Table 1: List of specimens and material properties

Group	Specimen	Lateral Reinforcement of Short column	Main Re-bars: Amount of Main Re-bars	Main Re-bars: f_y (MPa)	Concrete: f'_c (MPa)	Concrete: f'_{cc} (MPa)	Shear-span ratio M/(QD)	$\frac{N}{bDf'_c}$
First Group Specimens	RC	Hoop : #2 @30 (f_y=312MPa)	Parallel : 6-D13 (#4)	332	35.5	---	1.0	0
	SRC	Steel tube : t=4.5mm ($_tf_y$=339MPa)	Parallel : 6-D13 (#4)	342	28.3	---		
	N8D10		X-shape : 8-D10 (#3)	378	22.4	36.9		
	N6D13		X-shape : 6-D13 (#4)	342	28.3	42.8		
	H6D13		X-shape : 6-D13 (#4)	369	40.9	55.4		
	N6S13		X-shape : 6-13ϕ	316	27.5	42.0		
	H6S13		X-shape : 6-13ϕ	316	41.5	56.0		
	N4D16		X-shape : 4-D16 (#5)	364	28.4	42.9		
	N4D19		X-shape : 4-D19 (#6)	354	25.8	40.3		
	N4S19		X-shape : 4-19ϕ	308	24.7	39.2		
	N2D22		X-shape : 2-D22 (#7)	349	29.8	44.3		
	N2D19 4D10		X-shape : 2-D19 (#6) X-shape : 4-D10 (#3)	354 378	29.8	44.3		
	N2D22 4D6		X-shape : 2-D22 (#7) X-shape : 4-D6 (#2)	349 423	22.4	36.9		
	N6D13-0.5		X-shape : 6-D13 (#4)	369	26.7	41.2	0.5	
	N6S13-0.5		X-shape : 6-13ϕ	316	26.7	41.2		
Second Group Specimens	XRC-300-0	None	X-shape : 6-D13 (#4)	367	32.4	32.4	1.0	0
	XT2.3-300-0	Steel tube : t=2.3mm ($_tf_y$=316MPa)			31.1	34.6		
	XT3.2-300-0	Steel tube : t=3.2mm ($_tf_y$=300MPa)			31.2	37.6		
	XT4.5-300-0	Steel tube : t=4.5mm ($_tf_y$=339MPa)			31.1	45.6		
	XRC-200-0	None			20.1	20.1		
	XT2.3-200-0	Steel tube : t=2.3mm ($_tf_y$=316MPa)			19.4	22.9		
	XT3.2-200-0	Steel tube : t=3.2mm ($_tf_y$=300MPa)			18.1	24.5		
	XT4.5-200-0	Steel tube : t=4.5mm ($_tf_y$=339MPa)			18.7	33.2		
	XT2.3-300-0.1	Steel tube : t=2.3mm ($_tf_y$=316MPa)			34.6	38.1		0.1
	XT4.5-300-0.1	Steel tube : t=4.5mm ($_tf_y$=339MPa)			34.9	49.4		
	XT2.3-300-0.2	Steel tube : t=2.3mm ($_tf_y$=316MPa)		348	27.6	31.1		0.2
	XT4.5-300-0.2	Steel tube : t=4.5mm ($_tf_y$=339MPa)			29.3	43.8		
	XT2.3-300-0.3	Steel tube : t=2.3mm ($_tf_y$=316MPa)			29.9	33.4		0.3
	XT4.5-300-0.3	Steel tube : t=4.5mm ($_tf_y$=339MPa)			30.5	45.0		
	XT2.3-300-0.4	Steel tube : t=2.3mm ($_tf_y$=316MPa)			28.7	32.2		0.4
	XT4.5-300-0.4	Steel tube : t=4.5mm ($_tf_y$=339MPa)			28.7	43.2		
	XT2.3-200-V	Steel tube : t=2.3mm ($_tf_y$=316MPa)			20.8	24.3		0~0.4
	XT2.3-200-0.4				18.9	22.4		0.4

[Remarks]
f_y : Yield strength of Re-bar
f'_c : Compressive strength of concrete cylinder
f'_{cc} : Compressive strength of confined concrete
N : Axial load
bD : Cross-sectional area of short column
t : Steel tube thickness
$_tf_y$: Yield strength of steel square tube

bars, size and shape of Re-bars, reinforcing method for main Re-bars and shear-span ratio of the short column on seismic behavior of the elements under no axial loads. In case of providing a proposed aseismic element into a rectangular plane enclosed by the existing R/C beams and columns in ductile moment resisting frames, however, vertical (or axial) elongation of the confined R/C short column element induced by the cracks inside the steel tube are expected to occur. Herein, in order to investigate the confining effects of vertical elongation on structural behavior of the proposed aseismic element, main experimental parameters included in Second Group Specimens are the concrete strength, steel tube thickness and axial load ratio.

First Group Specimens

Specimen RC in Table 1 has an R/C short column with ordinary parallel longitudinal Re-bars (6-#4) and square hoops (#2-@30), while all of the short columns in other specimens in the First Group Specimens are confined by a steel square tube with 4.5 mm thickness. Except that the short column in Specimen SRC has a parallel longitudinal Re-bars (6-#4), other short columns confined by a steel square tube have special reinforcement by diagonal (X-shape) Re-bars as shown in Figure 2. These specimens with diagonal (X-shape) Re-bars are designated by a four symbol code such as (N8D10) and (H6D13). The first letter (N) or (H) represents that the Normal or High strength of concrete is cast in the short column cross-section, respectively. The second numerals such as (8) and (6) are total number of diagonal Re-bars provided in the steel square tube. The third symbol (D) or (S) shows that the Deformed bars or Smooth bars is used as the diagonal Re-bars, and the last numerals are bar-size (or nominal diameter) of these bars in mm. The last two specimens, (N6D13-0.5) and (N6-S13-0.5), have a shear-span ratio of 0.5, in which the height of short-column is one-half of other specimens.

Second Group Specimens

All of the Second Group Specimens are designated by a five symbol code such as (XT2.3-300-0) and (XT2.3-200-0.4). The first letter (X) represents that the X-shape or diagonal Re-bars (6-#4) is provided in all the short column, and the second letter (T) or (RC) represents that the R/C short column is confined laterally by a Steel Square Tube or short column dose not have any confinement by a steel tube, respectively. The third numerals such as (2.3) and (4.5) are the tube-thickness of the steel square tube in mm adopted for confining the R/C short column, and the forth numerals such as (300) or (200) are the specified concrete strength cast in the short column in kgf /cm^2. The last numerals (0) or (0.4) represent the axial load ratio : $n=N/(bDf'_c)$, where (N) is the axial load applied to the R/C short column elements, (bD) are the cross-sectional area of the R/C short column inside the steel tube, and (f'_c) represents the compressive strength of concrete in short column elements, respectively. The letter (V) in Specimen XT2.3-200-V represents that the variational axial loads between n=0 and 0.4 are applied to this specimen. In order to design the diagonally reinforced concrete short columns without any pinching phenomena, also, all the main diagonal (X-shape) Re-bars with adequate anchorage length are provided into the short columns on the basis of experimental results in First Group Specimens.

TEST SETUP AND INSTRUMENTATION

Test setup adopted in the present study is shown in Figure 3, where top- and bottom-girders of the specimen are fixed to the loading beam and reaction frame, respectively. Between loading beam and reaction frame, a pantograph is installed to prevent the out-of-plane deformation of the test specimen and to keep the top girder horizontally. Axial load to the column and alternately repeated lateral forces are applied by double-acting hydraulic jacks 1 and 2, and the longitudinal axis of the double-acting hydraulic jack 2 is always kept to be located at the mid-height of the short column element. All the displacements including interstory drifts between top- and bottom-girder, and elongation of the short column caused by cracking within the short column sections were measured by displacement transducers. All of the strains occurred at the top and bottom of the main parallel or diagonal (X-shape) Re-bars and strains on the steel tube surfaces were also measured by electrical strain gages. For all the test specimens, load-controlled procedure was adopted in the early stage of lateral loading application, and then displacement-controlled procedure was applied in the latter stage of loading until $R=5.0\times10^{-2}$ rad. All the information measured were sent to a personal computer and were processed simultaneously.

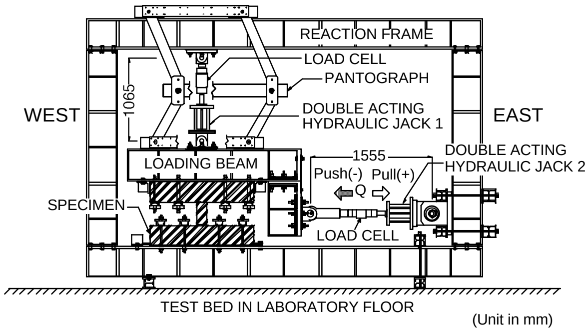


Figure 3: Test setup

EXPERIMENTAL RESULTS

Typical Q-R relations obtained from the experiments in First and Second Group Specimens are shown in Figures 4 and 8, where (Q) represents the lateral force applied to the specimen and (R) is the deflection angle defined as the relative lateral displacement between top and bottom of the short column divided by a clear column height of 30cm. Elastic (or initial) lateral stiffness given by dashed and dotted lines in Figures 4 and 8 are calculated by assuming that only the diagonal (X-shape) Re-bars located in the steel tube resist lateral forces, and ultimate lateral strengths presented by (Q_{u1}) and (Q_{u2}) are theoretical values by assuming that; (1) only the diagonal Re-bars resist lateral forces, and in case of the ultimate state, all the diagonal Re-bars yield in tension or compression perfectly, (2) in case of short columns subjected to axial compression loads, only the concrete in the steel tube can resist all the axial loads, and the ultimate lateral strength under axial compression can be determined by the lateral strength carried by the diagonal Re-bars and ultimate flexural moment capacity of the plane concrete column subjected to the axial compression loads [Park and Pauley (1975), Yamamoto and Minami (1990)], and (3) ultimate lateral strengths given by the (Q_{u1}) and (Q_{u2}) lines are calculated by assuming the two different concrete strengths, that is, (f'_c) is the cylinder strengths without any lateral confinement and (f'_{cc}) is the confined concrete compressive strength [Sun and Sakino (1996)], respectively.

First Group Specimens

Typical lateral force (Q) versus story drift (R) relations obtained from the experiments in the First Group Specimens are shown in Figure 4.

Summarizing the test results obtained;

1). The R/C short column with ordinary main longitudinal Re-bars and square hoops (Specimen RC) failed in brittle shear failure mode with poor deformability, and could not develop the ultimate flexural moment capacity (Q_{mu}) of the short column, which is given by horizontal dotted lines shown in Figure 4(a). However, shear failure did not occur in the short column in Specimen SRC which is confined by a steel square tube, and the column developed its ultimate flexural strength (Q_{mu}) given by horizontal dotted lines in Figure 4(b). This specimen showed excellent deformability, but had poor energy absorption capacity due to pinching caused by bond deterioration between longitudinal Re-bars and surrounding concrete into the steel tube.

2). All other short columns with diagonal (X-shape) Re-bars could develop the ultimate flexural moment capacity (Q_{u1}, Q_{u2}), and showed excellent deformation capacities as being observed in Figures 4(c) through 4(f).

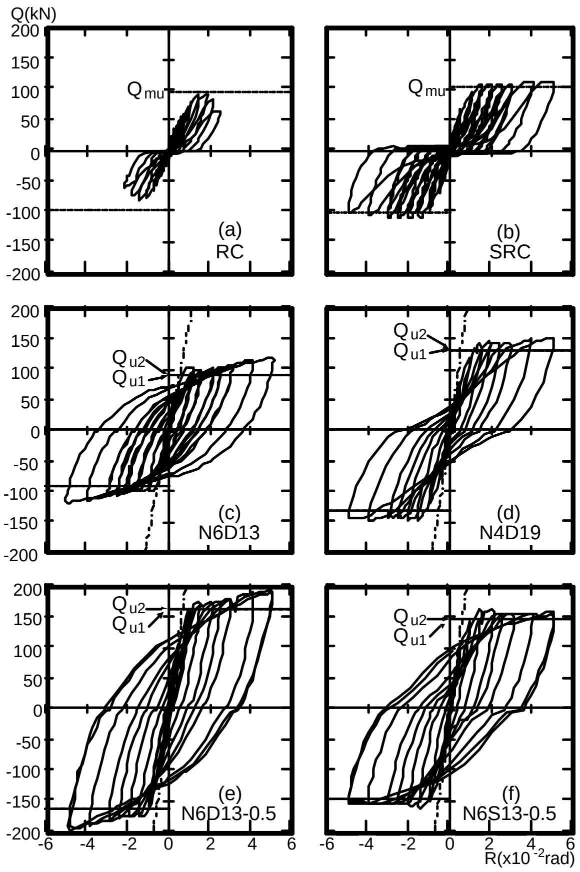


Figure 4: Typical Q-R relations in First Group Specimens

3). Hysteresis loops of diagonally reinforced concrete columns shown in Figures 4(c) through 4(f) are more excellent than Specimen SRC shown in Figure 4(b), because considerable pinching phenomena do not occur in their Q-R loading histories. However, Specimen N4D19 (see Figure 4(d)) showed slight pinching phenomenon.

In Figure 5, sum of the yield strengths of the diagonal Re-bars in short columns are plotted against their actual bond strengths, which were calculated based on the allowable short-term bond stresses specified in the current Architectural Institute of Japan Standard [AIJ (1988)] and measured anchorage lengths of the Re-bars anchored within the top and bottom girders. In the figure, specimens having pinching phenomena are shown by using solid symbols. This figure shows that the pinching phenomena occurs in the Q-R histories loops, if the yield strength of diagonal Re-bars (□af_y) is higher than the actual bond strength of the same Re-bars (□□lafa). This fact means that, by selecting appropriate bar size and anchorage length for diagonal Re-bars, it is possible to design this type of aseismic element without any pinching phenomena completely.

4). Considerable difference in size and shape of short column can be observed between hysteresis loops in Figures 4(c) and 4(e) or 4(f). This fact means that, by selecting the appropriate shear-span ratio of the short column, the ultimate lateral strength and energy absorption capacity as well as initial stiffness can be easily controlled.

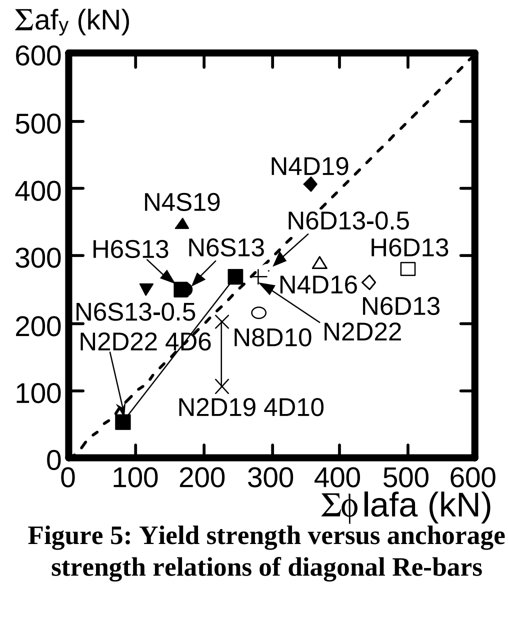


Figure 5: Yield strength versus anchorage strength relations of diagonal Re-bars

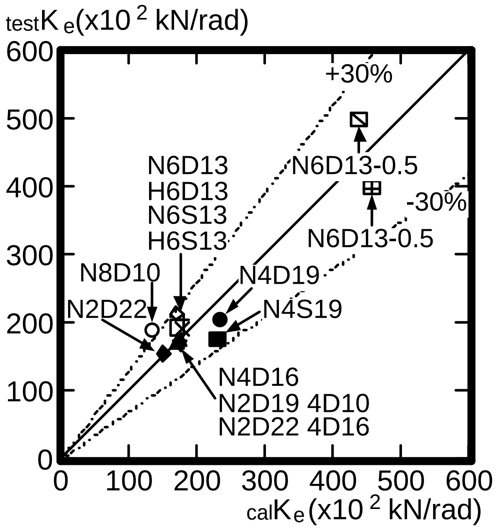


Figure 6: Initial (elastic) stiffness

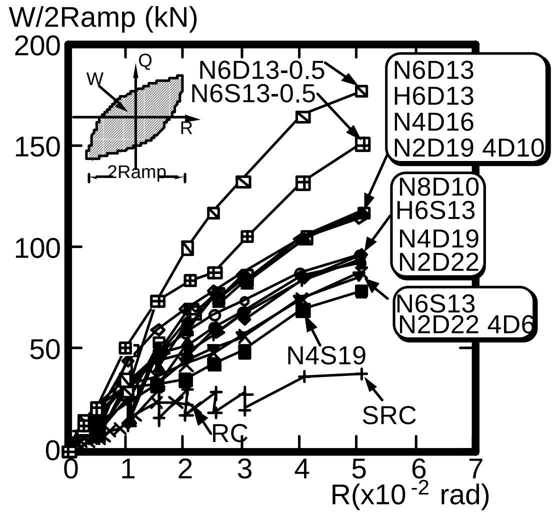


Figure 7: Energy absorption capacity

5). In Figure 6, initial (or elastic) stiffness obtained from the experiments ($_{test}K_e$) are plotted against their theoretical initial stiffness ($_{cal}K_e$) which were calculated by assuming that only the diagonal (X-shape) Re-bars located in the steel tube resist lateral forces. In this figure, initial stiffness ($_{test}K_e$) obtained from the experiments are the secant modulus at one-third strength of yield strength. It can be understood from Figure 6 that the initial stiffness of this type of aseismic element can be well predicted by a simple theory.

6). By using all the Q-R hysteresis loops obtained, energy absorption capacity of each specimen was calculated. Results are compared in Figure 7, in which the area within each hysteresis loop shown schematically in the same figure is plotted against the corresponding interstory displacement. It can be observed from this figure that the proposed aseismic element with diagonal Re-bars provided within the confined R/C short column has much more excellent energy absorption capacity than the ordinary R/C short-column elements with parallel Re-bar arrangement.

Second Group Specimens

Typical lateral force (Q) versus story drift (R) relations obtained from the experiments in Second Group Specimens are shown in Figure 8.

Summarizing the test results obtained from the Second Group Specimens:

1). Shear failure did not occur in all the short columns, and the columns could develop their ultimate lateral strengths (Q_{u1} and Q_{u2}) given by the theoretical approach. The ultimate strengths (Q_{u2}) which were calculated based on the compressive strength of laterally confined concrete (f'_{cc}) give the better theoretical prediction than the (Q_{u1}) based on the concrete cylinder test strength (f'_c).

2). Specimens without any lateral confinements by steel square tube such as Specimen XRC-300-0 (see Figure 8(a)) showed strength deterioration caused by buckling of compressive Re-bars provided into the short column. On the other hand, diagonally reinforced concrete short columns confined by a steel square tube showed quite excellent deformability without any strength deterioration up to the deflection angles of $5.0x10^{-2}$ rad. It can be noted, however, that in all the specimens subjected constant axial compression loads, pinching phenomena were observed in their Q-R hysteresis loops, and much more pinching occurred in the specimens subjected to higher constant axial compression loads. The reason why those pinching phenomena did not occur in the specimens without any vertical load but appeared in the specimens subjected to constant vertical compression, can be understood from the difference of yielding time of diagonal Re-bars shown in Figures 9, which are determined from the strain measurement in the diagonal Re-bars. In Figures 9, two typical Q-R relations subjected to no vertical load (Specimen XT4.5-300-0) and higher constant axial compression (Specimen XT4.5-300-0.4), are presented respectively, where Q-R curves from story-drift of $R=+2.5x10^{-2}$ rad through $R=-2.5x10^{-2}$ rad are respectively presented as well as the time of yielding in tension or compression of diagonal Re-bars. In these figures, $+Q_{max}$ and $-Q_{max}$ denote the lateral loads carried by the specimens at the lateral loading reversal points of $R=+2.5x10^{-2}$ rad and $R=-2.5x10^{-2}$ rad, and (T_y) or (C_y) represent that the diagonal Re-bars yielded in tension or compression, respectively. In case of the specimen having no axial compression (Figure 9(a)), yielding in compression (C_y) of No.3 Re-bar, which was yielded in tension at the initiation of loading reversal from $+Q_{max}$ to $-Q_{max}$, and yielding in tension (T_y) of No.1 Re-bar being yielded in compression at $+Q_{max}$ occurred almost simultaneously as being observed in Figures 9(a). In case of the specimen subjected to constant axial

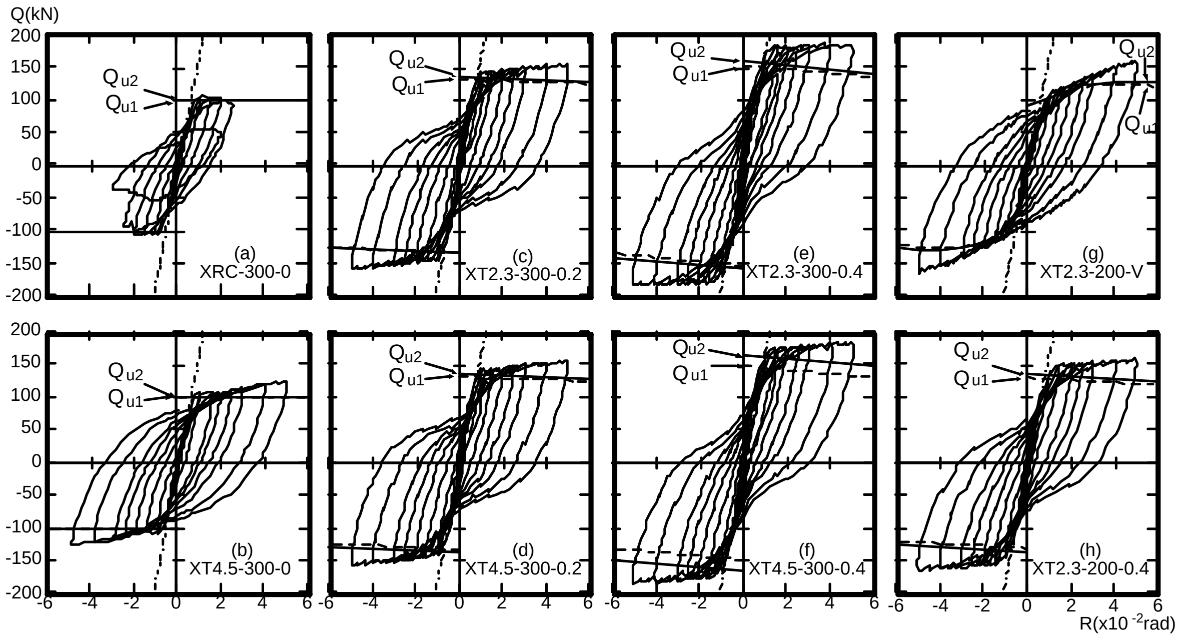
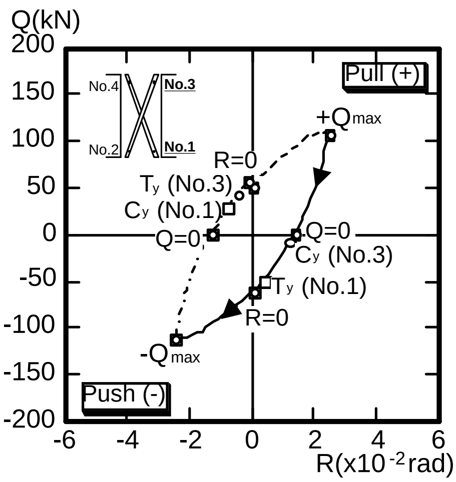


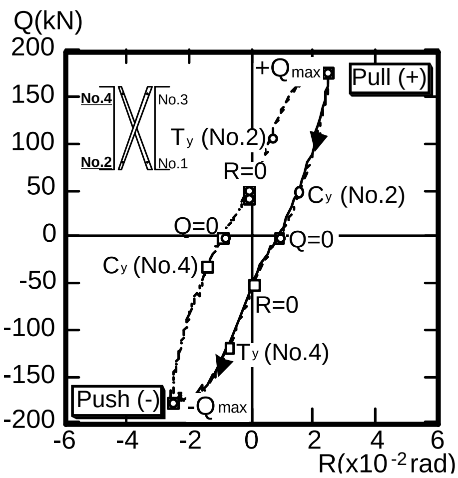
Figure 8: Typical lateral force (Q) versus story drift (R) relations in Second Group Specimens

compression (Figure 9(b)), however, these yielding in compression of No.2 Re-bar and yielding in tension of No.4 Re-bar did not occur at the same time, in other word, yielding in compression of the No.2 Re-bar occurred considerably earlier than the initiation of yielding in tension of the No.4 Re-bar. Because of these difference observed in the stress-strain hysteretic behavior between two specimens, pinching appeared in the later specimens.

3). By comparing the Q-R curves obtained from the specimens subjected to constant vertical loads of n=0 and 0.4, and the Q-R curve subjected to variational axial load as being shown in Figure 8, it can be understood that the hysteretic behavior of this kind of aseismic element which is subjected to variational axial compression can be predicted from the aseismic elements under constant vertical axial loads.



(a) Specimen XT4.5-300-0



(b) Specimen XT4.5-300-0.4

Figure 9: Typical Q-R relations

CONCLUDING REMARKS

In order to develop the new aseismic element with diagonally reinforced concrete column confined by a steel square tube, experimental studies were conducted by using thirty-three different aseismic element specimens, where concrete strengths, number of Re-bars, size and shape of Re-bars, reinforcing methods for main Re-bars, shear-span ratios of the short column, steel tube thickness and axial load ratios were main test parameters. In case when the vertical axial compression loads are not induced in the diagonally reinforced concrete short column confined by a steel square tube during lateral loading reversals, brittle shear failure did not occur in the short column, and could develop their ultimate flexural moment capacity. In addition, the short column showed excellent deformation capacity without any strength deterioration. By selecting appropriate bar size and anchorage length for diagonal (X-shape) Re-bars, also, it is possible to design this type of aseismic element without any pinching phenomena completely, and the ultimate lateral strength and energy absorption capacity as well as initial stiffness can be easily controlled by changing the shear-span ratio of diagonally reinforced concrete column. The ultimate lateral strength and initial stiffness can be evaluated by simple theory. In case when constant axial compression forces are induced in the diagonally reinforced concrete short column confined by a steel tube of the aseismic element during lateral loading reversals, pinching phenomena were observed in their Q-R hysteresis loops, while in the specimens without any axial compression, any pinching did not appear. In case of the specimen subjected to variational axial compression (Specimen XT2.3-200-V), its hysteretic behavior seems to be approximately predicted from the specimens with constant axial loads. In addition, extensive pinching did not appear in its Q-R hysteresis loops because this specimen was not subjected to considerably high axial compression around the deflection angle near R=0 rad.

ACKNOWLEDGEMENTS

The experimental study presented herein was made possible by a financial support of the Grant in Aid for Scientific Research of the Ministry of Education of Japanese Government. The authors wish to thank all the former students of the structural Engineering Laboratory of Oita University who contributed the experimental phase of the present study.

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