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**Citation:** Zimos, D.K., Papanikolaou, V.K., Kappos, A. J. & Mergos, P.E. (2020). Shear critical R/C columns under increasing axial load. *ACI Structural Journal*, 117(5), pp. 29-40. doi: 10.14359/51725886

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# SHEAR-CRITICAL R/C COLUMNS

## UNDER INCREASING AXIAL LOAD

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2 analysis, earthquake engineering and structural optimization.

### 3 **SYNOPSIS**

4 Structural elements in old reinforced concrete (R/C) frame buildings are often prone to shear  
5 or flexure-shear failure, which can eventually lead to loss of axial load capacity of vertical  
6 elements and initiate vertical progressive collapse of a building.

7 An experimental investigation of shear and flexure-shear critical R/C elements subjected to  
8 increasing axial load is reported herein. The focus is on the effect of vertical load  
9 redistribution from axially failing columns on the non-linear (pre- and post-peak) response of  
10 neighboring shear-dominated members. The test results along with an analysis of the  
11 recorded deformation, strength, stiffness and energy dissipation characteristics shed light on  
12 the performance of sub-standard columns under constant and increasing axial load  
13 subsequent, or just prior, to failing in shear, thus providing useful insights into the assessment  
14 of existing R/C structures.

15 **Keywords:** Existing structures; Experimental program; Reinforced concrete columns; Shear  
16 failure; Axial failure; Vertical load redistribution; Progressive collapse

### 17 **INTRODUCTION**

18 Many existing reinforced concrete structures have been designed according to older, less  
19 demanding, seismic codes or might not have been designed to withstand seismic loads at all.  
20 Transverse reinforcement in their structural elements is typically low, widely spaced and/or  
21 poorly anchored, rendering them vulnerable to shear failure, subsequent, or even prior, to  
22 yielding of their longitudinal reinforcement. Shear failure can eventually lead to loss of axial

1 load capacity of vertical elements, through disintegration of the poorly confined concrete  
2 core<sup>1</sup>. Loss of column axial capacity emerges from post-earthquake reconnaissance as one of  
3 the most common reasons of vertical progressive collapse of older R/C frame buildings<sup>2</sup>.  
4 Such a column failure means that the vertical loads previously carried by a failing member  
5 are subsequently redistributed to neighboring vertical elements. Therefore, the ability of a  
6 framing system to resist progressive collapse in such a ‘scenario’ depends on both the ability  
7 of horizontal elements to transfer the loads being redistributed to adjacent vertical elements  
8 and the latter's ability to resist them without significant reduction in their strength and  
9 deformation capacity<sup>3</sup>. Several numerical and experimental studies, as well as field  
10 investigations, have focused on the capacity of horizontal elements to redistribute vertical  
11 loads (e.g. <sup>4-7</sup>). The General Services Administration Guidelines<sup>8</sup> also focus on load  
12 redistribution systems of gravity loads to neighboring vertical load-bearing elements.  
13 Nevertheless, existing research work has not yet concentrated adequately on the vertical  
14 members adjacent to an axially failing column; when an abrupt increase of axial load occurs,  
15 the capacity to resist progressive collapse should be carefully assessed<sup>9</sup>. This effect has been  
16 given only limited consideration in the study of older R/C buildings (e.g. in <sup>10</sup>), without a  
17 rigorous treatment of post-peak response. In flexure-critical elements axial load increase can  
18 be included by accounting for axial-flexure interaction. However, this is not the case for  
19 shear- or flexure-shear-critical elements modeled with beam-column elements explicitly  
20 accounting for shear deformations, wherein axial load increase has not yet been modeled.  
21 A common assumption in progressive collapse assessment is that of undamaged vertical  
22 elements; this may be appropriate for blast-induced or similar collapse scenarios, with  
23 damage largely localized in a single element or a small set of elements. Nevertheless,  
24 earthquake-induced collapse scenarios pose a further difficulty when there is global damage

1 in a large part of, if not the entire, building, even before the loss of a column's axial capacity.  
2 Therefore, the damage state of a column neighboring an axially failed vertical member has to  
3 be appropriately addressed in earthquake-induced progressive collapse assessment (e.g. <sup>10</sup>).  
4 Previous experimental studies looking into the non-linear, especially the post-peak, lateral  
5 response of shear-critical R/C columns have looked extensively at the response under  
6 constant axial load (e.g. <sup>11,12</sup>, among several others) and axial load proportional to the lateral  
7 force acting on the column (e.g. <sup>1,12,13</sup>). Recently, Nakamura & Yoshimura<sup>14</sup> studied  
8 experimentally the effect of decreasing axial load on the non-linear seismic response of  
9 shear-critical columns, simulating the response of a column that starts failing axially and its  
10 axial load decreases due to vertical load redistribution. Nonetheless, to the best of the  
11 authors' knowledge, the effect of axial load *increase* on the lateral response of R/C columns  
12 failing in shear has not yet been studied.

13 An experimental campaign is presented herein, aiming to shed further light on this  
14 phenomenon, i.e. the effect of vertical load redistribution on the non-linear response of shear-  
15 and flexure-shear-critical R/C columns neighboring failing vertical members. Six cantilever  
16 specimens were tested under quasi-static lateral cyclic load along with an axial load, which  
17 was either constant throughout the experiment or increased just before, or just after, the onset  
18 of shear failure. Two series of specimens were tested, one failing in flexure-shear and one  
19 predominantly in shear, all of them being short columns representative of older construction  
20 practice. Key test results are provided herein, along with an analysis of these results. Data  
21 from this study can be implemented in existing numerical models (e.g. <sup>15,16</sup>) to improve the  
22 modeling of shear and flexure-shear critical members and hence progressive collapse  
23 response of R/C buildings in general.

## RESEARCH SIGNIFICANCE

Shear-critical columns in sub-standard R/C buildings may experience permanent increase of axial load due to the loss of bearing capacity of adjacent columns. This experimental study is the first one addressing the effect of axial load increase on the pre-peak and post-peak lateral response of shear-critical R/C columns. Its results can be used to enhance existing numerical models with the capability to accurately model failure of shear-critical column members and hence progressive collapse response of R/C buildings; such models are valuable in vulnerability analysis of old buildings for damage states close to collapse.

## EXPERIMENTAL INVESTIGATION

### Conceptual Design

Loss of axial load-bearing capacity of an R/C column leads to redistribution (through the horizontal members) of most of its vertical load to adjacent columns; this typically leads to a significant increase in the axial loads of the latter. Unlike the momentary fluctuations of axial load under earthquake loading, this increase is permanent and its effect should be clearly understood and modeled. To study the effect of axial load increase on the response of shear-dominated columns, shear-critical R/C column specimens were tested under cyclic lateral loading and increasing axial load. First, cyclic loading was applied along with constant axial load acting atop the specimen, simulating the conditions prior to vertical load redistribution. At some point, the vertical load was increased to the desired level and subsequently the lateral cycling resumed until reaching axial collapse. This procedure simulates the response to seismic loading of a column up to a certain point, redistribution of vertical loads due to axial failure of a neighboring column and continuation of the earthquake action up to vertical collapse of the first column.

1 Two series of specimens were fabricated, one failing in flexure-shear and another  
2 predominantly in shear. One column in each series is tested with constant axial load throughout  
3 the response to serve as reference. Table 1 presents the design details of each specimen. The  
4 focus is on older R/C construction lacking modern design and detailing rules, where column  
5 failure is not prevented by design.

6 A key parameter of the problem is the percentage of axial load increase. Usually, interior  
7 columns carry vertical loads of similar value and after axial failure of one of them, its load is  
8 redistributed to three or four columns around it. However, there are cases where higher load  
9 increase takes place, as when neighboring columns have different tributary areas. Based on  
10 these considerations, a 50% increase of the axial load is selected herein as a reasonably  
11 conservative value that may lead to a pronounced effect on the seismic response.

12 Another key parameter is the damage state at the instant of vertical load increase. In buildings  
13 struck by strong earthquakes there is substantial damage in most of the building before the loss  
14 of a column's vertical load bearing capacity, i.e. damage is not localized as in the case of e.g.  
15 blast loading; the extent of damage has a significant impact on the resulting response. For  
16 instance, an axial load increase at the early stages of pre-peak response might be beneficial for  
17 the overall response of the member, increasing its strength and stiffness, while the same axial  
18 load increase in the post-peak stage might prove detrimental. As the focus of this study is  
19 mainly on the peak and post-peak response, two different instants of axial load increase were  
20 selected to study its effect on the response. The first one is just before the onset of shear failure,  
21 and the second one immediately after it.

22 The aforementioned axial load increase intuitively seems likely to initiate at, or close to, the  
23 peak of a cycle of the displacement history. Nonetheless, according to previous shake-table  
24 tests (e.g. <sup>17,18</sup>), the loss of bearing capacity of a column and subsequent redistribution of

1 vertical loads takes place gradually over several load reversals. In the absence of a clearly  
2 defined “trigger point”, the beginning of a cycle was chosen as the point of vertical load  
3 increase during the tests, mainly with the safety of the testing equipment in mind.

#### 4 **Test Specimens**

5 Two sets of three columns with same geometry and materials but different reinforcement were  
6 designed and fabricated (Fig. 1); they were formed as cantilevers, representing the length  
7 between the base and the contraflexure point of short columns. The column cross-section is  
8 square,  $300 \times 300$  (mm), and their length (at lateral loading level) is 715 mm (aspect ratio of  
9 2.4). Consistent with old practice, the transverse reinforcement is sparse,  $\text{Ø}8/320$  (mm) and  
10  $\text{Ø}8/270$  for the shear critical (SC) and flexure-shear critical (FSC) specimens, respectively, and  
11 has  $90^\circ$  hooks (Fig. 1). The longitudinal reinforcement was designed to achieve the desired  
12 response and failure types; it is  $12\text{Ø}16$  (16 mm diam. bars) for the SC critical columns and  
13  $4\text{Ø}16+4\text{Ø}14$  for the FSC columns resulting in a total reinforcement ratio of 2.68% and 1.58%,  
14 respectively.

15 The specimen design is shown in detail in Fig. 1, including the column mounting bases which  
16 were heavily reinforced to avoid any unwanted failure and make them sufficiently stiff, thus  
17 minimizing the displacement of the column top due to deformations of the base.

#### 18 **Materials**

19 As per European Code<sup>19</sup>, the concrete grade is C20/25 (characteristic cylinder strength of 20  
20 MPa) and reinforcing steel grade is B500C (characteristic yield strength 500 MPa) for both the  
21 transverse and longitudinal reinforcement. Compression tests were performed on the same day  
22 as column tests. The measured strength was on average 27.7 MPa (individual specimen  
23 strengths shown in Table 1). Coupon tests on the ribbed reinforcement bars gave on average a  
24 yield stress of 565 MPa, tensile strength of 675 MPa and ultimate strain around 16%,.

## 1 **Test set-up and instrumentation**

2 Specimens are subjected to uniaxial bending and axial loading, as seen from the experimental  
3 set-up (Fig. 2). The double-acting double-hinged horizontal actuator applies a quasi-static  
4 cyclic load, operating in displacement-control mode, externally controlled by a dedicated  
5 displacement draw-wire sensor, since the standard actuator-based (internal) displacement-  
6 control may introduce significant ‘lash’ into the results, mainly due to the mounting setup and  
7 the non-negligible elastic deformations of the reaction frame, thus overestimating the actual  
8 lateral displacement of the tested specimens<sup>20</sup>.

9 The loading protocol consisted of three cycles per displacement level with a step of 3.0 mm,  
10 typical of quasi-static cyclic tests (e.g. see ISO Displacement Schedule in <sup>21</sup>). Displacement  
11 histories are applied at constant rate, hence having longer duration at later stages; this rate is as  
12 low as 0.4 mm/s, to prevent development of noteworthy strain rate and inertial effects <sup>21</sup>.

13 The double-hinged vertical actuator operates in force-control mode, dwelling at 180 kN, i.e. an  
14 axial load ratio (axial load over gross concrete cross-section axial capacity) of  $\nu = 0.10$ . Shortly  
15 before or soon after the onset of shear failure this load is increased to 270 kN, i.e.  $\nu = 0.15$ . A  
16 reference specimen in each set (FSC\_1 and SC\_1) is tested with constant axial load (180 kN).  
17 The axial load increase takes place within 9 s, corresponding to a load rate of 10 kN/s. This is  
18 done before the first cycle of 12 mm in FSC\_2 and SC\_2 and before the first cycle of 15 mm  
19 in FSC\_3 and SC\_3, as the onset of shear failure was found to occur at a displacement of  
20 12 mm.

21 The instrumentation of the experiment comprises load cells, LVDTs, draw-wire sensors and  
22 strain gages. The load cells are mounted on the two actuators, measuring the resisting force  
23 from the specimens. Draw-wire sensors are used to measure the top lateral displacement,  
24 displacements along the diagonal needed to calculate shear deformations, and the potential base

1 uplift, in order to ensure that no significant base deformations develop. In the vertical direction,  
2 the axial deformation is directly measured from the axial displacement sensor of the vertical  
3 actuator. Strain gages were installed on longitudinal and transverse bars near the base of a  
4 shear-critical column (see detailed instrumentation arrangement in Fig. 3).

5 In addition to instrumental measurements, digital image correlation (DIC) was used to  
6 measure column deformations. Using a high-resolution camera from a fixed position, column  
7 images already painted with a speckle pattern were collected at each cycle. The distance  
8 between the initial and the shifted positions of each individual speckle point on the front face  
9 of the column can be measured at each cycle, providing the entire displacement contour along  
10 the front surface of each column throughout the duration of the test.

11 All recorded data is collected by the test controller at a frequency of 10 readings per second.  
12 Safety limits (displacements, forces) were imposed to automatically terminate the  
13 experiment, in case of structural imbalance.

## 14 **TEST RESULTS AND DISCUSSION**

### 15 **Crack and Damage Propagation**

16 Crack widths were measured using digital image correlation (details are given in <sup>22</sup>). The  
17 general pattern of damage initiation and propagation involves a horizontal crack forming very  
18 close to the column/base interface. Further horizontal cracks form higher up along the  
19 specimen at some distance from the interface crack and from each other, as a certain distance  
20 is required between cracks for the tensile strength to rebuild through bond. These cracks cross  
21 the position of the longitudinal bars, not extending much deeper into the specimen, and  
22 initiate quite early on, mostly at the displacement level of 3 mm (0.42% drift). The initial  
23 crack is usually wider than the subsequent cracks; all of them tend to increase in width with

1 increasing lateral displacement, while generally remaining stable or closing towards the last  
2 displacement cycles of the test. Moreover, fine diagonal and horizontal cracks appeared at the  
3 column/base joint at displacement levels of 6 mm and 9 mm, their width peaking at 12 mm  
4 (1.68% drift) (Fig. 4). The widest of these cracks reached a peak of about 0.35-0.45 mm. FSC  
5 specimens developed more flexural cracks in total along the height of the specimen – four to  
6 five – being affected more by flexure, while the SC ones developed two or three. Specimen  
7 SC\_3's corner longitudinal bars were found to reach yield strain around the displacement  
8 levels of 9 to 12 mm and exceed it at 15 mm (2.10% drift).

9 Cross-inclined shear cracks appeared at a displacement level of approximately 6 mm (0.84%  
10 drift) or 9 mm (1.26% drift) and started opening considerably from about 12 mm (Fig. 4),  
11 reaching large widths of approximately 4 to 10 mm near the final cycles (Fig. 5). Their  
12 bottom end was always at the column/base interface and their inclinations were usually  
13 around 28°-33° on average. The SC specimens seem to have larger average shear crack angles  
14 than the FSC ones, which all exhibit 28° angles on average. Spalling of concrete cover was  
15 observed close to the bottom ends of the inclined cracks, due to local decrease of the  
16 compression zone depths at those sections resulting from the shear cracks. Despite substantial  
17 opening of these diagonal cracks, no fracture of transverse bars occurred, as the 90°-  
18 anchorage of the ties led to their slippage at high displacement levels. The strain gages  
19 mounted on transverse bars in SC\_3 show that the tie at about 350 mm from the interface  
20 reached its strain-hardening branch at a displacement level of 15 mm (2.10% drift),  
21 developing very high strains afterwards. This is due to the opening of the full-depth crack at  
22 that point of the test, with the consequent opening of the gap. The tie placed about 30 mm  
23 above the interface did not yield, as it was not crossed by any shear crack.

24 Longitudinal bars of almost all specimens showed residual curvature due to buckling,

1 initiating near the end of the experiment. Their buckling length clearly exceeded the tie  
2 spacing, due to their 90° hook and low anchorage length that do not provide adequate  
3 restraint. Moreover, disintegration of the concrete core was obvious, with parts of it having  
4 shattered during cycling, particularly near the last cycles.

## 5 **Lateral Hysteretic Response**

6 The specimens' hysteretic responses in terms of horizontal force (kN) vs lateral displacement  
7 (mm) or lateral drift (%) are shown in Fig. 6. Due to high sampling rate, smoothing has been  
8 applied to all hysteretic responses; original responses and smoothing method are given in <sup>22</sup>.

9 The responses of the FSC (flexure-shear critical) specimens are quite similar, with peak  
10 strengths of around 150-160 kN developing at 12 mm (1.68% drift). Limited cyclic strength  
11 degradation and reloading stiffness degradation are exhibited in the pre-peak domain, which  
12 however increase significantly after peak.

13 The SC specimens remained almost 'elastic' up to a strength of around 130 kN (peak of the  
14 first displacement level), followed by a rather stiff strain-hardening branch up to about 200  
15 kN at 12 mm displacement. One specimen (SC\_3) did not reach its peak strength at a  
16 displacement of 12 mm (4<sup>th</sup> cycle), but in the next cycle. This led to the increase in axial load  
17 occurring before the onset of shear failure, instead of just after it, as initially planned. The SC  
18 specimens also exhibit much higher cyclic strength degradation in the post-peak domain.

19 The highest cyclic strength degradation in each specimen takes place at the displacement  
20 level where the peak is reached, i.e. at the onset of shear failure. This coincides with the  
21 formation of a full-depth diagonal shear crack in each specimen (Fig. 4) in each loading  
22 direction and occurred in most specimens at a displacement of 12 mm (1.68% drift). In-cycle  
23 strength degradation, which in general was minor (recall that three cycles per displacement  
24 level were applied), was observed near the onset of shear failure in most specimens.

1 While the loops of both FSC and SC specimens are quite full at the first displacement levels,  
2 i.e. the specimens dissipate a large amount of energy (despite being shear critical), the loops  
3 become much thinner in the post-peak range. Pinching is observed in most responses, but is  
4 lower than expected given that the specimens are shear-critical. Of course, the ‘low-stiffness’  
5 part of the response due to closing of cracks of one side and reopening of the other side’s  
6 cracks upon reversal is observed, especially near the final cycles.

7 The displacement capacities of the specimens vary substantially; SC specimens reach higher  
8 displacements in absolute terms than the FSC ones, largely due to higher longitudinal  
9 reinforcement content, which leads to higher post-peak displacements<sup>15</sup>. Attained  
10 displacement ductilities are compared in Table 2 at peak strength (i.e. onset of shear failure),  
11 at the maximum attained displacement and (wherever applicable) at the onset of axial failure.

12 The yield displacement is taken for convenience as the displacement on the cyclic envelope  
13 curve corresponding to a strength equal to 70% of the peak strength. The displacement  
14 ductility achieved by most specimens (notwithstanding the definition of yield point) is  
15 remarkable given their poor design and their shear-dominated response – usually  
16 characterized as ‘non-ductile’ or even ‘brittle’. All of them reach their peak resistance at a  
17 ductility between 4 and 6 (drifts between 1.7% and 2.1%). The specimens that do fail axially  
18 reach a ductility of 6.5 to 7.5 (drifts between 2.1% and 2.9%), while the specimens that do  
19 not fail axially are shown to exceed a ductility of 10 (drifts between 2.9% and 3.8%), far  
20 more than would normally be expected from such designs.

## 21 **Axial Response**

22 The average (over the section) vertical displacements at the top of the specimen (mm) vs.  
23 lateral displacements (mm) are presented in Fig. 7. Since the recording system was reset after  
24 the axial load was applied, the vertical displacement at the initial position is taken as 0.0 mm;

1 in reality, it is lower and was estimated based on the specimens' properties as 0.048 mm.

2 Vertical displacements of all specimens follow the typical U-shaped pattern up to the onset of  
3 shear failure, i.e. having a specific negative displacement (compressive strain) at the  
4 'vertical' position (zero lateral displacement) with increasing displacements towards the  
5 peaks of each cycle. The increased vertical displacements at the extremes of each cycle come  
6 from the well-known phenomenon of member elongation in the nonlinear range of the  
7 response; curvatures lead to high tensile strains of the tension reinforcement, also  
8 accompanied by opening of cracks; with consecutive cycles at increasing lateral  
9 displacements, plastic strains accumulate leading to further elongation.

10 However, the shape of the observed pattern changes from the onset of shear failure onwards;  
11 from a U-shape, it turns flat and eventually into an inverted-U-shape, while vertical  
12 displacements generally decrease further with each cycle. This corresponds to a change in the  
13 physical behavior of a member; as the peak of each cycle is reached after the full depth  
14 diagonal crack has formed, the upper discrete parts of the column are pushed downwards  
15 under the influence of the constant axial load. Of course, as the displacement reverses, the  
16 cracks partly close and a part of this downward displacement is recovered (hence the  
17 inverted-U-shape); after a given point, the accumulation of downward displacements  
18 becomes very significant with vertical displacements decreasing to even less than -5 mm (i.e.  
19 an average normal strain of -0.7%). The sudden increase of axial deformations accompanying  
20 the onset of axial failure is shown to start at around -7 mm for this test series. Specimens  
21 FSC\_2, FSC\_3 and SC\_2 exhibited this behavior, while FSC\_1, SC\_1 and SC\_3 were  
22 stopped before the onset of axial failure either for the safety of the equipment or because the  
23 specimen was observed to have been damaged extensively and its resistance had fallen to a  
24 small fraction of the previously attained maximum strength.

## 1 **Effect of Vertical Load Increase**

2 It is clear in both experimental series that specimens with an axial load increase before the  
3 peak strength (namely FSC\_2, SC\_2 and SC\_3) reach a higher strength than the ones with  
4 constant axial load. This was expected, as higher compression loads increase shear strength,  
5 so long as failure is caused by diagonal tension. This increase is about 3-4%, rather shy of the  
6 predictions of 4-8% based on existing shear models<sup>23-26</sup> for an axial load increase of 50%.  
7 Fig. 8a shows the descending branch slope values estimated from the envelopes of the  
8 experimental loops. It is clear that increasing the axial load leads to higher degradation rate in  
9 the post-peak range. In all specimens with increasing axial load the descending branches are  
10 steeper than in the constant load ones; only FSC\_2 is almost equal to FSC\_1, most likely due  
11 to the higher concrete strength, partly compensating for the increased applied axial load.  
12 The maximum horizontal displacement attained by each specimen is presented in Fig. 8b with  
13 specimens that failed axially having a gradient filling; note that this is a lower bound of  
14 deformability for the ones that did not fail axially. FSC\_1 with low constant axial load is  
15 cycled up to 21 mm (2.94% drift) without losing its vertical load-bearing capacity. FSC\_2  
16 and FSC\_3 (specimens with increased axial load) fail well before that, reaching a lateral  
17 displacement at the onset of axial failure of 18 mm (2.52% drift) and 15 mm (2.10% drift),  
18 respectively. In this series, increasing the load after the peak is reached led to the axial  
19 capacity being lost sooner than increasing it before the peak. In the SC series, the axial load  
20 in both specimens (SC\_2 and SC\_3) was increased before the peak, due to SC\_3's  
21 unexpected higher displacement at onset of shear failure (compared to all other specimens).  
22 SC\_2 had lower deformability than SC\_1, i.e. 21 mm (2.94% drift) instead of 27 mm (3.78%  
23 drift), while SC\_3 achieved the same displacement as SC\_1 whose axial load was kept  
24 constant, being however much closer to axial failure than the reference specimen, reaching a

1 vertical displacement of 5.6 mm as contrasted to the 2.8 mm of SC\_1. Judging from the trend  
2 of vertical responses, SC\_3 would fail axially before completing the three 27 mm (3.78%  
3 drift) cycles, while SC\_1 managed to complete all of them without nearing axial failure.

#### 4 **Strength prediction**

5 Yield and ultimate moments were calculated from moment vs. curvature (M- $\phi$ ) analysis using  
6 the RCCOLA.NET<sup>27</sup> software. Shear strength was calculated based on four models<sup>23-26</sup>  
7 predicting the maximum resistance, i.e. before shear strength degradation due to increasing  
8 inelastic flexural deformations starts (Table 3); Priestley<sup>23</sup> model's predictions are presented  
9 for shear crack angles of both 30° and 45°. The Eurocode 8-3<sup>25</sup> equation is applied with mean  
10 material values, without safety factors, and with displacement ductility  $\mu_{\Delta,pl}$  and compression  
11 zone depth corresponding to yielding. For the *fib* Model Code 2010<sup>26</sup> equation, safety factors  
12 are disregarded and it is based on a level III approximation (a rather detailed approach).

13 Comparing the predicted with the experimentally recorded strengths, one can see that the FSC  
14 specimens exceeded the predicted ultimate flexural strength, perhaps due to discrepancies  
15 between the modeled and actual steel yield strength, steel hardening and concrete strength. On  
16 the other hand, the SC specimens are controlled by shear strength. It is clear from Table 3 that  
17 the prediction of the maximum shear resistance of an R/C element is subject to significant  
18 variability, mostly deriving from different weighting of the influence of various column  
19 properties on shear strength. The Priestley model<sup>23</sup> and the Eurocode 8-3<sup>25</sup> equations seem to  
20 predict the SC specimens' shear strength well, while the rest underestimate it. The FSC  
21 specimens' shear strength is underestimated by all models except Priestley's<sup>23</sup> that  
22 overestimates it, especially when the recommended strut angle (30°) is used.

#### 23 **Deformation Analysis**

24 Specimen deformations were calculated based on displacement sensors (LVDTs) and Digital

1 Image Correlation (details in <sup>22</sup>). It is observed (Fig. 9) that shear-induced displacements  
2 always start off low, around 10-15% of the total displacement, at a displacement level of 3  
3 mm (0.42% drift). They increase steadily as damage propagates and much more sharply from  
4 the onset of shear failure onwards. They reach percentages of 40 to 70% at the final  
5 displacement levels. Conversely, the flexural (also including bond-slip) displacements start as  
6 a high proportion of the total, around 85-90%. Although they increase considerably in  
7 subsequent cycles in absolute terms, they decrease as a percentage of the total displacement  
8 up to the onset of shear failure. After the onset of shear failure, flexural and bond-slip  
9 displacements either remain constant or decrease in absolute values leading to significant  
10 further decrease in their relative contributions to the total displacements up to axial failure.  
11 These findings clearly indicate the predominance of shear mechanisms after peak strength.  
12 FSC specimens have higher percentages of flexural displacements than the SC specimens.  
13 This observation, combined with the fact that in FSC specimens more flexural cracks form,  
14 are clear indications of the higher influence of flexure in these specimens than in the SC ones.

### 15 **Lateral stiffness degradation**

16 The secant stiffness at peaks of the hysteretic response is presented in Fig. 10 for  
17 representative specimens of each set, taking into account the average of positive and negative  
18 directions. Overall, stiffness degradation is similar in all specimens with few discrepancies.  
19 There is a very significant decrease in stiffness with increasing ductility, the stiffness  
20 decreasing by about 50% from the 3 to the 6 or 9 mm displacement.; thereafter, it keeps  
21 decreasing, reaching zero stiffness asymptotically after 18 mm (2.52% drift). The second and  
22 third cycles have only slightly lower stiffness than the first cycles at initial displacement  
23 levels. From 9 or 12 mm (1.26% to 1.68% drift), the difference becomes larger, due to higher  
24 cyclic strength and reloading stiffness degradation. The elastic (gross) flexural stiffness,

1 assuming a cantilever of 715 mm length, 20 MPa concrete and  $300 \times 300$  cross-section,  
2 would be 166 kN/mm. Nonetheless, the measured stiffness at the first peak of the first  
3 displacement level is found to be considerably lower, roughly 25% of that value. An  
4 important source of the difference from the estimated elastic flexural stiffness is that at 3 mm  
5 flexural cracking has already started, while early shrinkage cracking is also contributing to  
6 stiffness reduction; as seen in the hysteresis loops (Fig. 6), the first cycle by no means  
7 corresponds to a linear elastic response. At the same time, shear deformations were found to  
8 be a noticeable fraction of the total lateral displacement at this stage (Fig. 9), about 10 to  
9 15%. Other possible minor sources of discrepancy are bending of the plates connecting the  
10 actuator to the column, as well as some added flexibility from the deformation of the  
11 specimen base. It cannot be known exactly to what extent each factor influences the recorded  
12 value, but flexural cracking and shear deformations are considered the principal sources.

### 13 **Energy dissipation**

14 SC specimens are found to cumulatively dissipate more energy than the FSC ones in absolute  
15 terms, primarily due to the significantly higher strength owing to a higher longitudinal  
16 reinforcement ratio and the difference with regard to the attained ultimate displacement.  
17 Nonetheless, when normalized by their respective strength (Fig. 11), FSC specimens seem to  
18 be dissipating more energy than the SC ones at any given displacement, which is in line with  
19 what would be expected from specimens with a more ductile (FSC) as opposed to a more  
20 brittle (SC) behavior. The rate of energy dissipation is found to increase considerably after 6  
21 mm (0.84% drift), when plastic deformations increase significantly. They tend to slightly  
22 decrease again after 21 mm (2.94% drift), due to the drastic strength and stiffness  
23 degradation, leading to very pinched hysteresis loops.

## SUMMARY AND CONCLUSIONS

1  
2 The experimental program presented herein sheds more light on the non-linear response of  
3 shear-critical and flexure-shear-critical R/C columns, addressing for the first time the effect  
4 of axial load increase (triggered by loss of axial load capacity of neighboring columns). Six  
5 cantilever specimens (three flexure-shear and three shear critical), representative of older  
6 construction, were tested under a quasi-static cyclic lateral loading, having their axial load  
7 increased just before or after the onset of shear failure.

8 Both specimen sets exhibited relatively similar hysteretic response, with limited cyclic  
9 degradation in the pre-peak domain that increases significantly post-peak, and remarkable  
10 displacement ductility. Shear critical specimens attained higher strength and displacement,  
11 owing to their considerably higher longitudinal reinforcement.

12 All specimens initially developed horizontal flexural cracks , which kept opening up to about  
13 the onset of shear failure, remaining stable or closing thereafter. These were followed by  
14 cross-inclined shear cracks that appeared before the onset of shear failure, turned into full-  
15 depth cracks at the peak and kept opening substantially with increasing displacement post-  
16 peak, accompanied by slippage and opening of the insufficiently anchored ties. Following the  
17 typical for shear failure transition of axial deformations from a U-shape to an inverted U-  
18 shape, a sudden increase in downward displacement, with a corresponding drop of axial load  
19 resistance, signaled the onset of axial failure.

20 Deformation decomposition showed a clear trend of increasing shear deformations with  
21 increasing displacement in all specimens, which became much more pronounced after the  
22 onset of shear failure, accompanied by retraction of flexural and bond-slip deformations.

23 Between half and two thirds of the total deformations were attributed to shear by the end of

1 all tests. Flexure-shear critical specimens exhibited higher percentages of flexural and bond-  
2 slip displacements than shear critical specimens throughout the test, as well as more moderate  
3 increase of shear deformations post-peak.

4 The increased axial load just before or after the onset of shear failure was found to adversely  
5 affect the post-peak response of sub-standard R/C members. It led to higher rate of post-peak  
6 shear strength degradation and lower displacement at onset of axial failure of shear-damaged  
7 R/C columns – accompanied by comensurate reduction in total dissipated energy. On the  
8 other hand, it didn't seem to have any considerable impact on the energy dissipation capacity  
9 or lateral stiffness degradation of the members of this test series. Further experimental studies  
10 are necessary to establish clear patterns with regard to the amount of axial load increase and  
11 to the instant of axial load increase. No clear difference between the application of the load  
12 before or after the peak could be detected, as there were only three and one such specimens,  
13 respectively. More experimental studies should be performed with a broad range of design  
14 characteristics, initial axial loads, increased/decreased axial loads and points of axial load  
15 change, to improve the prediction of the impact of axial load change on the non-linear  
16 hysteretic response of sub-standard RC columns and be able to comprehensively model and  
17 assess sub-standard R/C frame buildings.

## 18 **ACKNOWLEDGMENTS**

19 The authors would like to sincerely thank all the staff of the Laboratory of R/C and Masonry  
20 Structures, AUTh, where this experimental study was carried out. The first author would also  
21 like to gratefully acknowledge the support provided by City, University of London to carry out  
22 the experiments as part of his doctoral degree scholarship and Basler & Hofmann AG for the  
23 support during the write-up of this research work.

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1 Concrete and Masonry Structures, Department of Civil Engineering, Aristotle University of  
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3 **Table 1 – Details of column specimens**

Specimen	Failure mode	Axial load (kN)	Point of axial load increase	Concrete Strength (MPa)	Transverse reinforcement	Longitudinal reinforcement
SC_1	Shear	180	-	32.8	Ø8/320	12Ø16
SC_2	Shear	180 → 270	before 1 <sup>st</sup> cycle 12 mm	27.2	Ø8/320	12Ø16
SC_3	Shear	180 → 270	before 1 <sup>st</sup> cycle 15 mm	24.3	Ø8/320	12Ø16
FSC_1	Flexure-Shear	180	-	26.0	Ø8/270	4Ø16+4Ø14
FSC_2	Flexure-Shear	180 → 270	before 1 <sup>st</sup> cycle 12 mm	28.3	Ø8/270	4Ø16+4Ø14
FSC_3	Flexure-Shear	180 → 270	before 1 <sup>st</sup> cycle 12 mm	27.7	Ø8/270	4Ø16+4Ø14

4

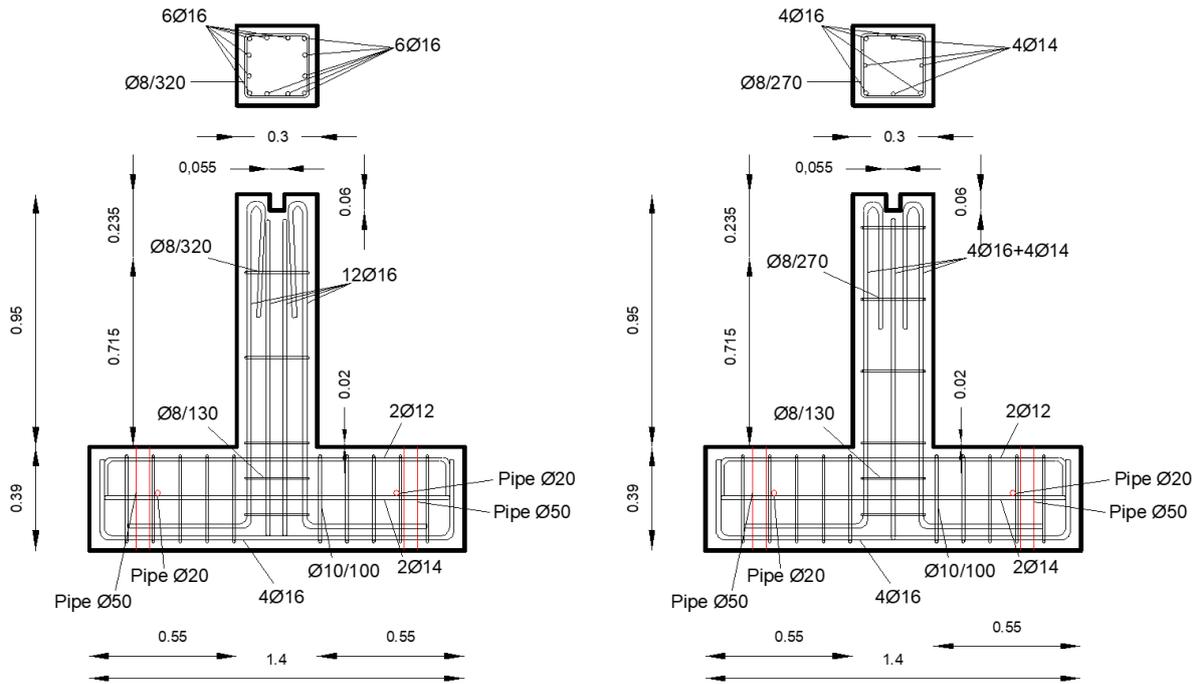
5 **Table 2 – Displacement ductilities of specimens at various levels**

Specimen	$\mu_{peak}$	$drift_{peak}$ (%)	$\mu_{max}$	$drift_{max}$ (%)
FSC_1	6.0	1.7	10.5	2.9
FSC_2	4.3	1.7	6.4	2.5
FSC_3	5.5	1.7	7.0	2.1
SC_1	4.6	1.7	10.4	3.8
SC_2	4.3	1.7	7.5	2.9
SC_3	5.7	2.1	10.3	3.8

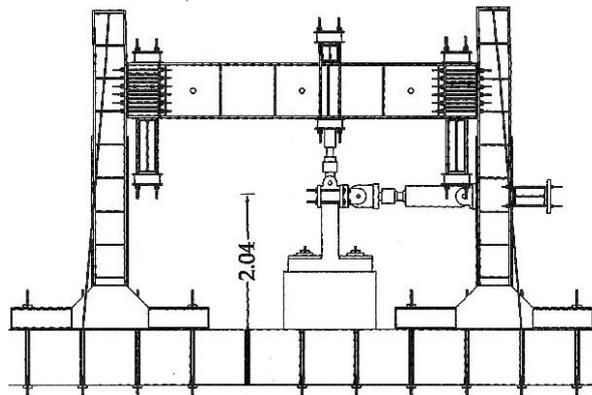
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7 **Table 3 – Maximum experimentally recorded strength and predicted flexure- and**  
 8 **shear-controlled resistances (kN).**

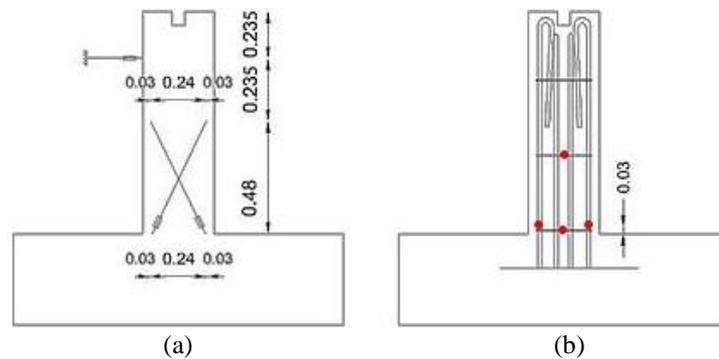
Specimen series:		SC	FSC
Shear at flexural strength (from $M-\phi$ analysis)	Yield	198	141
	Ultimate	204	146
Predicted Shear strength	Priestley <i>et al.</i> 30°	198	211
	45°	171	179
	EC8-3	198	143
	Sezen & Moehle	134	142
	MC2010	137	143
Maximum shear measured in tests		183	161



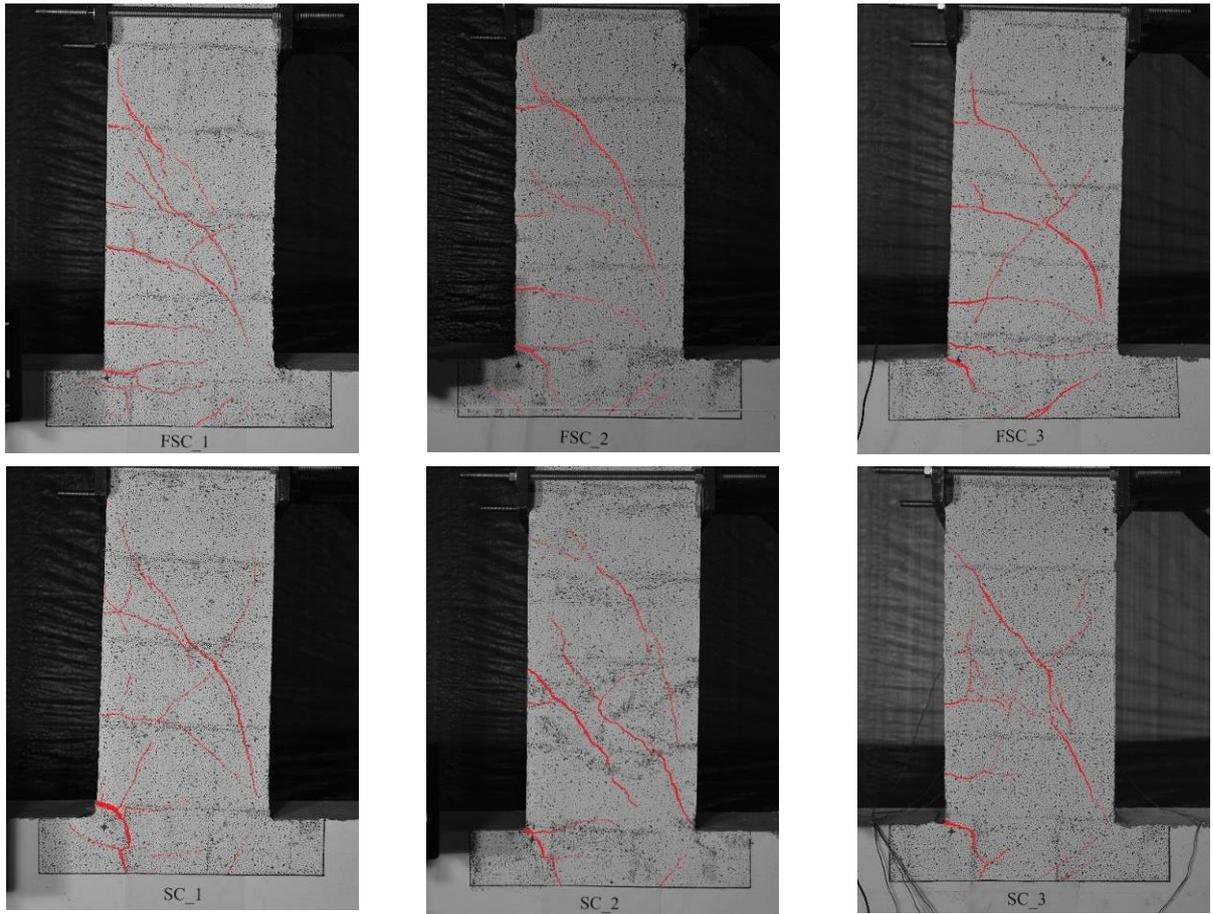
1  
2 *Fig. 1: Design of (a) shear critical (SC) and (b) flexure-shear critical (FSC) specimens (lengths*  
3 *in m; rebar and pipe diameters in mm).*



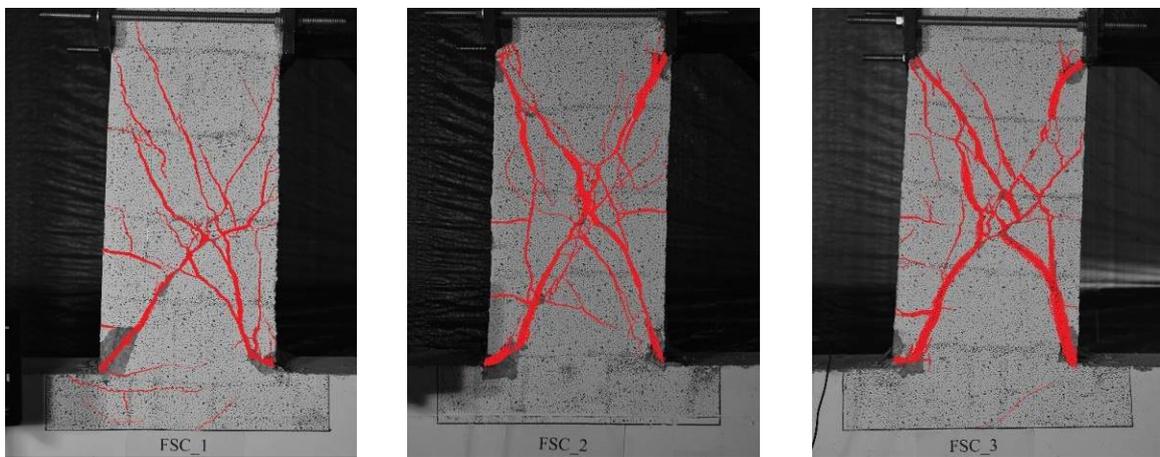
*Fig. 2: Experimental set-up shown schematically.*

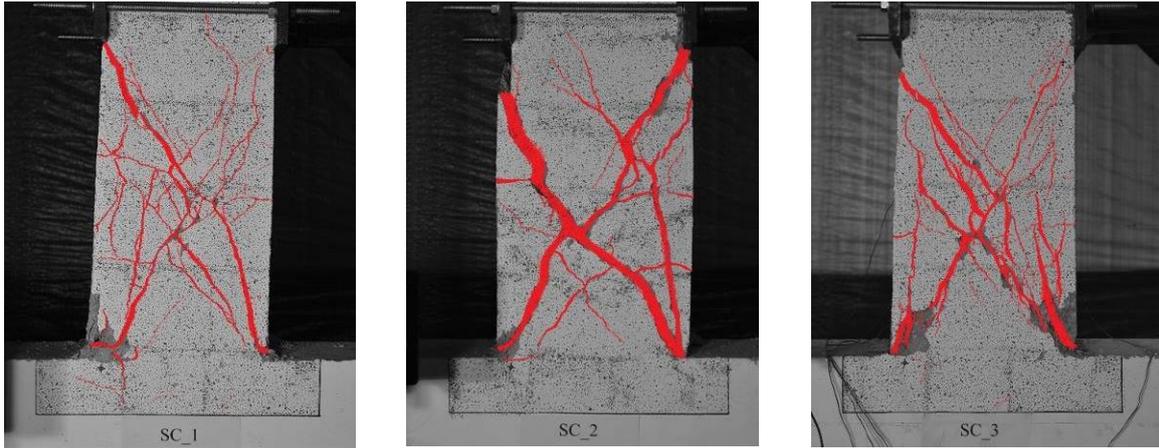


4 *Fig. 3: Instrumentation of specimens: (a) draw-wire sensors and (b) strain gages.*

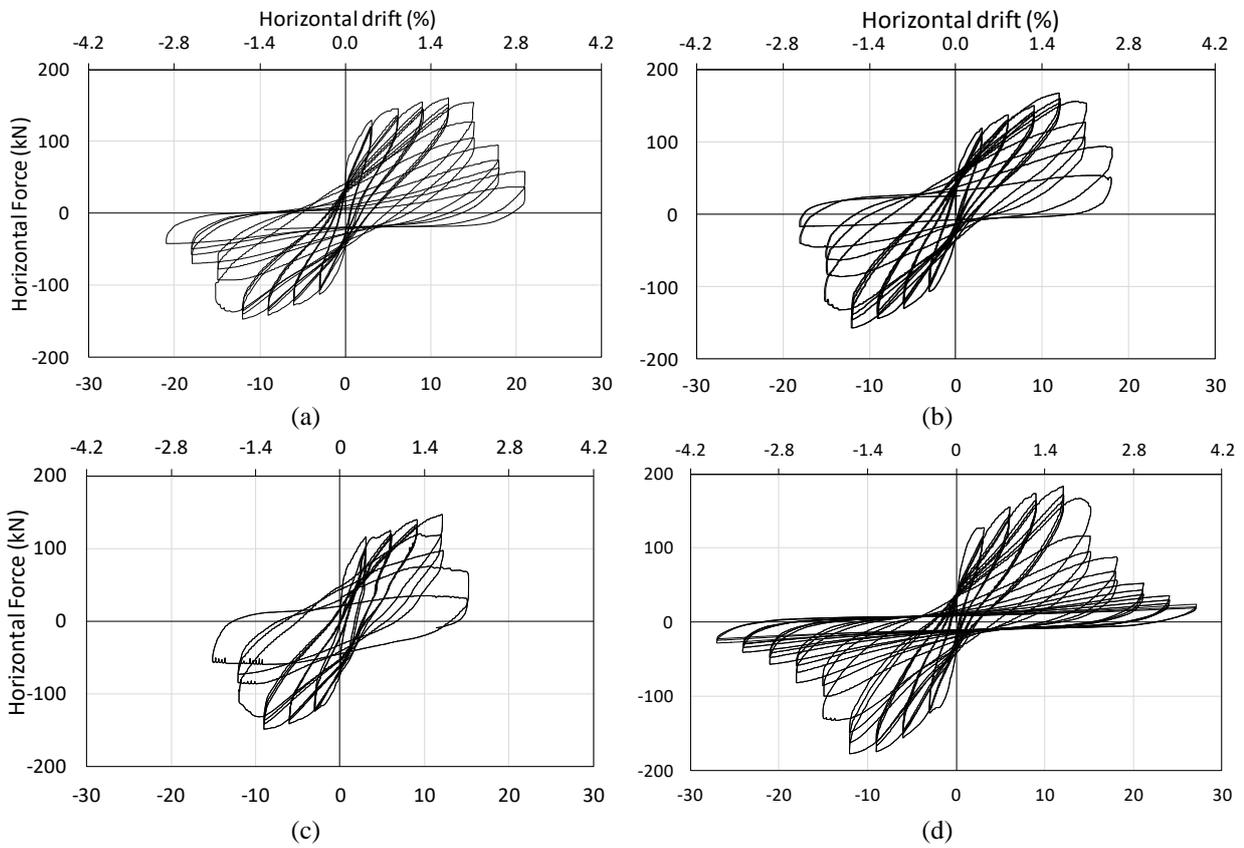


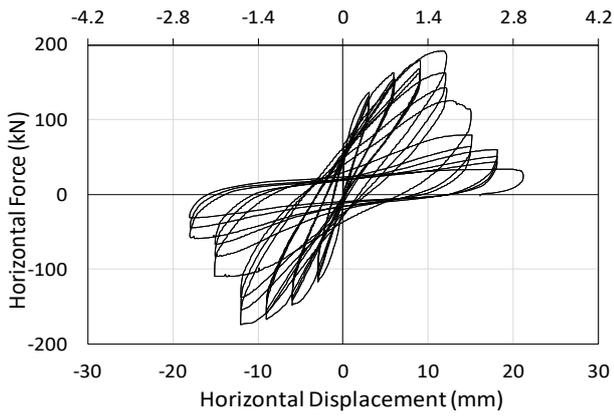
1 *Fig. 4: Damage state (surface crack patterns) of specimens at displacement level of 12 mm.*



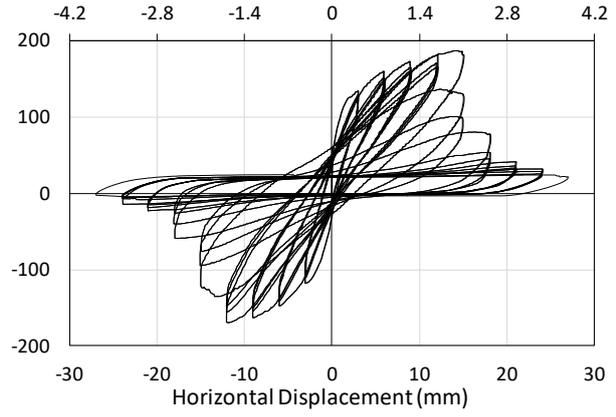


1 Fig. 5: Damage state (surface crack patterns) of specimens at displacement level of 18 mm (15 mm for FSC\_3).



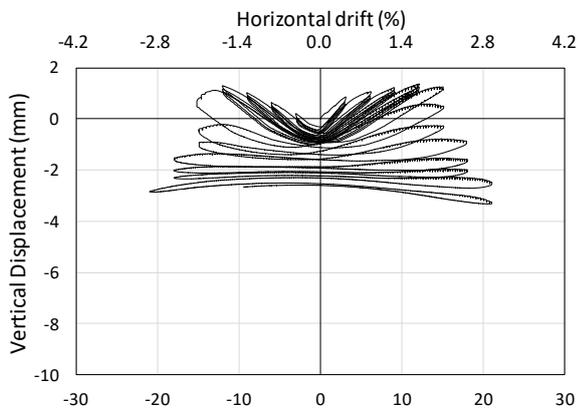


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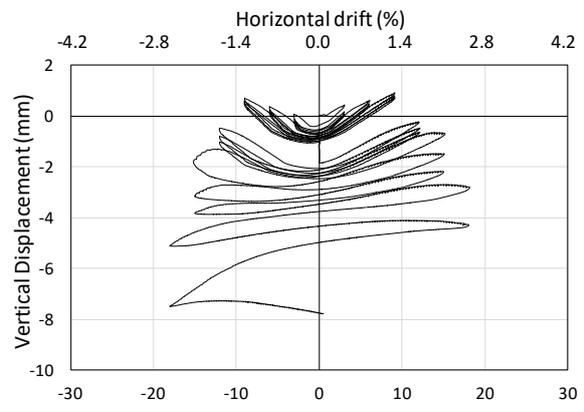


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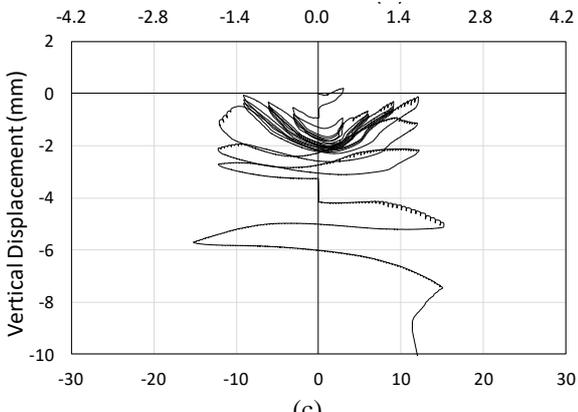
1 Fig. 6: Hysteretic response of specimens (a) FSC\_1, (b) FSC\_2, (c) FSC\_3, (d) SC\_1, (e) SC\_2  
2 and (f) SC\_3.



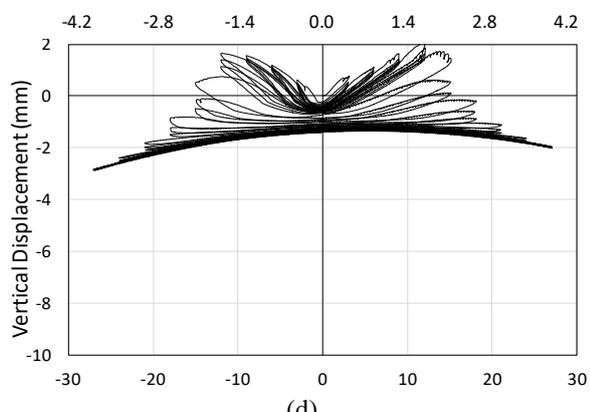
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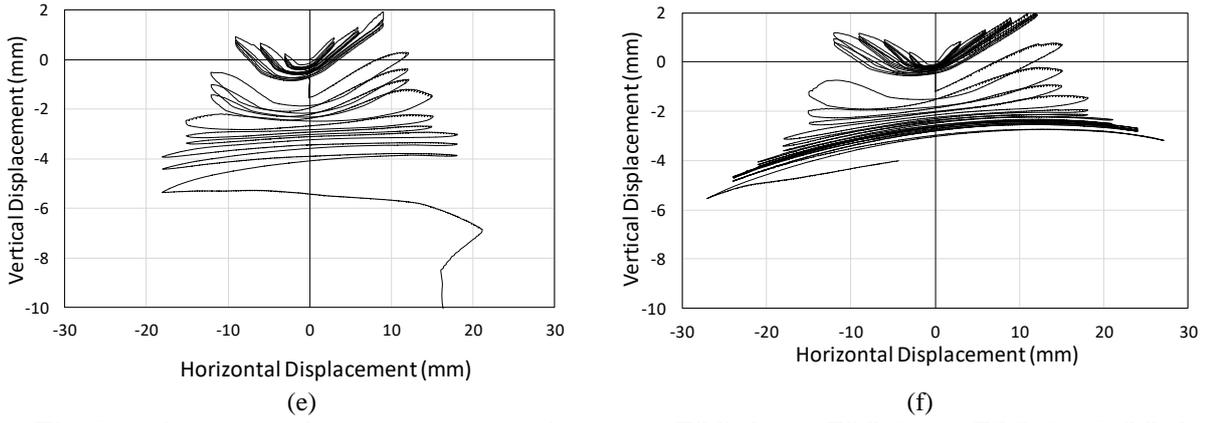
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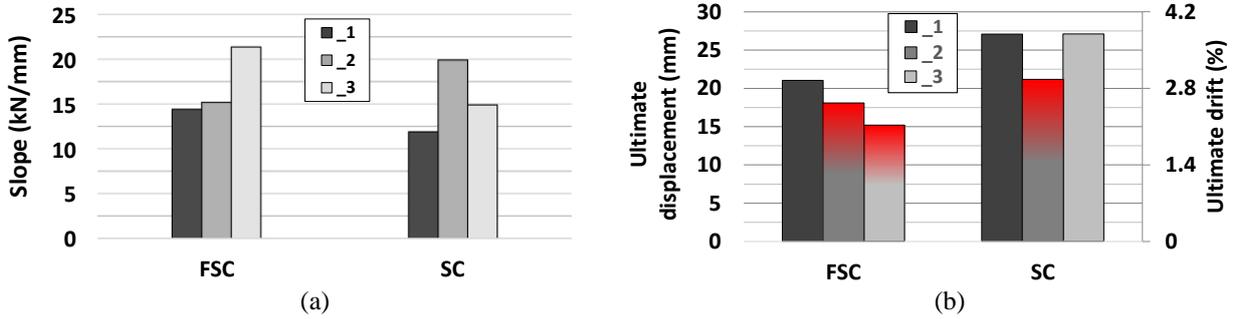
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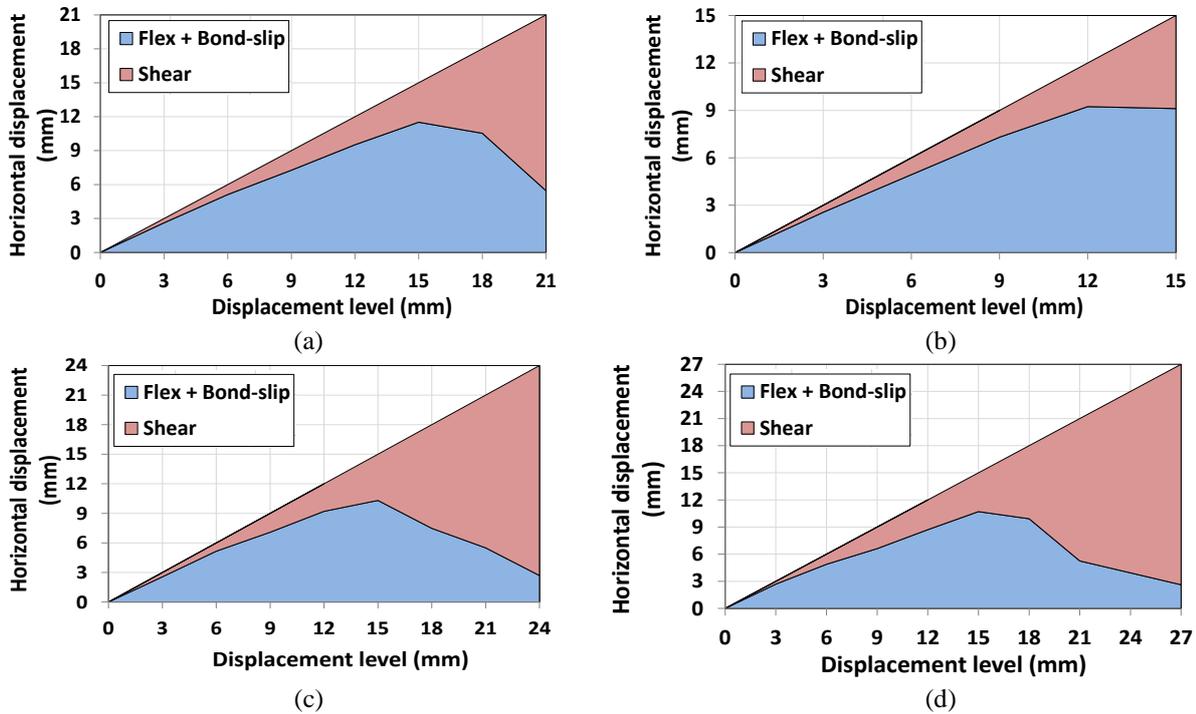
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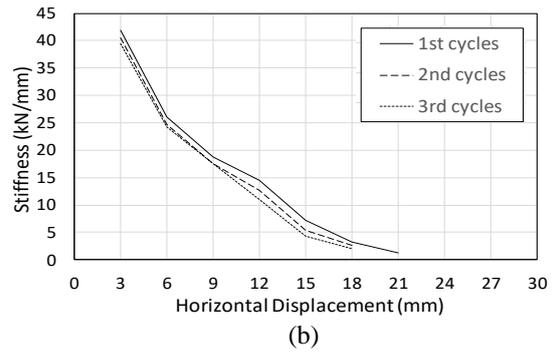
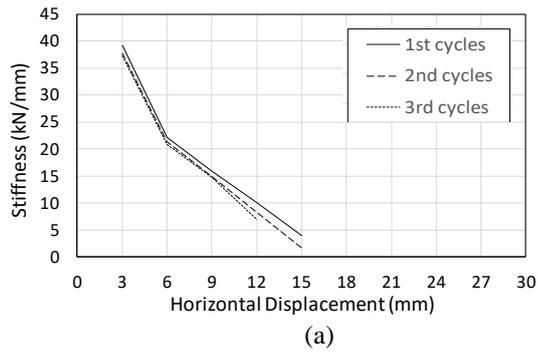
1 Fig. 7: Axial hysteretic response of specimens (a) FSC\_1, (b) FSC\_2, (c) FSC\_3, (d) SC\_1, (e)  
 2 SC\_2 and (f) SC\_3.



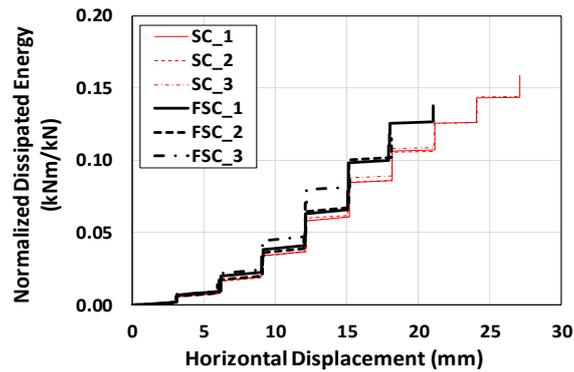
3 Fig. 8: (a) Experimentally obtained descending branch slopes, and (b) maximum horizontal  
 4 displacements of FSC and SC specimens.



5 Fig. 9: Lateral displacement decomposition: (a) FSC\_1, (b) FSC\_3, (c) SC\_1, and (d) SC\_3.



1 *Fig. 10: Lateral displacement secant stiffness against attained lateral displacement for (a)*  
 2 *FSC\_3, and (b) SC\_2.*



3  
 4 *Fig. 11: Cumulative dissipated energy normalized to recorded strength vs. displacement level*  
 5 *for all specimens.*

6

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