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Experimental Investigation of Performance of Externally Collared Reinforced Concrete Short Columns

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ABSTRACT

This paper presents the experimental study of nine pieces of reinforce concrete (RC) and short columns. RC short columns were tested with cyclic loading with displacement control under the influence of constant axial load with load index of 0.2. Three columns within the tested nine columns are reference columns which have the details of the reinforcement given in the modern regulations and six of them are 150mm and 100mm externally collared columns. In addition to the parameter of the collar spacing, the cutoff rate (α_S=2-1.5-1) is also considered as a parameter. The data obtained from experimental results have shown that externally collar contributes significantly to increasing the shear resistance of RC short columns and limiting the shear dominant behavior. It has been observed that the effectiveness of the externally collar increases with the decrease of the aspect ratio. The values of externally collared columns are much higher than reference columns with perfect secant stiffness, effective stiffness and energy consumption values.

1. INTRODUCTION

The shear dominant behavior of a reinforced concrete carrier system component reveals that safety factor must be greater in the design of this component because the failure of the component displaying shear dominant behavior occurs instantaneously. This sudden failure causes a significant increase in risk of loss of life and property. Considering the vertical carrier system elements, this critical cutting behavior is most clearly seen in short columns. The short columns cannot meet the demand for floor displacement caused by the lateral load effect due to their shorter effective length than the other floor columns. This leads to the necessity of meeting the demand for displacement with the strength, so the shear dominant behavior develops. It is very important that the elements that display or have to display shear dominant behavior are designed and dimensioned to have sufficient strength, sufficient stiffness and / or

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ductility. The requirement given in almost all regulation in the design of reinforced concrete short columns is that the reinforcement conditions of the junction region are maintained throughout the entire column. However, it is expressed in Fema274 (1997) that this detailing is not sufficient in meeting the demand that a short column is subjected to and Japan-Kobe earthquake is given as an example for this situation. Therefore, it is seen as a need to search for new applications that could create alternatives to the details of the reinforcement in modern regulations.

In order to improve the cutting behaviors of the columns from the outside applications, the wrapping applications of reinforced concrete jacketing, steel jacketing, FRP and its derivation came to the fore. Bett et al. (1988) tested three short columns with the aspect ratio of 1.5 under constant axial load and reversible lateral load. Sprayed concrete and reinforced concrete jacketing were applied to the two columns. Rodriguez and Park (1994) applied reinforced concrete jacketing with 100 mm thickness to full-scale columns with 350 * 350 cross-sectional dimensions. These two studies have resulted that the applications of reinforced concrete jacketing increase the strength and stiffness of the columns. In the second study, it was stated that this rehabilitation technique is laborious and time consuming. Priestley et al. (1994a-1994b) examined the effectiveness of steel jacketing in strengthening columns with insufficient shear strength. In this study, 8 circular columns and 6 rectangular columns with the aspect ratio of 1.5 and 2 were tested. It has been stated that the steel jacketing very effectively increases the shear strength and bending ductility of the columns with insufficient shear strength. Xiao and Wu (2003) suggested the use of a partially rigid steel jacketing for the rehabilitation of square and rectangular columns. Zhou and Liu (2010) investigated a total of eight columns, 3 of which are placed in circular pipe and the other 3 of which are placed in square pipe. Liu et al. (2011) tested ten short column samples, two of which were control specimens and eight of which were strengthened by steel collar. The methods applied in the studies have shown that there is an increase in the stiffness and shear strength of short columns and there is also an increase in ductility and energy absorption values. Promis et al. (2009) conducted studies on seven samples reinforced with CFRP and GFRP wrappers which were applied continuously or discontinuously. While fully wrapped specimens show rigid behavior, it has been reported that many cracks occur in the interstices between the bands which were wrapped with interval wrapping. It has been stated that the elastic energy capacity of the fully wrapped columns is considerably higher than the others, and 3-fold wrapped sample at frequent intervals has more ductility and energy absorption capacity than the others.

2. RESEARCH SIGNIFICANCE

Conducting short column experiments is very difficult. In order to be able to capture the behavior, the aspect ratio needs to be at a very low level. This situation leads to considerable increase in lateral load levels. Previous studies have shown that the applications of steel jacketing and collar contribute to short column behavior.

However, in the large amount of these studies, faulty columns are referred to as control sample. In this study, reference columns are perfect elements that are designed and dimensioned according to the requirements of modern regulations. Therefore, it is first investigated whether the proposed method can create alternatives as rehabilitation method to the design requirements in current regulations. Full-scale columns were used in the study. The range of the proposed collar application was changed and the winding effect was examined. In addition to this, by changing the aspect ratio, the effectiveness of shear dominant behavior was investigated and the effects of the methods on the behavior were revealed.

3. TEST COLUMNS and EXPERIMENTAL SETUP

Nine columns with a cross-sectional dimension of 400x400 were used as a test column. Three of these are reference column reinforced according to winding region conditions. The shear reinforcements of the reference columns are Ø10/100mm. The shear reinforcements of the other six collared columns are Ø10/150mm. Collar spacing of three of these collared columns is s_2=150mm, and collar spacing for the other three columns is s_2=100mm. Longitudinal reinforcement of all columns is 8Ø16 and the material properties used in production are the same. RC short columns were subjected to axial load using the 0.2 load index during the test. Double repetitive lateral loads were applied to the columns with the controlled displacement. The lateral load was applied to the test columns with levels of 800mm, 600mm and 400mm on the foundation. Therefore, the aspect ratios (*M/Vd*) of the test columns are 2, 1, 5 and 1 respectively. Thus, in the columns tested, the effectiveness of the application was evaluated both in terms of spacing and aspect ratio. The lateral loading procedure was implemented following the quasi-static load application for the displacement-controlled loading of the structural components specified in FEMA461. The details of the column reinforcement, the representation of the collar application and an image of the experimental setup are given in Fig.1-3. The column notation is made as SC_{α} - *X* - *s(d)*

SC: Short Column

α: is the lateral load height from upper limit of the foundation which defines aspect ratio

X: Suggested method or reference

Ref: Reference

C: Collar

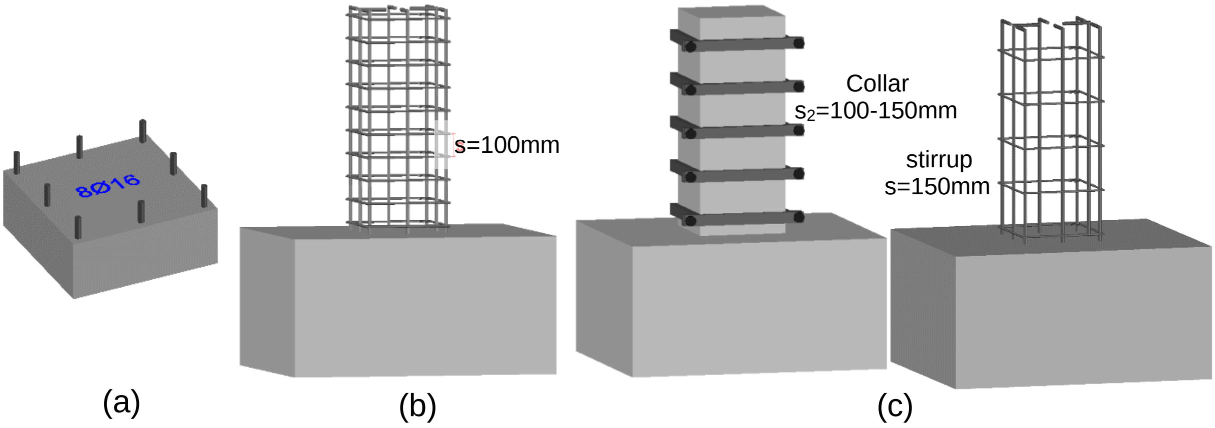


Fig. 1. (a) Cross section (b) Reference Column (c) Collared Column

Externally applied collars consist of 4 separate parts. On two edges, the long flat parts, and the other two edges, which were curved like a "U", were connected by bolts at two edge corner points. In this way the wrap is formed. (Fig. 2). The experimental loading setup consists of two lateral loading walls and an axial loading setup with hydraulic jacks, connecting pieces, load cells, joints and measuring equipment (LVDT, Encoder, strain-gauge etc.). The reason for choosing two lateral loading walls in experimental studies is that the lateral load level is especially high in columns with an aspect ratio of 1. When the lateral load level is more than a certain level, sudden break in the fasteners may happen due to the shear effect during the pulling is done. An image of the experimental setup and images of the reference column and collared column in the experimental setup are shown in Fig. 3.

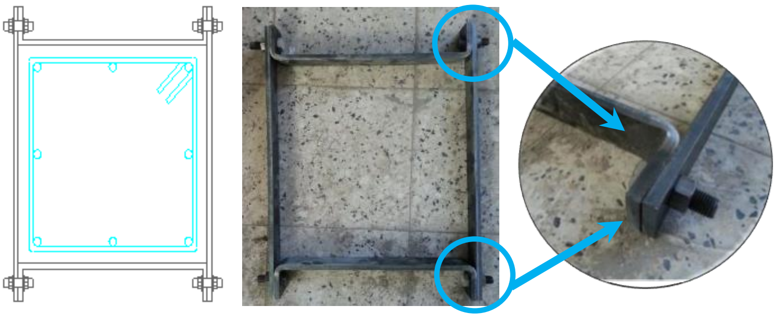


Fig. 2. Externally collar

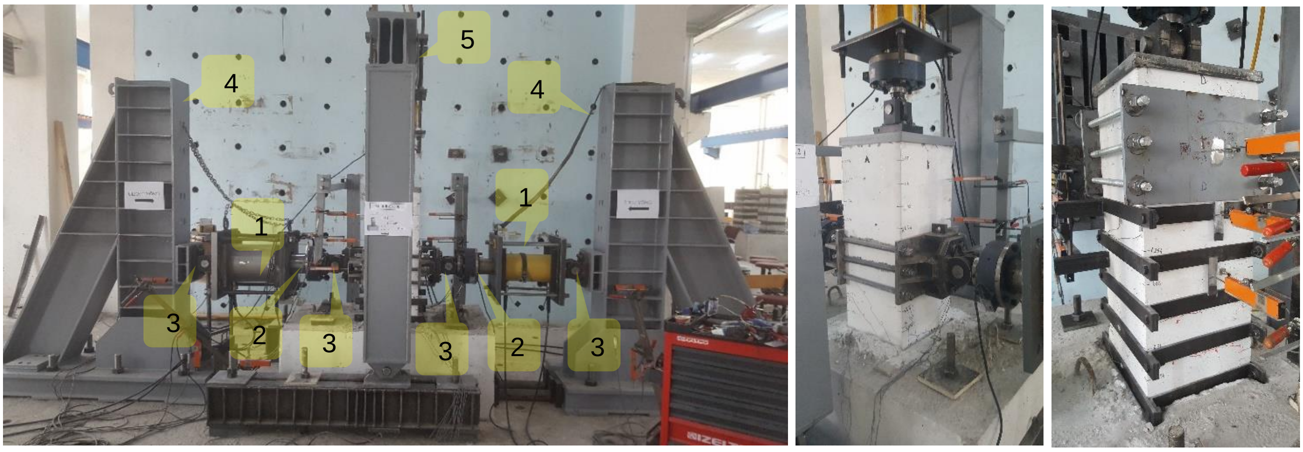


Fig. 3. Experimental setup and test columns
(1-Hydraulic jack, 2-Hinge, 3-Loadcell, 4-Lateral loading wall, 5-Axial loading setup)

4. RESULT AND DISCUSSION

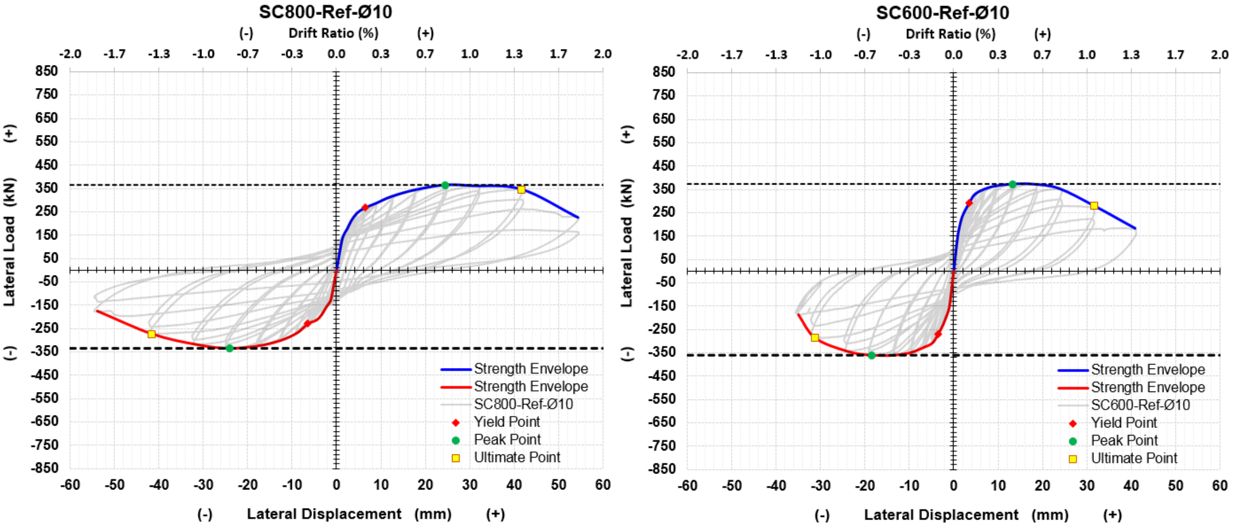
In experimental studies, a static thrust test was performed under cyclic loading of 9 pieces of RC short columns with aspect ratios of 1, 1.5 and 2. Using the experimental data, the performance of the columns was numerically evaluated with hysteretic behavior, strength envelopes, ductility and stiffness findings. Moreover, dominance effect on behavior is examined using the shear strength envelopes.

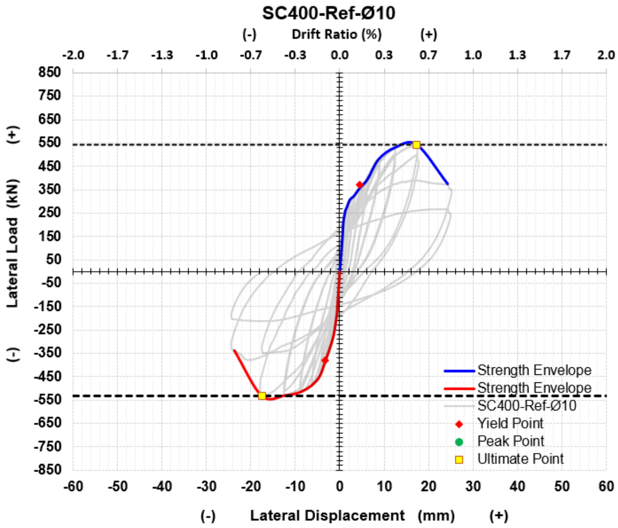
4.1. Hysteretic Behavior

The performance of the columns is assessed by peak load, moment capacity, reduction rate of strength and hysteretic behaviour. Hysteretic behavior is so important in terms of seismic performances of structural elements. The upward slope area of the first region of the hysteretic behavior forms the linear behavior of the element. At this stage, the opening and closing capillary cracks occur. As the cycles continue, new crack developments occur depending on the brittle or ductile behavior of the element. The hysteresis loop has an upward slope in the linear region and a descending slope in the nonlinear region. Both of them reveal the strength, ductility and energy absorption capacity of the element. They also reveal the behavioral character of the element.

The hysteresis loops and strength envelopes of the columns tested in the study are shown in Fig. 4. The hysteresis loops are given using the entire data set up to the end of the experiment so that behavior can be seen.

However, in the previous cycle, the envelope loops given on the same graph is marked as "ultimate point" (🟨) after the peak load (V_{max}) before falling below the 80% level. Thus, the meaningful endpoint for evaluating the performance of the columns is limited to 0.8 V_{max}. Furthermore, "yield point" (♦) and "peak load" (●) are also marked on the strength envelopes.

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850 750 650 550 450 350 250 150 50 -50 -150 -250 -350 -450 -550 -650 -750 -850
(+) Lateral Load (kN) (-)
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
(-) Lateral Displacement (mm) (+)
Strength Envelope
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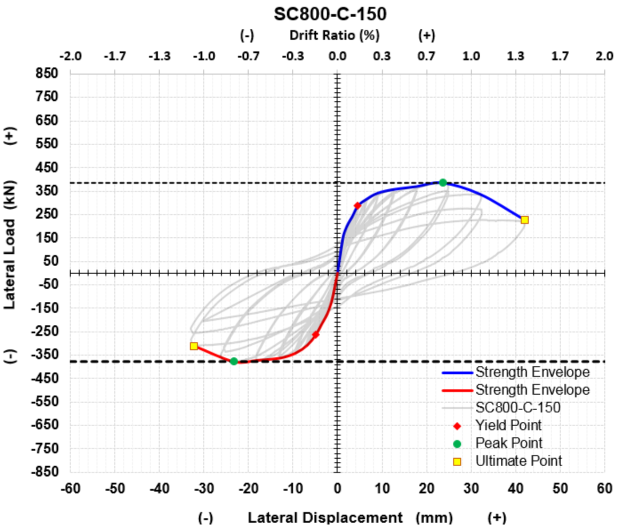
SC400-Ref-Ø10
Yield Point
Peak Point
Ultimate Point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(+) Lateral Load (kN) (-)
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
(-) Lateral Displacement (mm) (+)
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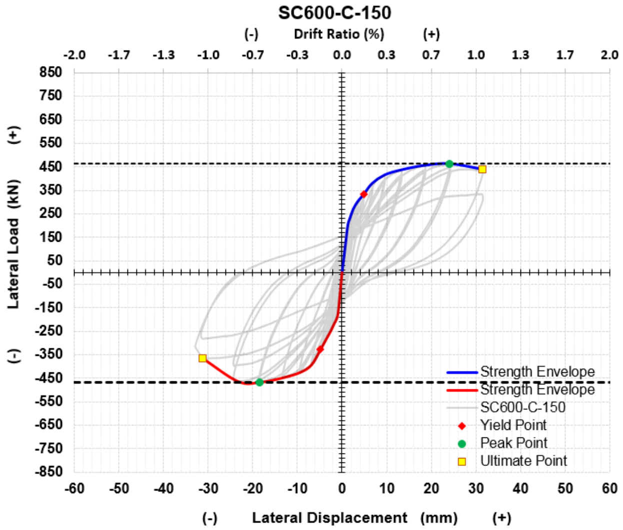
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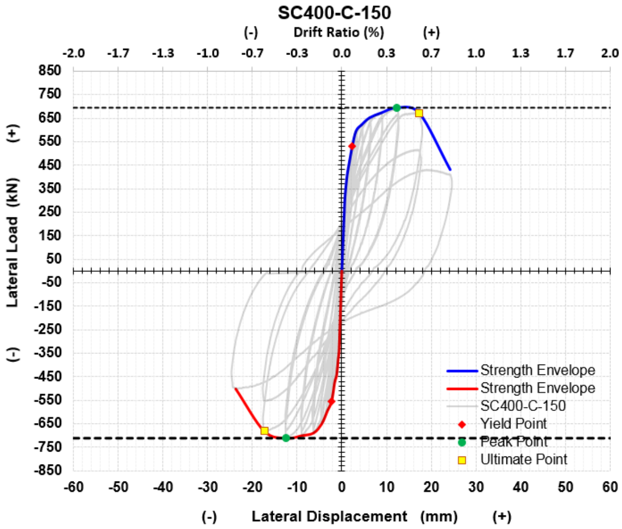
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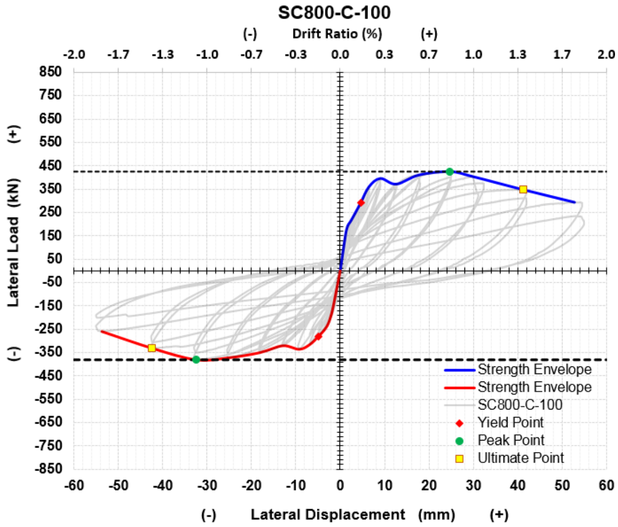
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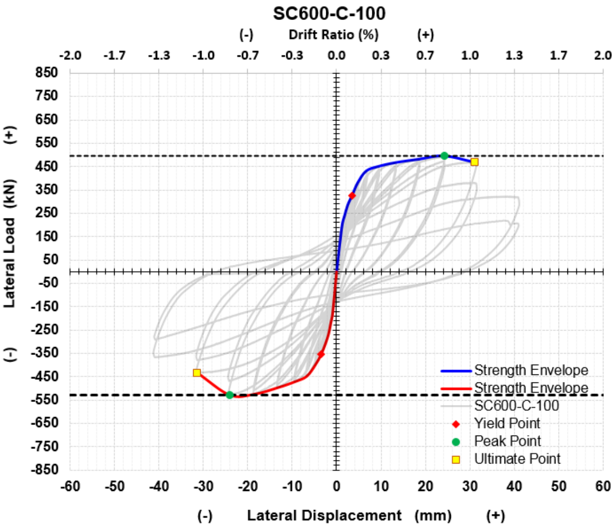
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850 750 650 550 450 350 250 150 50 -50 -150 -250 -350 -450 -550 -650 -750 -850
(+) Lateral Load (kN) (-)
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60
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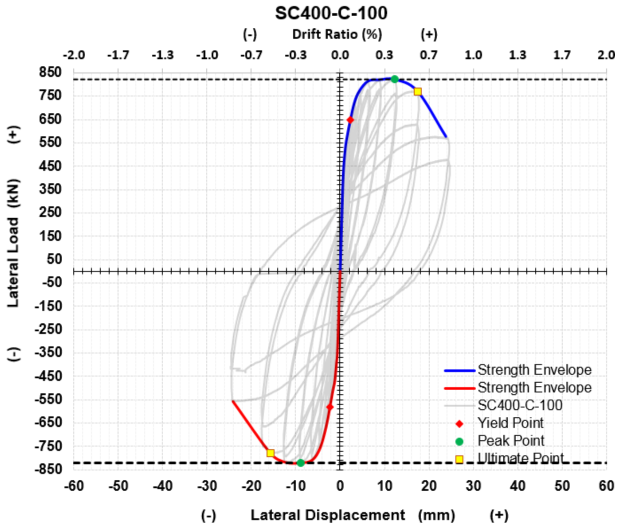

Fig. 4. Hysteresis loops and strength envelopes of all test columns

The descending slope of the load after the peak load of the SC800 series columns with aspect ratio of 2 was lower, while the descending slope of the load was increased in the SC600 and SC400 columns as the aspect rate decreased. The drift ratios (%) are given on the graph as the secondary axis in Fig. 4, by taking into account the 3m. normal floor height. The ultimate points of the SC800 series columns reached the level of 1.4%, while the SC600 and SC400 series remained at the level of 1.05% and 0.58% respectively. In Table 1, the load/displacement data of the columns are given numerically. In the SC800 series columns, the peak load values were close to each other and the largest peak load was reached in the SC800-C-100 column. As the aspect ratio decreases, the difference between the peak loads of the reference columns and the peak loads of the externally collared columns was increased. The difference between the peak loads of the (C-150)-(Ref-Ø10) and (C-100)-(Ref-Ø10) columns in the SC800 series columns was 19.90 kN/43.08kN (push/pull) and 59.72kN/46.57kN respectively. This difference was 90.72 kN/107.28kN and 122.96kN/168.01kN in the SC600 series and 151.64kN/179.12kN and 279.37kN/288.51kN in the SC400 series columns. In each series C-100 column has a maximum peak load. The peak load of the C-100 columns is 1.15 times higher in the SC800 series columns, 1.40 times higher in the SC600 series columns and 1.53 times higher in the SC400 series columns than the reference columns.The shear reinforcement spacing of the externally collared columns are less than the reference columns. Considering this, it is seen that the collar is very effective in increasing the shear strength.

Table 1. Load/Displacement Relationship and Peak Load Values of test columns

Column		**Cycle**	**Load/Displacement**		
			V_{max} / Δ_{peak}	**V_e / Δ_e**	**V_u / Δ_u**
1	SC800-REF-Ø10	Push	365.07 / 24.45	267.60 / 6.50	346.21 / 41.72
		Pull	-334.70 / -24.16	-230.24 / -6.46	-273.17 / -41.56
2	SC800-C-150	Push	384.97 / 23.60	286.76 / 4.59	209.42 / 42.01

		Pull	-377.77 / -23.36	-264.53 / -4.91	-206.65 / -32.29
3	SC800-C-100	Push	424.79 / 24.74	290.90 / 4.62	293.32 / 41.20
		Pull	-381.27 / -32.46	-281.28 / -4.94	-331.96 / -42.39
4	SC600-REF-Ø10	Push	372.84 / 18.05	258.49 / 5.02	279.06 / 41.23
		Pull	-360.39 / -27.53	-271.41 / -4.53	-286.49 / -44.87
5	SC600-C-150	Push	463.56 / 29.17	332.32 / 5.22	429.43 / 38.50
		Pull	-467.67 / -23.06	-327.42 / -5.59	-366.64 / -41.06
6	SC600-C-100	Push	495.80 / 30.28	326.08 / 4.37	468.56 / 39.05
		Pull	-528.40 / -30.05	-354.97 / -5.09	-433.07 / -40.36
7	SC400-REF-Ø10	Push	542.41 / 31.00	395.38 / 6.67	542.41 / 31.00
		Pull	-532.17 / -22.59	-381.52 / -4.72	-532.17 / -22.59
8	SC400-C-150	Push	694.05 / 24.71	528.71 / 4.62	430.70 / 34.79
		Pull	-711.30 / -20.76	-555.80 / -4.09	-501.94 / -30.45
9	SC400-C-100	Push	821.77 / 22.71	649.20 / 4.17	576.88 / 32.77
		Pull	-820.68 / -14.72	-581.11 / -3.87	-557.62 / -27.41

* V_{max} / Δ_{max}: *Peak point load/disp.;* V_e / Δ_e: *3/4Vmax point load/disp.;* V_u / Δ_u: *Ultimate point load/disp.*

Some sample illustrations for the post-test damage of the columns are given in Fig 5.

SC800-Ref-Ø 10

SC400-Ref-Ø 10

SC800-C-150

SC400-C-150

SC800-C-100

SC400-C-100

Fig. 5. Damage cases of the test columns after the some experiments

4.2. Stiffness and Ductility

Stiffness is an important parameter in terms of the behavior of the columns under the influence of the lateral load. A structural element must have sufficient stiffness in terms of the design of earthquake-resistant structures. In this section, the secant and effective stiffness of the test columns are compared. Secant stiffness is the slope of the Ky line passing 75% of the peak load, and the effective stiffness is the slope of the line combining the starting point and the ultimate point. Effective stiffness is defined as the slope of the line combining the starting point with the design point. In the scope of the study, the performance of the test columns was investigated. For this reason, the effective stiffness was calculated by taking into account the ultimate point (Δ_u). Furthermore, the design point can be examined at the ultimate point where the load falls to 80% because the response spectrum of the test columns does not intersect the spectrum curve in the Acceleration Displacement Response Spectrum (ADRS) diagram for the displacement-based design. The displacement at this ultimate point is used in the evaluation of ductility ($\mu=\Delta_u/\ \Delta_{mak}$). K_{pl} line is defined to obtain the yield displacement (Δ_y). K_{pl} line is the line which combines the coordinates of the peak point of the circle (V_{mak}, Δ_{max}) and the coordinates of the peak point of the cycle before the two cycles (V_{mak-2}, Δ_{mak-2}). One of the graphical representations used to calculate the secant and effective stiffness and ductility values of the columns is given as an image in Fig. 6. Ductility and stiffness values of the columns are given numerically in Table 2 and Table 3 respectively.

Table 2 shows the Δ_y, Δ_u and μ values obtained at each level of the columns. The reference column SC600 series showed more ductile behavior than the collared columns in the column. However, ductility of collared column is higher in SC800 and especially in SC400 series columns. The aspect ratio of 1 causes a considerable decrease in the ductility of the reference column. The comparison of ductility is based on the results obtained from the displacement in the loading levels.

Although the collared columns cannot be effective at the desired level due to increasing the ductility, they are considerably effective in obtaining sufficient stiffness due to the increase of strength. The secant and effective stiffness values obtained from the data which is gathered from each level (400-600-800mm) are also given in Table 3. These values are considered important to examine the effect of the aspect ratio on the stiffness values of the measured heights. In addition to this, the assessment should be based on the values obtained from each loading level for each column series. Therefore, the stiffness values which were obtained from the load-displacement relation, carried out at 800mm level for the SC800 series, 600mm level for the SC600 series and 400mm level for the SC400 series. They are highlighted in the table. As the aspect ratio decreases, the stiffness increases. The mean initial stiffness (push-pull) values of the reference columns increased by 2.08 and 2.71 times for SC600/SC800 and SC400/SC800 respectively, while the effective stiffness ratios increased by 1.21 and 4.14 times. These increase rates were 1.18-4.03 and 2.18-6.61 for the C-150 columns and 1.63-4.43 and 1.78-5.78 times for the C-100 columns. Descending in aspect ratio (α_s) is very effective in increasing the effective stiffness. The stiffness value is the C-100 column, which is the highest of every series. The initial stiffness ratio of SC800-C-100/SC800-Ref-Ø10 was 1.56 in SC800 series columns with α_s=2, while this ratio increased up to 1.22 when α_s=1.5 to 2.56 when α_s=1. The increase in the effectiveness of shear dominant behavior of externally collar provides a significant contribution to the stiffness.

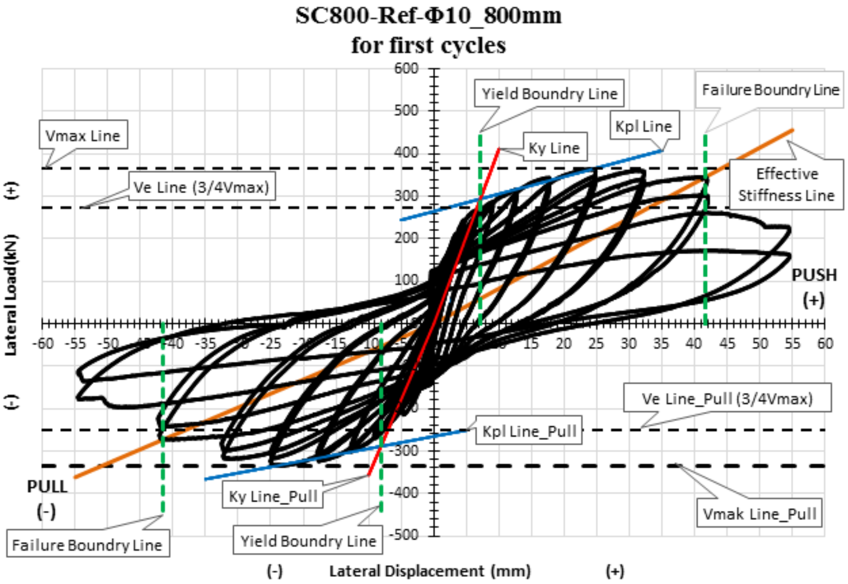

Fig. 6. Visualization of the stiffness and ductility calculation diagram

Table 2. Displacement and ductility values of short columns

Column	**Loading Level** (mm)	Δ_y (mm)			Δ_u (mm)			**μ**		
		Push	Pull	Mean	Push	Pull	Mean	Push	Pull	Mean
SC800-REF-Ø10	800	7.14	-8.10	7.62	41.72	-41.56	41.64	5.84	5.13	5.49
	600	5.67	-5.76	5.72	33.20	-31.37	32.28	5.85	5.44	5.65
	400	4.18	-4.49	4.34	24.43	-20.26	22.34	5.85	4.51	5.18
SC800-C-150	800	5.41	-6.55	5.98	42.01	-32.29	37.15	7.76	4.93	6.35
	600	4.09	-3.37	3.73	32.48	-21.20	26.84	7.93	6.28	7.11
	400	2.70	-2.20	2.45	23.82	-10.01	16.92	8.82	4.55	6.69
SC800-C-100	800	5.37	-5.68	5.53	41.20	-42.39	41.79	7.66	7.46	7.56
	600	4.17	-3.30	3.74	30.91	-30.36	30.64	7.41	9.19	8.30
	400	2.89	-2.12	2.51	20.67	-19.19	19.93	7.15	9.03	8.09
SC600-REF-Ø10	800	5.87	-5.64	5.75	41.23	-44.87	43.05	7.02	7.96	7.49
	600	4.12	-4.41	4.26	31.70	-31.24	31.47	7.70	7.09	7.39
	400	2.86	-3.06	2.96	21.13	-21.01	21.07	7.40	6.87	7.14
SC600-C-150	800	6.59	-6.99	6.79	38.50	-41.06	39.78	5.84	5.88	5.86
	600	6.10	-6.00	6.05	31.49	-31.18	31.33	5.16	5.19	5.18
	400	4.53	-5.07	4.80	22.01	-21.14	21.58	4.86	4.17	4.51
SC600-C-100	800	5.98	-6.83	6.40	39.05	-40.36	39.70	6.53	5.91	6.22
	600	4.75	-4.63	4.69	31.04	-31.38	31.21	6.53	6.78	6.66
	400	3.11	-3.43	3.27	21.34	-21.02	21.18	6.87	6.13	6.50
SC400-REF-Ø10	800	7.78	-6.10	6.94	31.00	-22.59	26.80	3.98	3.71	3.85
	600	5.97	-5.57	5.77	23.43	-20.00	21.72	3.93	3.59	3.76
	400	5.10	-4.25	4.67	17.37	-17.55	17.46	3.41	4.13	3.77
SC400-C-150	800	5.50	-4.99	5.24	34.79	-30.45	32.62	6.33	6.10	6.21
	600	4.22	-3.96	4.09	26.10	-23.96	25.03	6.18	6.04	6.11
	400	2.76	-2.79	2.78	17.31	-17.36	17.33	6.26	6.21	6.24

SC400-C-100	800	5.21	-4.90	5.06	32.77	-27.41	30.09	6.29	5.59	5.94
	600	4.03	-3.88	3.96	24.87	-21.56	23.22	6.17	5.55	5.86
	400	2.90	-2.90	2.90	17.43	-15.68	16.56	6.01	5.41	5.71

Table 3. Stiffness values obtained by load-displacement relation at 800mm, 600mm and 400mm height

Test Column	**Cycle Definition**	**800mm Level**			**600mm Level**			**400mm Level**		
		Initial Stiffness K_y (kN/mm)	**Effective Stiffness K_{eff} (kN/mm)**	**K_y / K_{eff}**	**Initial Stiffness K_y (kN/mm)**	**Effective Stiffness K_{eff} (kN/mm**	**Ky / Ks**	**Initial Stiffness K_y (kN/mm)**	**Effective Stiffness K_{eff} (kN/mm**	**K_y / K_{eff}**
SC800-REF-Ø10	Push	41.19	8.30	4.96	51.43	10.43	4.93	68.79	14.17	4.85
	Pull	35.62	6.57	5.42	49.95	8.71	5.74	64.74	13.49	4.80
SC800-C-150	Push	62.53	5.41	11.56	82.62	7.00	11.81	125.06	9.54	13.11
	Pull	53.92	6.40	8.43	104.67	9.75	10.74	160.68	20.65	7.78
SC800-C-100	Push	63.02	8.43	7.47	81.19	11.24	7.22	117.09	16.81	6.96
	Pull	56.99	7.83	7.28	98.91	10.93	9.05	153.34	17.30	8.86
SC600-REF-Ø10	Push	58.17	6.77	8.59	82.77	8.80	9.40	119.57	13.21	9.05
	Pull	59.96	6.38	9.39	77.39	9.17	8.44	111.47	13.64	8.17
SC600-C-150	Push	63.63	11.43	5.57	68.71	13.97	4.92	92.41	19.99	4.62
	Pull	58.55	8.93	6.56	68.16	11.76	5.80	80.82	17.34	4.66
SC600-C-100	Push	74.59	12.00	6.22	93.59	15.10	6.20	142.83	21.95	6.51
	Pull	69.68	10.73	6.49	101.79	13.80	7.38	137.06	20.60	6.65
SC400-REF-Ø10	Push	59.30	17.50	3.39	76.04	23.15	3.28	88.83	31.23	2.84
	Pull	80.87	23.55	3.43	90.13	26.61	3.39	119.34	30.32	3.94
SC400-C-150	Push	114.47	19.32	5.92	148.79	25.76	5.78	226.99	38.83	5.85
	Pull	135.75	22.39	6.06	170.85	28.46	6.00	242.04	39.28	6.16
SC400-C-100	Push	155.67	23.53	6.62	201.20	31.01	6.49	279.51	44.24	6.32
	Pull	150.03	28.47	5.27	189.19	36.19	5.23	252.70	49.75	5.08

4.3. Energy Dissipation

The energy consumption capacity is an important parameter in assessing the performance of columns that are very important structural system components in reinforced concrete frames and / or mixed systems. The energy consumption of the columns depends on axial load level, yield displacement, number of cycle, support conditions, cross sectional details, material properties and reached peak load level. The identification of energy consumption zones are given visually at Fig. 7.

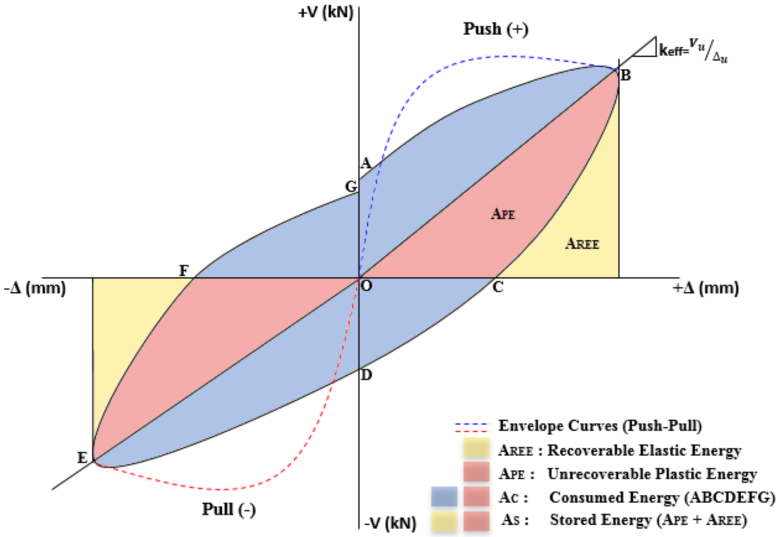

Fig.7. Definitions of energy consumption zones

Table 4. Energy data calculated for test columns

Test Column	**Et** (kNmm)*	**Ed** (kNmm)	**Recoverable Elastic Energy** (kNmm)	**Unrecoverable Plastic Energy** (kNmm)
SC800-REF-Ø10	98477.42	94193.79	42829.16	51364.63
SC800-C-150	81209.61	76898.58	38184.73	69233.69
SC800-C-100	96673.85	109897.56	57502.67	52394.89
SC600-REF-Ø10	100676.47	103084.94	42328.45	60756.50
SC600-C-150	113298.30	111567.95	50486.38	61081.57
SC600-C-100	122210.84	127804.80	63617.05	64187.74
SC400-REF-Ø10	92152.24	85099.49	49134.77	28148.45
SC400-C-150	128970.44	135070.93	64976.62	70094.31
SC400-C-100	148012.66	151032.20	72043.12	78989.08

** kNmm=Nm*

Energy consumption values of test columns are given in Table 4. Due to the bending-dominated behavior in SC800 series column, no significant difference is observed in energy consumption data between the SC800 series column. However, the energy data of the collared columns differs from the reference column by the reduction of the aspect ratio. The energy of the collared columns is well above the reference column especially in the SC400 series columns (α_s=1). The energy consumption of the Ref column in the SC800 series (E_t) is higher than the collared columns, while the energy consumption of the collared columns in the SC600 and SC400 series is higher than the Ref column. The recoverable elastic energy and unrecoverable plastic energy values of the collared columns are higher than the reference column in each series. This difference increases prominently as the aspect ratio decreases.

4.4. Shear Strength Envelope

Many researchers are studying the evaluation of shear strength of reinforced concrete columns. Most of these studies are mainly based on the testing of columns.The contribution of the shear strength envelope, depending on some parameters, to the shear strength of the concrete is expressed by evaluating the obtained results. These shear strength envelopes are formed in the reinforced concrete column. The most important design parameters considered for assessing the contribution to the shear strength of concrete are; displacement ductility (μ), axial load level (P), longitudinal reinforcement ratio (ρ_t), size effect and effective shear area (A_{sh}).

In most of the models, the effective shear area is expressed as 80% of the gross cross-sectional area (A_g) of the column. In some models, it is expressed as the product of the section width (b_w) and effective depth (d). ($A_{sh}=0{,}80A_g$ *or* $A_{sh}=b_wd$)

Priestley et al. (1994) evaluated the shear strengths of reinforced concrete columns in part of concrete contribution, the contribution of the shear reinforcement and axial load. They have defined the decrease in the shear strength of concrete according to increasing ductility with the following Eq. (1).

$$V_c = \gamma\sqrt{f_c'}(0{,}8A_g) \tag{1}$$

Here γ is 0.29 if the displacement ductility (μ) is less than 2, 0.10 if it is greater than 4. The γ factor is linearly decreasing when the ductility is between 2 and 4.

A few years later, Xiao and Martirossyan (1998) proposed that the contribution of concrete to shear decreases more dramatically when they investigate the seismic performances of high strength concrete columns. Accordingly, the γ factor is defined by the following equations.

$$\begin{aligned}
&\gamma = 0.29 && \text{for } \mu \le 2\\
&\gamma = 0.29 - 0.12(\mu - 2) && \text{for } 2 \le \mu \le 4\\
&\gamma = 0.05 - 0.025(\mu - 4) && \text{for } 4 \le \mu \le 6\\
&\gamma = 0 && \text{for } 6 \le \mu
\end{aligned} \tag{2}$$

Recently, Howser et al. (2010) have conducted a numerical parameter study. They evaluated the change of ductility depending on the longitudinal reinforcement ratio and concrete strength (Eq. (3)). Therefore, the determination of the γ factor and the contribution to the shear strength of the concrete has been revised by taking into consideration both the strength and the longitudinal reinforcement of the section.

$$
\begin{aligned}
&\gamma = 0.29 && for\ \ \mu \le 2\\
&\gamma = 0.29 - 0.12(\mu - 2) && for\ \ 2 \le \mu \le r\\
&\gamma = 0.53 - 0.095r - 0.025\mu && for\ \ r \le \mu \le q\\
&\gamma = 0.53 - 0.095r - 0.025q && for\ \ q \le \mu\\
\\
&r = 35\rho_t - 0.011 f_c^{'} + 3.8 &&\\
&q = -144\rho_t - 0.03 f_c^{'} + 4.3 && for\ \ r \le q\\
&q = r && for\ \ q < r
\end{aligned}
\tag{3}
$$

The strength envelopes of the test columns were reduced to the shear force-ductility axis in Fig. 8. In these graphs, the shear strength envelopes and the strength envelopes of the test column are compared. Therefore, depending on the ductility, an important visual is generated in the shear effect of the behavior of the column. It is seen that the strength envelopes of the reference columns intersect the shear strength envelopes at each α_S ratio. This indicates that the reference columns are directed to shear failure in each series. Reference columns are directed to shear failure after μ=3.5 when α_S=2 and α_S=1.5, and after μ=2 when α_S=1. When the C-150 column α_S = 1, intersect the shear strength envelope at μ = 3.5 level. The C-100 column did not intersect the shear intersect envelope and reached its capacity due to damage at the column-foundation junction.

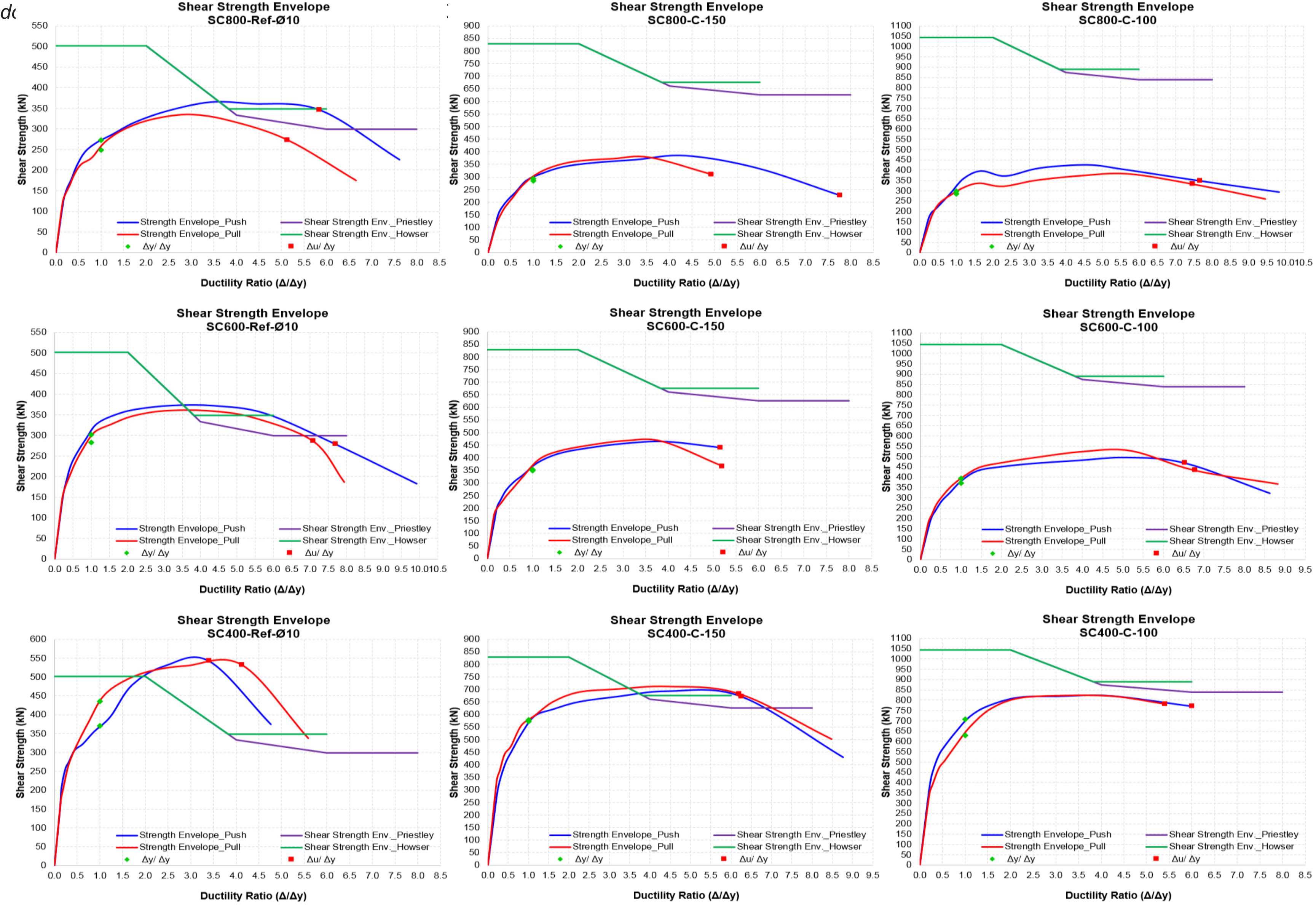

Fig. 8. Shear strength envelope and failure behavior

5. CONCLUSIONS

Based on a comprehensive experimental study of the behavior of nine collared RC columns under combined constant axial loading and cyclic loading, suggested collared rehabilitation is shown to be effective for application to deficient short RC columns. The main observations and conclusions of this study are summarized as follows:

- The crack widths and characters differ depending on the aspect ratio. In the SC800 series columns with $\alpha_s = 2$, joint damages were apparently effective in behavior. The effect of bending is more determinative than the effect of the shear effect in the behavior of these columns. While the shear dominant behaviour increases in SC600 series columns, the behaviour of Ref. and C-150 columns in the SC400 series columns has been completely under the shear effect. The SC800 and SC600 series were observed to be buckled in longitudinal columns after 10th step (20-21th cycles). In the intermediate area of the collars, spalling of the cover concrete and section reduction were observed. Moreover, buckling of the longitudinal reinforcement was found in collar intermediate regions. Collars have been severely deformed by preventing the longitudinal reinforcement from being buckled. The decrease of the collar spacing (150mm to 100mm) makes it difficult to buckle the longitudinal reinforcement.
- Due to the failure in the SC400-Ref-Ø10 columns, the development of the classic X crack has happened. Shear crack damage that occurs in the collared columns is not at the level that will cause failure. During the experiment the slippage did not occur. Even if crushing and spalling of the cover concrete occurred between the collars, deformation was prevented in the zones where collars were present.
- As the aspect ratio decreases, the difference between the peak loads of the reference columns and the peak loads of the externally collared columns was increased. The difference between the peak loads of the (C-150)-(Ref-Ø10) and (C-100)-(Ref-Ø10) columns in the SC800 series columns was 19.90kN/43.08kN (push/pull) and 59.72kN/46.57kN respectively. This difference was 90.72kN/107.28kN and 122.96kN/168.01kN in the SC600 series and 151.64kN/179.12kN and 279.37kN/288.51kN in the SC400 series columns. In each series C-100 column has a maximum peak load. The peak load of the C-100 columns is 1.15 times higher in the SC800 series columns, 1.40 times higher in the SC600 series columns and 1.53 times higher in the SC400 series columns than the reference columns. The peak loads of the C-100 columns are higher than that of the C-150 columns, so the reduction of the collar spacing (150mm to 100mm) increases the shear strength of the column. The C-100 / C-150 peak load ratios in the SC800, SC600 and SC400 series columns were 1.06, 1.27 and 1.17 respectively.
- As the aspect ratio decreases, the stiffness increases. The mean initial stiffness (push-pull) values of the reference columns increased by 2.08 and 2.71 times for SC600 / SC800 and SC400 / SC800 respectively, while the effective stiffness ratios increased by 1.21 and 4.14 times. These increase rates were 1.18-4.03 and 2.18-6.61 for the C-150 columns and 1.63-4.43 and 1.78-5.78 times for the C-100 columns.

Descending in aspect ratio (αs) is very effective in increasing the effective stiffness. The stiffness value is the C-100 column, which is the highest of every series. The initial stiffness ratio of SC800-C-100 / SC800-Ref-Ø10 was 1.56 in SC800 series columns with α_s=2, while this ratio increased up to 1.22 when α_s=1.5 to 2.56 when α_s=1. The increase in the effectiveness of shear dominant behavior of externally collar provides significant contribution to the stiffness.

- From the shear strength envelope graphs, it is clear that the behavior of the reference columns is the shear dominant behavior. Apart from the SC400-C-150 column, collared columns did not intersect the shear strength envelope.

- Due to the bending-dominated behavior in SC800 series column, no significant difference is observed in energy consumption data between the SC800 series column. However, the energy data of the collared columns differs from the reference column by the reduction of the aspect ratio. The energy of the collared columns is well above the reference column especially in the SC400 series columns (α_s=1). The recoverable elastic energy and unrecoverable plastic energy values of the collared columns are higher than the reference column in each series. This difference increases prominently as the aspect ratio decreases.

Experimental studies and results have shown that collared steel is very effective in increasing the performance of columns with low aspect ratio. The increase in the stiffness, strength and energy consumption capacities of columns with collared steel is regarded as a positive contribution to the literature. In addition to the material, spacing, and geometry of the collar, further studies can be done by the diversification of the cross section dimensions of the column. This situation shows that the study is open to new developments.

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