

## Parametric study on contribution of combined confining steel and steel fiber to column's displacement ductility

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### Abstract

This study examines the contribution of confinement with variations in spacing  $s_h = (50, 65, \text{ and } 80)$  mm and concrete reinforced with steel fiber to displacement ductility. Eight test column specimens (No. 1, 2, 3, 6, 7, 8, 11, and 12) were also reinforced with stirrups according to ACI 318M:19 provisions while four test column specimens (No. 4, 5, 9, and 10) deliberately reinforced with a slightly wider spacing of stirrups with different yield strengths ( $f_y$ ) (lower than the code requirements). However, the volumetric ratio of the steel fiber was varied, i.e.  $V_f = 0\%, 0.5\%, 1\%, 1.5\%, \text{ and } 2\%$ . The column was then subjected to a quasi-cyclic and a constant axial load of  $P_a = 0.121 \cdot A_g \cdot f_c'$ . The test results indicated that all test column specimens could attain the full ductile/fully ductile criteria since  $\mu_{\Delta} > 4$ . When the drift ratio required by ACI 318M-19 is observed, the use of combined confining stirrups and steel fiber works together simultaneously to achieve a drift ratio capacity that exceeds the minimum required target of 3%, meaning that the columns could perform satisfactorily.

**Keywords:** Confinement, Disaster risk reduction, Drift ratio, Ductility, Quasi-cyclic, Steel fiber

### 1. Introduction

Structural beams are very important to be designed to have adequate strength and ductility [1, 2]. However, structural columns are even more important members of building structures because they must sustain axial loads and lateral loads simultaneously, such that the demand for ductility must be adequate. The ductility value ( $\mu_{\Delta}$ ) is considered based on the ultimate displacement value ( $\Delta_u$ ) divided by the displacement at first yielding ( $\Delta_y$ ). It must be evaluated whether it has reached a certain ductility criterion according to the code [3]. If the value of  $\mu_{\Delta}$  is less than 2 then it can be defined as Low Ductility Demand, if 2 to 4 is defined as Moderate Ductility Demand, and if greater than 4 is defined as High Ductility Demand/full ductile. The  $\mu_{\Delta}$  value is taken from the drift ratio value at  $0.80P_{max}$  or when there is a 20% reduction in strength after the maximum load [4]. The code also requires that the column must be able to achieve a drift ratio of 3% without experiencing a drastic reduction in strength, which means the column must be ductile.

Achieving ductility can be done by providing confinement in the form of stirrups in the concrete [5-13] or many others [14-17]. Particularly for seismic-resistant structures, they are usually confined using densely-spaced stirrups. This condition causes the detailing to become congested, resulting in harder implementation on site.

Currently, the use of higher concrete strength has also been widely used, including the use of steel fiber in several structural elements [18-22] its use is based on volumetric fiber  $V_f$  between 0.5% and 2%, the results show an increase in the strength of the structural members.

Based on the above discussion, the study aims to find the contribution from the combination of confinement values according to [8] and the use of steel fiber. The confinement in the study used square stirrups with a diameter of D8 mm with various spacings ( $s_h = 50, 65, \text{ and } 80$  mm). To improve the performance, steel fiber was introduced according to the volumetric ratio with intermediate values, namely  $V_f = 0\%, 0.5\%, 1\%, 1.5\%, \text{ and not more than } 2\%$ . It was observed that the drift ratio was achieved at 3% under inelastic conditions and the ductility was satisfactory.

The primary aim of the study is to investigate the contribution of steel fiber in combination with confining steel to the displacement ductility of concrete columns due to combined axial and lateral cycling loads. The contribution of steel fiber in reducing the need for stirrups as confinement in columns has been found to significantly alleviate the congestion of steel reinforcement in concrete columns required by the seismic code provisions in achieving comparable performances.

### 2. Materials and methods

This research was carried out in the laboratory by making twelve column test specimens. The column confinement used was square stirrups with spacings  $s_h = 50, 65, \text{ and } 80$  mm. The concrete used was normal-strength concrete. The concrete was then reinforced with

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steel fiber with the volumetric ratio ( $V_f$ ), while the main reinforcement ratio of the column  $A_{st} = 2.48\%$ . Column cross-sectional dimensions  $b \times h = 200 \times 200$  mm and column height  $L = 800$  mm. Columns were designed with  $FSSR < 0.6$  [23]. This ratio was chosen such that the column collapses due to flexural failure. The columns were tested under quasi-cyclic loading with a  $P_{axial-constant}$  load =  $0.121 A_g f_c$  and a horizontal load  $P_h$  starting from zero until the column collapsed. The test adopted the displacement-controlled method, then analyzed for achieving a drift ratio of 3% in post-peak load conditions of  $0.8 P_{h-max}$  and also analyzed if the ductility is achieved.

This research also observed the effect of using  $A_{sh-provided} < A_{sh-ACI}$ , namely column test specimens No. 4-5 and 9-10, where  $A_{sh-provided}$  should be at least the same as  $A_{sh-ACI}$ . This was conducted to find how far the contribution of stirrups and steel fiber when used simultaneously as concrete reinforcement, particularly for reinforced concrete columns.

2.1 Materials and specimens

The concrete used in this research is normal strength concrete with  $f'_{c-target} = 25$  MPa produced by the manufacturer. This option was selected such that the consistency of the concrete strength was uniform and thus, the designed strength target was attained. However, the details of material use in the mix design are still given in Table 1. Likewise, the steel fiber used is also provided by the manufacturer with a double hook shape. The amount used was based on volumetric ratio, namely ( $V_f$ ) = 0%, 0.5%, 1%, 1.5%, and 2%.

Table 1 Mix design for a volume of 1 m<sup>3</sup> of concrete with  $f'_c$  of 25 MPa

No.	Materials	1 m <sup>3</sup> SSD (kg/m <sup>3</sup> )
1.	Cement, OPC type 1	322
2.	Fly ash, ex. Jepara (Indonesia)	57
3.	Sand, ex. Merapi (Indonesia)	823
4.	Coarse Agg, ex. Merapi (Indonesia) split size 10-20 mm	962
5.	Water	170
6.	Admixture, Sika VZ (in Indonesia)	1,22
	Density	2335

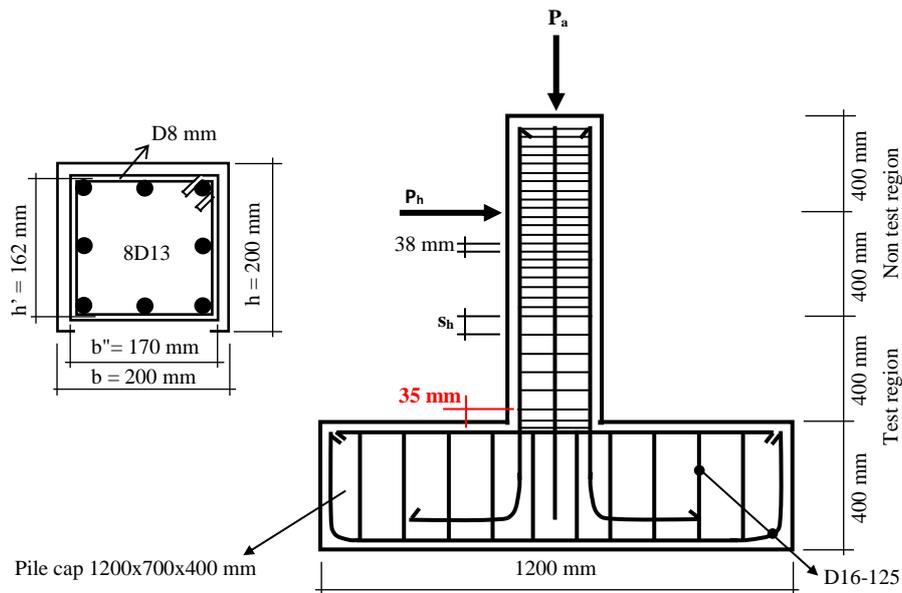


Figure 1 Details of column reinforcement



Figure 2 Column reinforcement cage and steel fiber used with aspect ratio  $l/d = 80$

The reinforcing steel used was D8 mm for square stirrups and D13 mm for the main column reinforcement, while the pile cap was strengthened using reinforcement using D16 mm with a spacing of 125 mm. This pile cap was designed to be as strong as possible so that failure did not occur in the pile cap region. Concrete reinforcement design, such as spacing of stirrups at  $s_h = 50, 65,$  and  $80$  mm, was intended such that the column reaches full ductility of  $\mu_{\Delta} > 4$  [3, 8].

The combination of using stirrups, main reinforcement, and a constant axial load of  $P_a = 0.121 A_g f'_c$  was also intended such that all columns reached  $FSSR < 0.6$  [23]. This condition aims to prevent damage to plastic joints due to bending. Based on this design, the column reinforcement and anchorage were made as in Figures 1 and 2 [24] with detailed column test specimens given in Table 2.

**Table 2** Details of column test specimens

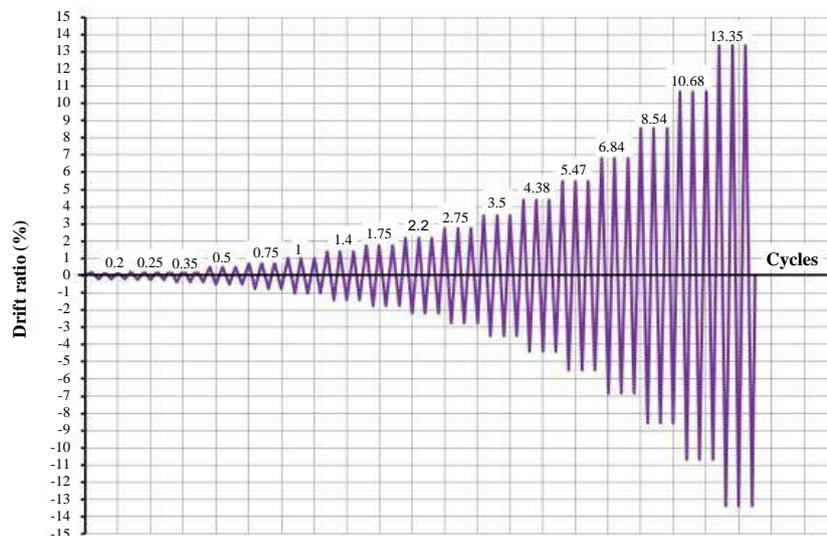
No.	Specimen ID	b=h (mm)	L (mm)	Main reinforcement	Stirrups		$V_f$ steel fiber	$f_y$ (MPa)	$f_{yh}$ (MPa)	$f'_c$ average (MPa)	$A_{sh-1-ACI}$ (mm <sup>2</sup> )	$A_{sh-2-ACI}$ (mm <sup>2</sup> )	$A_{sh-provided}$ (mm <sup>2</sup> )
					D (mm)	$s_h$ (mm)							
1	Col.2.a	200	800	8D13	8	65	0	405.87	546.83	27	60.02	46.88	93.33
2	Col.3.a	200	800	8D13	8	80	0	405.87	546.83	27	73.87	57.69	93.33
3	Col.1.b	200	800	8D13	8	50	0.5%	317.01	344.30	27	73.45	57.37	86.67
4	Col.2.b	200	800	8D13	8	65	0.5%	317.01	344.30	27	95.48	74.58	86.67
5	Col.3.b	200	800	8D13	8	80	0.5%	317.01	344.30	27	117.52	91.79	86.67
6	Col.2.c	200	800	8D13	8	65	1%	405.87	546.83	27	60.02	46.88	93.33
7	Col.3.c	200	800	8D13	8	80	1%	405.87	546.83	27	73.87	57.69	93.33
8	Col.1.d	200	800	8D13	8	50	1.5%	317.01	344.30	27	73.45	57.37	86.67
9	Col.2.d	200	800	8D13	8	65	1.5%	317.01	344.30	27	95.48	74.58	86.67
10	Col.3.d	200	800	8D13	8	80	1.5%	317.01	344.30	27	117.52	91.79	86.67
11	Col.2.e	200	800	8D13	8	65	2%	405.87	546.83	27	60.02	46.88	93.33
12	Col.3.e	200	800	8D13	8	80	2%	405.87	546.83	27	73.87	57.69	93.33

Note: Col.1=  $s_h$  50 mm, Col.2=  $s_h$  65 mm, Col.3=  $s_h$  80 mm, a= $V_f$  0%, b= $V_f$  0.5%, c= $V_f$  1%, d= $V_f$  1.5%, e= $V_f$  2%.

**2.2 Experimental works**

The experiments in this study were set with a constant axial load on the column of  $P_a = 0.121 A_g f'_c$  and given a horizontal load. This horizontal load was considered to represent the lateral load or earthquake load. The test was carried out using the displacement-controlled method according to the loading pattern as in Figure 3 [25]. The loading pattern was then changed into displacement (drift) form as in Table 3. Table 3 is a reference for carrying out the displacement-controlled test, meaning that the test specimen is given a drift according to Table 3 and then the drift and load that causes the drift are automatically recorded. If the amount of drift has been completed in the test then it is called one phase of testing, but in this test three phases with the same drift are held, after three phases have been passed then one test cycle has occurred. The cycle is stopped if the column has collapsed or plastic joints have appeared in the test area. The steps in Figure 3 are elaborated as follows:

1. The column test specimen is loaded in a displacement-controlled sequence representing drift ( $\Delta$ ). This condition is considered to represent the conditions during an earthquake.
2. Three full cycles should be performed at each drift ratio (see Figure 3).
3. The initial condition of the drift ratio should be in the linear elastic behavior of the column test specimen. The next drift ratio should not be less than 1.25 times, and not more than 1.5 times the previous drift ratio.
4. Testing of column test specimens should be carried out in stages by gradually increasing the drift ratio until a minimum drift ratio value of 0.035 is reached.
5. Data recording of drift (see Table 3) versus horizontal force ( $P_h$ ) should be carried out continuously to interpret the performance of the column test specimen qualitatively and must be documented.



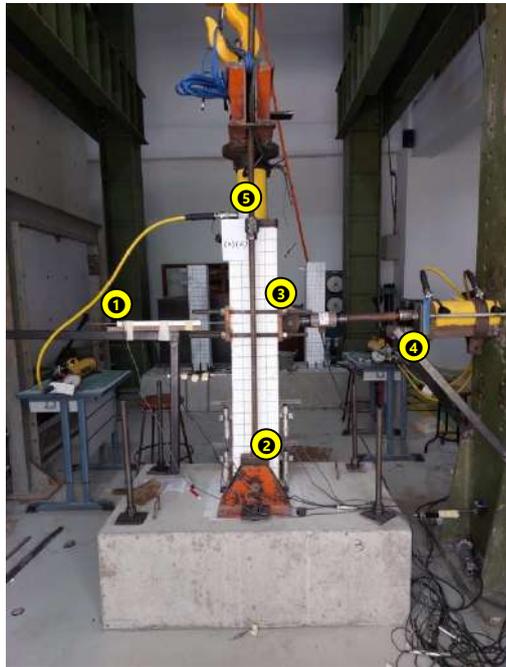
**Figure 3** Displacement-controlled loading pattern

**Table 3** Drift ratio of  $L_{\text{column}} = 800 \text{ mm}$ 

Cycle no.	Drift ratio (%)	Displacement (mm)	Cycle no.	Drift ratio (%)	Displacement (mm)
1	0.20	1.60	10	2.75	22.00
2	0.25	2.00	11	3.50	28.00
3	0.35	2.80	12	4.38	35.00
4	0.50	4.00	13	5.47	43.75
5	0.75	6.00	14	6.84	54.69
6	1.00	8.00	15	8.54	68.36
7	1.40	11.20	16	10.68	85.45
8	1.75	14.00	17	13.35	106.81
9	2.20	17.60			

### 2.3 Test setup for quasi-cyclic loading

The quasi-cyclic column experiment carried out in the laboratory in this study gave a constant axial load of  $P_a = 0.121A_g f'_c$  and was also given a horizontal load. The test setup for quasi-cyclic loading using the displacement-controlled method has been designed to be able to properly measure the displacements in Table 3, and the load that occurs. Several data recording devices are connected to the Kyowa brand recorder unit, during testing it is connected directly to the computer. The actual test setup is shown in Figure 4.



**Figure 4** Actual test setup, ① = LVDT horizontal, caps. 200 mm, ② = LVDT vertical, caps. 50 mm, ③ = double-acting load cell, caps. 100 kN, ④ = double-acting hydraulic jack, caps. 200 kN, ⑤ = single-acting hydraulic jack, caps. 200 kN.

## 3. Result and discussion

### 3.1 Concrete compression test results

The concrete compression test used six concrete cylinders with a diameter of 150 mm and a height of 300 mm. Casting the concrete cylinders was at the same time as casting the column test specimens. After the concrete cylinders were 28 days old, compression tests were then carried out. The results of the compression test are given in Table 4.

**Table 4** Compressive strength of concrete

No.	Specimen ID	Compressive strength of concrete (MPa)
1	S <sub>1</sub>	26.07
2	S <sub>2</sub>	29.95
3	S <sub>3</sub>	24.96
4	S <sub>4</sub>	26.45
5	S <sub>5</sub>	27.80
6	S <sub>6</sub>	26.77
	Average	27.00

3.2 Reinforcing steel tensile test results

The tensile test results of D8 stirrup steel reinforcement were found to be  $f_{yh} = 317.01$  and  $546.83$  MPa, while the tensile tests of longitudinal column reinforcement D13 were found to be  $f_y = 344.30$  and  $405.87$  MPa. All the reinforcement used, both D8 and D10, had an average elongation value of larger than 11%, meaning the reinforcement was applicable for seismic purposes [4, 26, 27].

3.3 Quasi-cyclic test results of column specimens

After the column test specimens were 28 days old, the quasi-cyclic tests were then carried out as described in the previous explanation. The results were then graphed after which the analyses of the achieved drift ratios and displacement ductility values were carried out. The results are shown in Figure 5 (1-12) and the values are summarized in Table 5.

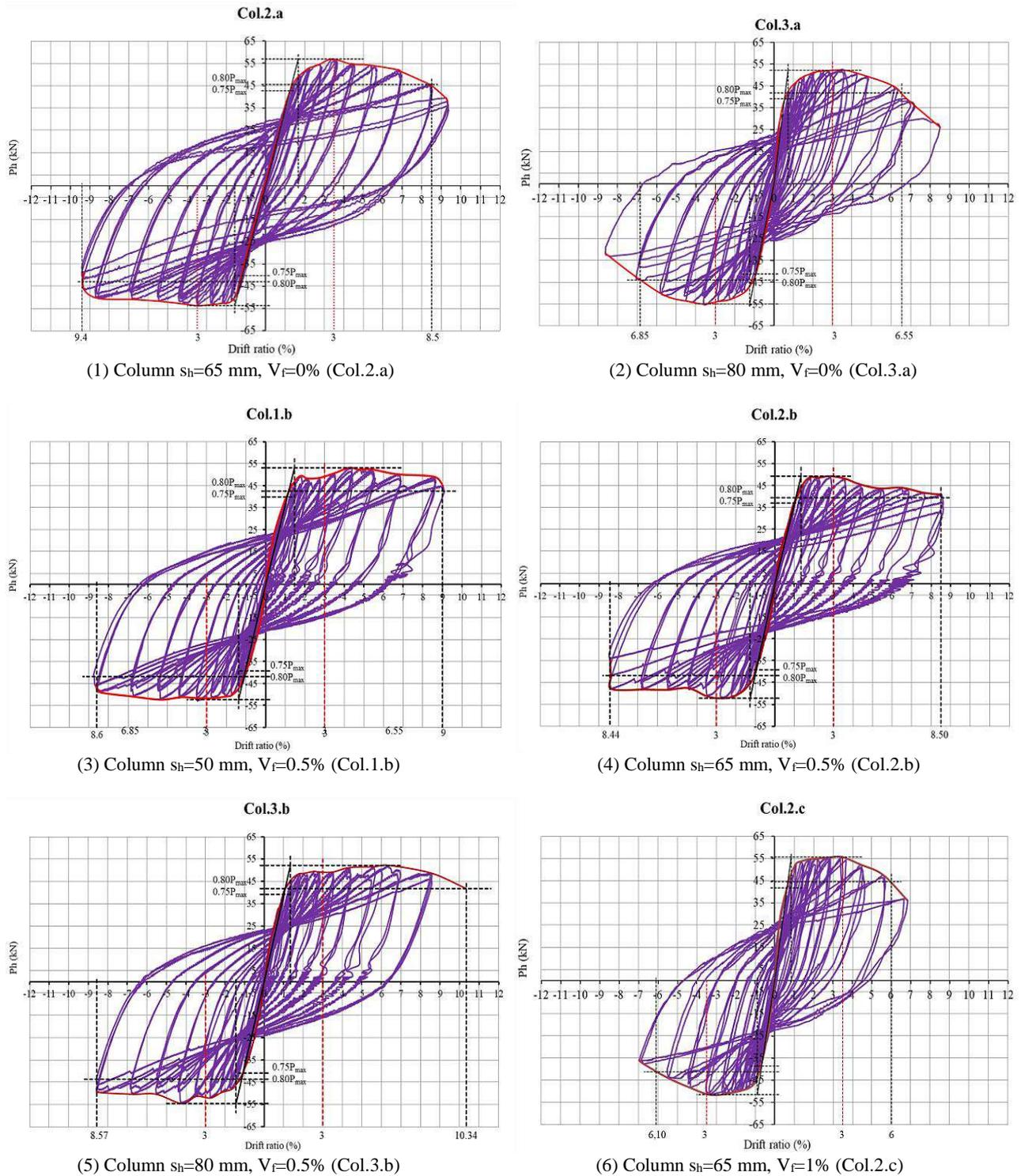


Figure 5 Loop hysteresis curve based on drift ratio vs column  $P_h$

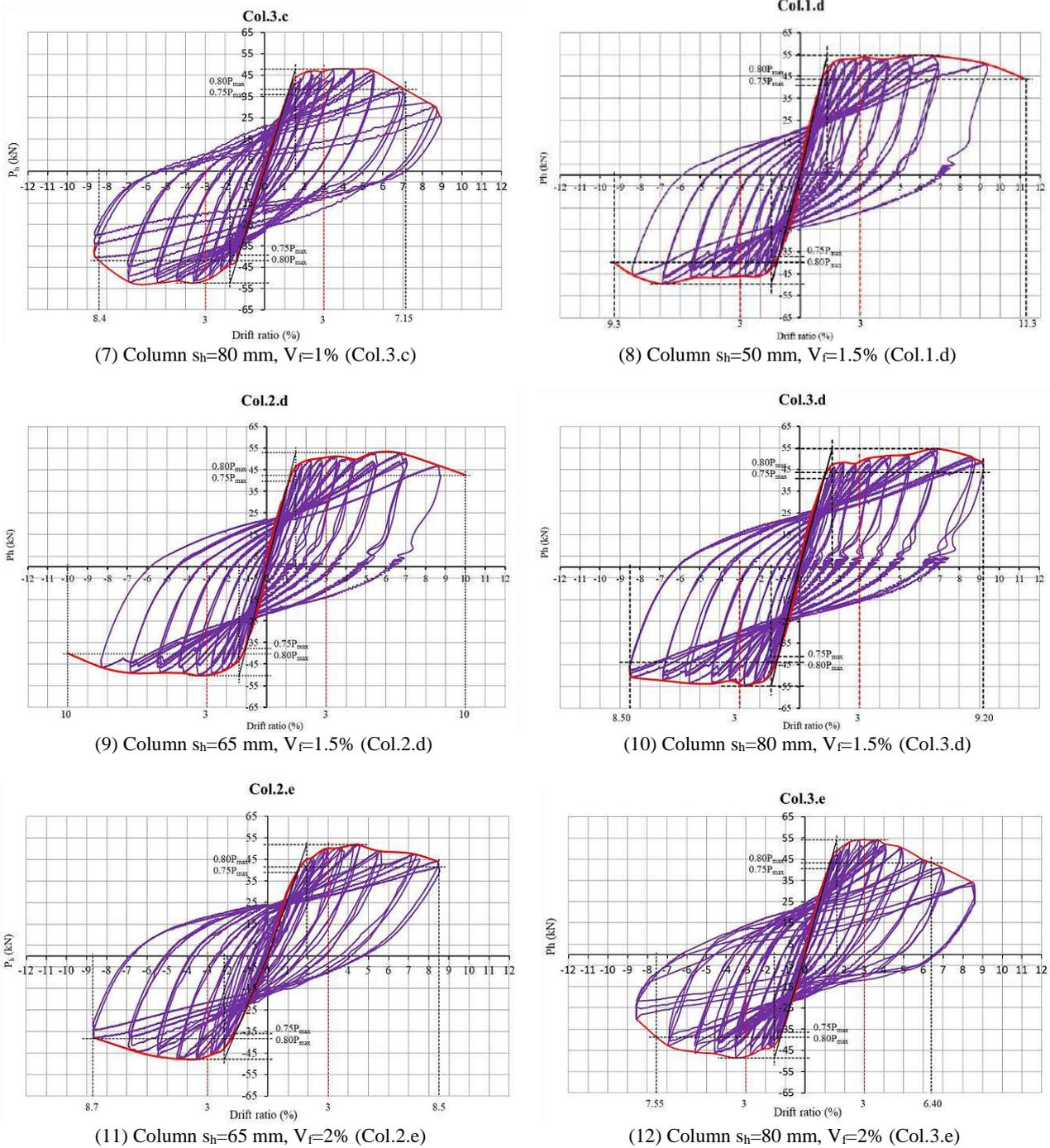


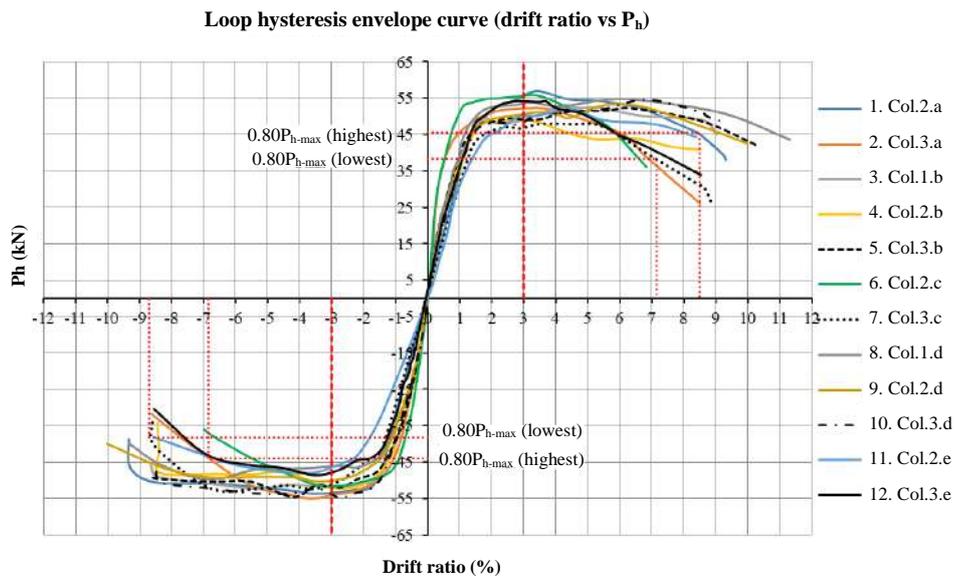
Figure 5 (continued) Loop hysteresis curve based on drift ratio vs column  $P_h$

Table 5 Recapitulation of experimental results  $\mu_{\Delta-exp}$  at  $0.80P_{max}$

No.	Specimen ID	$\mu_{\Delta-exp}$ compression (mm)	$\mu_{\Delta-exp}$ tension (mm)	$\mu_{\Delta-exp}$ average (mm)	Criteria	Drift ratio <sub>exp</sub> compression (%)	Drift ratio <sub>exp</sub> tension (%)	Drift ratio <sub>exp</sub> average (%)
1.	Col.2.a	5.95	5.09	5.52	Full ductile	9.40	8.50	8.95
2.	Col.3.a	5.50	9.03	7.27	Full ductile	6.85	6.55	6.70
3.	Col.1.b	6.23	6.12	6.18	Full ductile	8.60	9.00	8.80
4.	Col.2.b	6.65	6.34	6.50	Full ductile	8.44	8.50	8.47
5.	Col.3.b	5.95	7.70	6.82	Full ductile	8.57	10.34	9.45
6.	Col.2.c	6.85	7.06	6.96	Full ductile	6.10	6.00	6.05
7.	Col.3.c	4.77	4.58	4.68	Full ductile	8.40	7.15	7.78
8.	Col.1.d	6.46	8.41	7.43	Full ductile	9.30	11.30	10.30
9.	Col.2.d	7.25	6.80	7.02	Full ductile	10.00	10.00	10.00
10.	Col.3.d	5.94	5.64	5.79	Full ductile	8.50	9.20	8.85
11.	Col.2.e	4.01	4.40	4.21	Full ductile	8.70	8.50	8.60
12.	Col.3.e	4.84	4.00	4.42	Full ductile	7.55	6.40	6.98

Note: Col.1=  $s_h$  50 mm, Col.2=  $s_h$  65 mm, Col.3=  $s_h$  80 mm, a= $V_f$  0%, b= $V_f$  0.5%, c= $V_f$  1%, d= $V_f$  1.5%, e= $V_f$  2%.

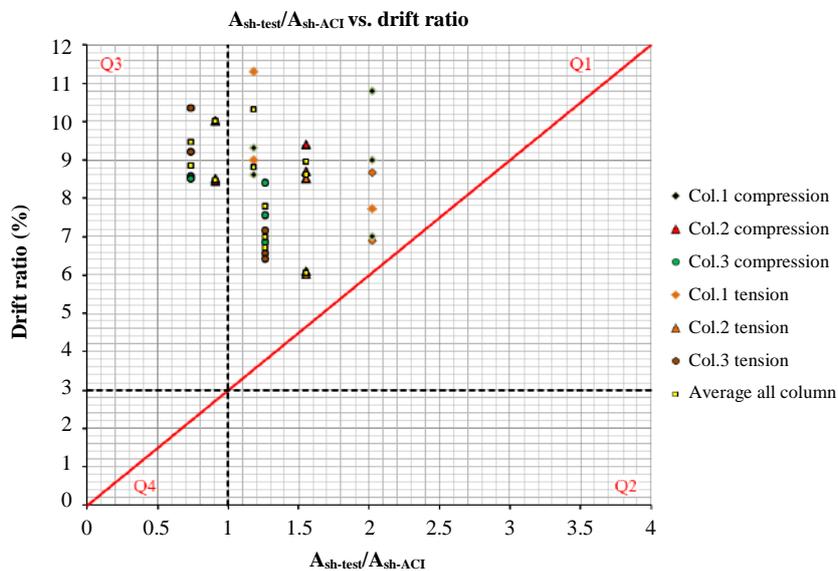
Based on Figure 5, the loop hysteresis envelope curve is depicted (see Figure 6) which is grouped based on volumetric steel fiber and stirrup spacing. Figure 6 shows the difference in drift ratio vs.  $P_h$  among twelve column test specimens. It can be seen that the largest displacement was attained by column test specimen Cl.1.d, while the smallest displacement was achieved by column test specimen Cl.2.c. However, all twelve column test specimens were in full ductile criteria (see Table 5). Figure 6 also shows that the displacement of the column test specimen with  $s_h = 80$  mm is seen to be in the middle of all twelve column test specimens, meaning that the column test specimen with  $s_h = 80$  mm can be said to be in a conservative condition (safe condition), so it does not need to be designed using stirrups with  $s_h = 50$ mm. This can be beneficial in the process of constructing the concrete column members because the work will be less complicated. Apart from that it can be understood that the design and implementation of concrete construction might deviate and be an issue on site. All twelve column test specimens have conformed to the requirements of ACI 318M-19, i.e. the drift ratio has exceeded 3% at  $0.8P_{h-max}$ . Figure 5 shows the column test specimen's capabilities to withstand the horizontal load  $P_h$ , ranging from 47.87 to 56.95 kN. However, their capability to experience lateral displacement at  $0.80P_{h-max}$  varied. This drift is very important to consider because it is an inseparable part of the ACI 318M-19 requirement that after the post-elastic response at  $0.80P_{h-max}$ , it should be able to sustain at least a 3% drift ratio. In this research, it turns out that the column test specimen with  $s_h = 80$  mm was still able to sustain a displacement equivalent to the column test specimen with  $s_h = 50$  mm. Thus, it indicates that the co-existence of both steel fiber and stirrups as confinement has a significant impact on displacement ductility. This is because the displacement ductility at the highest/lowest tension or highest/lowest compression has exceeded the drift ratio limit of 3%.



**Figure 6** Backbone curves of the hysteretic loops from test column specimens

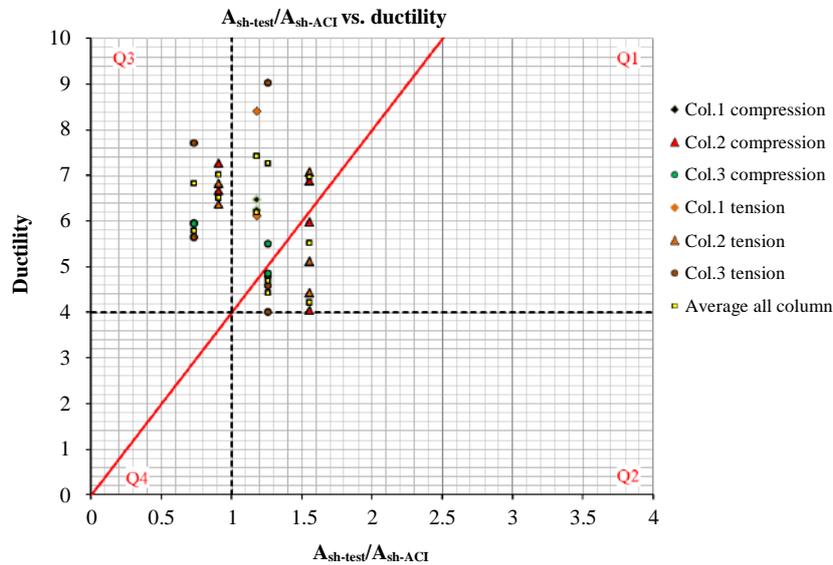
Some of the data mentioned above are then discussed using the reference of Elwood et al. [28]. This is also a reference to ACI 318-19 [4] which is automatically included in article R18.7.5.4 SNI 2847:2019 [29]. It is stated that the column must be able to achieve a drift ratio of 3% without experiencing a drastic reduction in strength. The reduction in question is  $0.8P_{h-max}$  in inelastic conditions.

Figure 7 shows the column drift ratio capacity between the  $A_{sh}$  ratio of the installed confining reinforcement ( $A_{sh-test}$ ) to the confining reinforcement based on ACI ( $A_{sh-ACI}$ ). It also shows the column drift ratio capacity as a function of concrete confinement and displays the column performance target represented by the horizontal line in drift ratio of 3%.



**Figure 7** Relationship between stirrup area ratio vs. drift ratio [28, 29]

In Figure 8, data in quadrant 1 (Q1) is a column with constraints that exceed ACI requirements but have a drift capacity that is the same or greater than the performance target ( $\geq 3\%$ ). Data in quadrant 4 (Q4) represents columns with less confinement gain than the ACI requirement but with drift capacity less than the performance target. The data appearing in the upper left quadrant 3 (Q3) represents columns with confining reinforcement that is less than the ACI requirement but shows a drift capacity that exceeds the target, thus indicating that the results in Q3 can be considered very conservative. In contrast, the data in the lower right quadrant 2 (Q2) represents columns with more confinement than required by the provisions but shows a drift capacity below the target, so the results in Q2 can be considered not conservative. The confinement conditions above the red line in Q2 show a trend of proportional increase in drift due to the increase in Ash usage, where it can be seen that all experimental columns Col.1, Col. 2, and Col. 3 have shown confinement results that can be categorized as ideal and Col. 1 shows a relatively higher drift. However, if you look at the results of the displacement ductility test, all groups of test specimens have entered the full ductile criteria ( $\mu_{\Delta} > 4$ ), however, several test specimens are in Q3, this is because the Ash-provided are less than the  $A_{sh-ACI}$  value so the condition very conservative.



**Figure 8** Relationship of  $A_{sh}$  vs. displacement ductility ( $\mu_{\Delta}$ )

#### 4. Conclusion

In this research, the combination of stirrups and steel fiber shows that:

- Columns confined by stirrups with a distance of  $s_h = 50, 65,$  and  $80$  mm and using  $V_f = 0\%, 0.5\%, 1\%, 1.5\%$ , and  $2\%$  all have the same drift ratio capacity or even greater than the drift ratio performance target of  $\geq 3\%$  so that the use of  $s_h = 80$  mm and adding a certain  $V_f$  can be said to be in fairly conservative conditions, at least conforming the requirements of ACI 318-19 or R18.7.5.4 SNI 2847:2019.
- In Figure 7, the column test specimen is in the upper right quadrant 1 (Q1). This indicates that the confinements are in ideal conditions so that the stirrup distance can be reduced from  $s_h = 50$  mm to  $s_h = 80$  mm.
- The achievement of ductility in the study can also be said to be quite conservative, where all the test specimens entered the full ductile criteria, so it can also be said that the stirrup confinement with a distance of  $s_h = 80$  mm reinforced with steel fiber have satisfied the demands of ductility requirements, so there is no need to use  $s_h = 50$  mm.
- The use of installed stirrups should be at least the same as  $A_{sh-ACI}$ , but several column test specimens in this study have been tested with  $A_{sh-provided} < A_{sh-ACI}$  and reinforced with steel fiber in columns with  $A_{sh} < A_{sh-ACI}$ , the results show that the ductility achieved is still within the full criteria ductile, this indicates that steel fiber contributes to column strength, such as the achievement of column numbers 4-5 and 9-10 in this study.

#### 5. Acknowledgment

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