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# Evaluation of Mechanical Characteristics of High-Strength Reinforced Concrete Columns with Hexagonal Chicken Wire Mesh Under Cyclic Loading

Morteza Bastami<sup>\*</sup> , Ahmad Elmi Mousavi and Mostafa Abbasnejadfar

## Abstract

Recently, new materials and methods have been implemented to improve the performance of reinforced concrete columns. This paper studies experimentally the behavior of reinforced high-strength columns, with additional internal confinement using hexagonal chicken wire mesh (HCWM) to enhance ductility, energy absorption, and ultimate strength and reduce the brittleness of traditional columns. Eight double-ended one-third-scale columns with different volumetric ratios of transverse rebar have been constructed and loaded under the uniform axial compression and lateral cyclic loads. Different volumetric ratios of transverse rebar were provided based on special, intermediate, and ordinary moment frames specifications of ACI 318–14 (named SD, ID, and OD, respectively). The specimens were confined by transverse rebars and HCWM and the results were compared with reference specimens with traditional transverse ties. Experimental findings demonstrated that HCWM specimens exhibited better performance compared to their control specimens concerning crack control efficiency, load capacity, ductility, energy dissipation, and failure modes. Implementation of HCWM increased the ultimate deformation, ductility, and energy absorption of OD specimens up to 21%, 50%, and 175%, respectively, compared to their control specimen. Confinement of the concrete columns by HCWM increased the ultimate strength of OD and ID specimens up to 15% and 22% under the cyclic load, but has a negligible effect on SD columns due to enough ratio of transverse and longitudinal rebars in SD specimens. As a result, confinement of specimens by HCWM could be regarded as a simple and effective method to improve the seismic characteristics of RC columns, particularly those members constructed with a minimal number of transverse rebars.

**Keywords:** high-strength concrete, hexagonal chicken wire mesh, self-consolidating concrete, RC column, ductility, energy dissipation

## 1 Introduction

Reinforced concrete is widely used in the building of structures across the world because of its high strength and low cost of manufacture. Because high-strength concrete (HSC) has more compressive strength than normal

concrete and requires less reinforcement in structural elements, high-strength concrete (HSC) has attracted the attention of engineers to employ it in the construction of bridges and high-rise structures in recent years. (NRMCA. CIP, 2000). The implementation of HSC decreases the dimension of beams and columns and more space will be provided for the interior design of buildings. Also, smaller dimension elements reduce the overall dead load of the structure that leads to a lower lateral load from the earthquake (Panagopoulos & Mendis, 2000).

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Although compressive strain related to maximum strength in HSC is higher than the conventional concrete, its ductility decreases after the maximum peak point (ACI, 2010). Therefore, HSC has a brittle behavior which leads to sudden failure during the loading. In the seismic design of structures, providing ductility in structural elements such as columns is critical since it increases energy absorption during the earthquake and prevents the sudden destruction of the structural elements. In columns constructed by HSC, ductility improved by increasing the confinement of core concrete using transverse bars. On the other hand, by enhancing the volumetric ratio of reinforcement bars in structural elements the construction process becomes more arduous, as little space provides for equipment for fabrication. Self-consolidating concrete (SCC) is a great way to solve this problem because it is a highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation (ACI Committee, 2007).

Several methods have been proposed to improve the ductility of the concrete by providing confinement for core concrete. Sheikh (1978) firstly reported that the strength and ductility of RC columns are increased by a uniform distribution of vertical bars and providing appropriate transverse reinforcement along with the columns. Nemecek et al. (2005) experimented with six series of RC columns constructed by different grades of concrete and different volume ratio of transverse rebars. They concluded that the distance between the ties has a minor effect on the strength of columns, while ductility has been enhanced by decreasing their distance for both ordinary and high-strength concrete. Kwan and Ho (2010) conducted several tests on beams and columns fabricated by HSC. They found that flexural ductility decreases by increasing the strength of concrete and this reduction could be compensated by using more confining reinforcement.

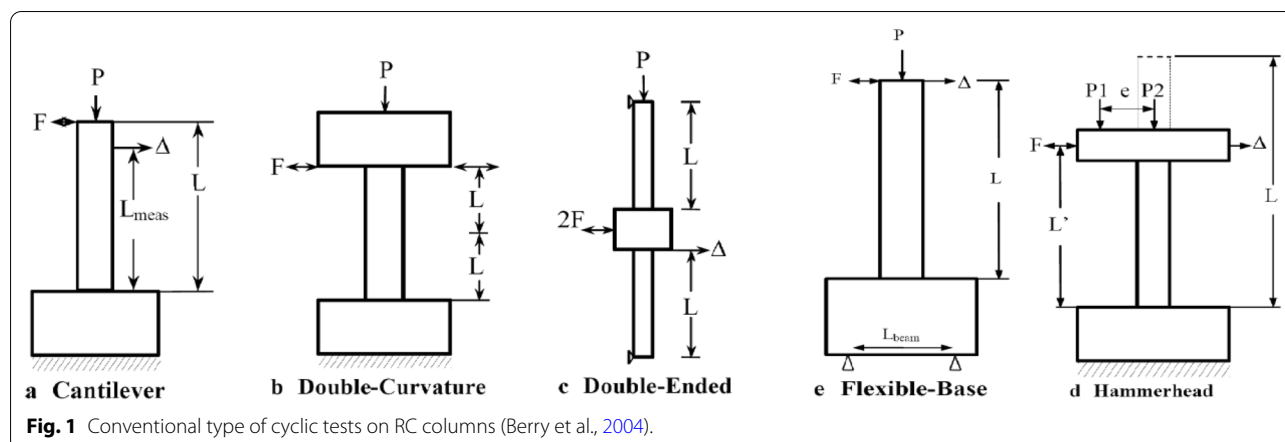
Many studies in the last few decades have used novel materials and processes, such as welded wire reinforcements (WWR) and extended metal mesh (EMM). Saatioglu and Grira (1999), Lambert-Aikhionbare, and Tabsh (2001) tested RC columns in axial compression using welded wire reinforcements (WWR) as lateral reinforcement. The results indicated that WWR improves the ductility and strength of RC columns compared to the conventional transversal reinforcements. Welded wire fabrics (WWF) were also implemented in the previous studies to confine the HSC and normal concrete columns (Damodaran Chitra & Rugmini, 2022; Khatri & Hinge, 2022; Kusuma & Tavio, 2011; Tabsh, 2007). Enhancements in performance were also reported by improving the strength, ductility, and energy absorption

in comparison with conventional confinement as lateral rebar. Several experiments have been conducted to investigate the effect of EMM wrapped around the vertical bars as confinement of RC columns (El-Kholy & Dahish, 2016; El-Kholy et al., 2018; Krishnapriya et al., 2017). The results indicated that the columns, confined with EMM, revealed significant improvement in strength and ductility. Hadi and Zhao (2011) also reported that confinement of HSC columns by galvanized steel wire mesh (S12.7 WM) improved their load-carrying capacity under both concentric and eccentric loading but it did not significantly increase the ductility of the columns for each load case. Experimental investigations were conducted by Bastami et al. (2021) to study the effect of wrapped hexagonal chicken wire mesh (HCWM) on the flexural performance of reinforced concrete beams. It was observed that in HCWM specimens, more cracks spread along with the specimens while the depth of cracks was reduced, resulting in a higher contribution of concrete in energy dissipation. Confinement of RC beam by HCWM increased the ultimate deformation and maximum strength of specimens up to 18% and 10%, respectively, compared to the controlling beam.

It should be mentioned that substantial research has been done on the utilization of WWM and EMM in beams and columns, as well as the effect of welded wire mesh confinement for columns subjected to just monotonic loads. No study has been done on the effect of HCWM on the cyclic responses of RC columns. This paper deals with a new application to provide confinement for HSC reinforced columns. The current research includes the investigation of HCWM as confinement and the main objective of this study is to evaluate the effect of the HCWM on the seismic performance of HSC RC columns under lateral cyclic load considering the axial compressive load. Three levels of ductility were implemented on eight double-ended RC column specimens. The confinement of column specimens was provided by wrapping double HCWM layers around the transverse rebar. They were tested under lateral cyclic displacements and uniform axial load. The results are compared in terms of ultimate capacity, lateral displacement, ductility, energy absorption, and failure modes.

## 2 Experimental Investigation

The experiments were carried out to explore the use of HCWM as confinement in HSC RC columns with cyclic lateral loading and a constant axial load. The tests were conducted on eight one-third scale double-ended columns (Fig. 1) with  $200 \times 200$  mm cross-section dimensions and lateral displacement cyclic loads applied to the middle beam with  $300 \times 200$  mm cross-section dimensions. Three types of columns have been fabricated based



on special, intermediate, and ordinary moment frames specifications of ACI 318–14 (ACI Committee, 2014) and they were named SD, ID, and OD. Moreover, two types of HCWM with 40 mm and 25 mm mesh grids were implemented to confine the RC columns and they were referred to “4” and “2” in specimens’ names. Fig. 2 demonstrates the schematic diagram of the specimens including the size and reinforcement details of OD, ID, and SD specimens. HCWM has been used for confining the specimens which wrapped twice around the ties (Fig. 3). The number and diameter of rebars and their yield strength for all specimens are mentioned in Table 1.

### 2.1 Material

Four mix designs were created to reach an optimum mixture proportion (aggregates, cement, and admixtures proportions), taking into account the strength, stability, and workability. To obtain desirable passing ability and filling ability of SCC, coarse aggregates have been considered to be less equal or less than 12.5 mm and sand grains should have a well-graded distribution (ACI Committee, 2007). Concrete Portland cement type II has been used in all mixtures. superplasticizer based on polycarboxylate ether added to mixtures to compensate the low amount of water to cement ratio and increase the workability and strength of SCC.

After 28 days of curing, cubic concrete specimens with dimensions of  $150 \times 150 \times 150$  mm were fabricated and tested to determine the compressive strength of four concrete mixtures. Compressive strength was converted to cylindrical compressive strength according to British Standard (BS) (En, 2013). The workability of four mixtures was estimated using a slump flow test based on ACI 237R-07 (ACI Committee, 2007) and the results are shown in Table 2. Mix design C has been considered as the best mixture based on slump flow criteria of ACI 237R-07 (ACI Committee, 2007) and EFNARC (2002) and

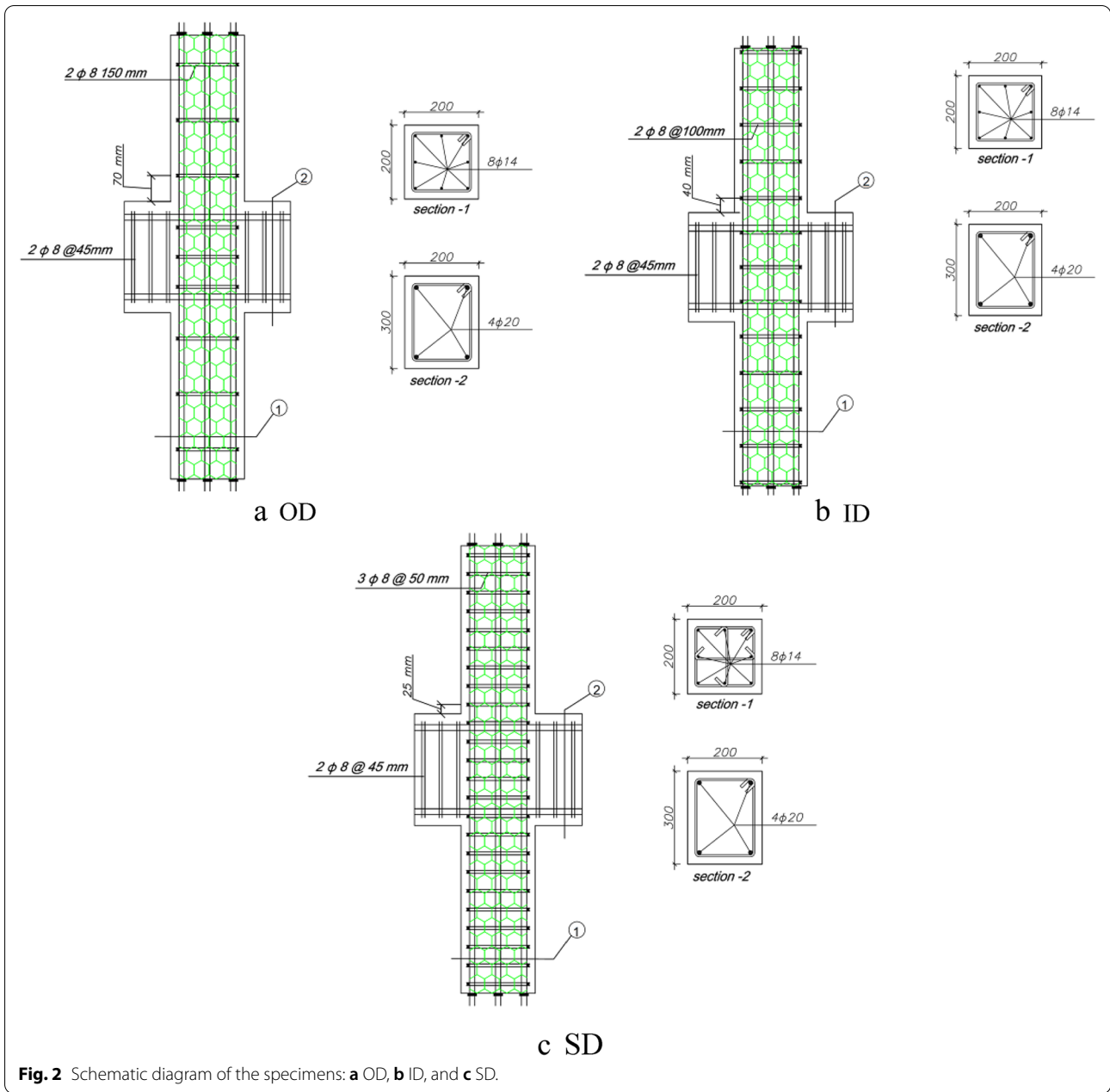
compressive strength of samples. Then, J-Ring, L-Box, and T50 tests have been conducted to investigate the workability and passing ability of the mixture C. based on ASTM C1621/C1621M-14 (2014), ACI 237R-07 (Committee, 2007), and EFNARC (2002) considerations, mixture C has met all the mentioned criteria. The results of all material experiments are presented in Table 3.

### 2.2 Test Setup

The tests were carried out in the laboratory of International Institute of Earthquake Engineering and Seismology (IIEES) in Tehran, Iran. A schematic figure of the test device is demonstrated in Fig. 4. Specimens were applied with a constant axial load which is about 18% of the theoretical load resistance capacity of the specimens using a push–pull hydraulic jack of 600-kN capacity. Cyclic lateral loading was applied by using a hydraulic actuator of 500-kN capacity in the middle of the beam. A schematic diagram of the test setup in the lab is shown in Fig. 4. To provide the pinned support for the Double-ended specimens, the specimens were connected to a steel beam at one end and the rigid floor at the other end with pine joints. The lateral displacement was logged simultaneously as the lateral cyclic load was applied by the 500-kN capacity hydraulic jack while the vertical and out-of-plane displacement was recorded by two Linear Variable Displacement Transducers (LVDT). Moreover, two vertical braces were attached to the two ends of the middle beam to avoid torsion or out-of-plane displacement of specimens during the loading. The vertical braces were connected to the rigid floor by rolled supports (see Fig. 4).

### 2.3 Lateral Loading

The lateral quasi-static cyclic load was applied to the center of beams in all specimens according to FEMA 461 loading protocol in the form of displacement control



(FEMA, FEMA, 2007). Amplitude for  $a_{i+1}$  of step  $i + 1$  is given based on Eq. (1):

$$a_{i+1} = 1.4a_i. \tag{1}$$

$a_i$  is the amplitude of the preceding step. Load cycles were repeated two times in each amplitude and the started displacement was equal to 0.2 mm. The loading rate was slow at the first steps and it was enhanced by

increasing the number of steps. Fig. 5 shows the load-history details acted to the samples.

### 3 Observed Behavior and Test Results

To understand the effect of HCWM on the seismic behavior of RC columns, the results of maximum and ultimate capacity, ductility, and energy dissipation of RC columns have been presented here. Moreover, a



**Fig. 3** Fabrication of RC columns confined by HCWM.

method has been used to describe the lateral load–drift curves. Also, failure modes and cracking patterns of all specimens have been discussed and compared. The ultimate point of loading in this study was defined as 80 percent of maximum strength after the pick point (Sheikih & Khoury, 1990).

### 3.1 Envelope Curve of Hysteresis Loading and Bilinear Envelope Curve

Lateral load–displacement hysteretic responses are presented in Fig. 6. To define the exact yielding and ultimate points of each response, it is necessary to draw the envelope curves and bilinear curves. To obtain the envelope curve, the method presented by Sheikh and Khoury (1990) has been used. Based on this method, the maximum force and displacement of the initial cyclic loading are obtained in each loading step for both positive and negative deformations and the absolute average of the obtained numbers describe the average envelope curve (Fig. 7).

As the behavior of reinforced concrete columns is not fully elasto-plastic, the force–displacement behavior could be described as a bilinear envelope curve. The ideal curve has an elastic section which is a straight line that starts at zero and intersects the average envelope curve at a point where the maximum resistance is 75 percent of peak strength ( $u_y, 0.75H_{max}$ ) and continues to reach a point with a maximum resistance ( $u_{y1}, H_{max}$ ). The post-elastic part of the diagram is defined in a way that the area below both the envelope curve and the ideal curve between ( $u_y, 0.75H_{max}$ ) and the ( $u_{max}, 0.8H_{max}$ ) become equal (ASCE. FEMA, 2000; Park, 1989; Sheikih &

Khoury, 1990) (Fig. 7). Bilinear envelope curves are presented in Fig. 8.

### 3.2 Strength and Deformation

Lateral load–displacement hysteretic responses and bilinear envelope curve are presented in Figs. 6 and 8. As a general result, confining the columns by HCWM increases the ultimate drift and ultimate strength of OD and ID specimens. At the same time, it increases the maximum strength of specimens in IDN (Fig. 8). The confinement of SN specimens by HCWM has not changed the maximum strength and ultimate deformation of columns when the results were compared with the control specimen due to the adequate ratio of longitudinal and transverse rebars.

In ODs, ultimate drifts of OD2 and OD4 increased up to 20% and 21%, respectively, compared to the control specimen (ODN). The drift of ultimate point increased 7% and 8.3% in ID2 and ID4, respectively, compared to IDN specimen (see Fig. 8). Moreover, the drift ratio related to maximum strength point in ODs and IDs specimens did not change significantly (Fig. 8). The ultimate strength of ODs and IDs specimens was increased 15% and 22% compared to ODN and IDN specimens, respectively. The maximum strength of ID2 and ID4 are slightly improved concerning the IDN. No significant improvement has been seen in the maximum and ultimate drift of SN4 compared to SND column.

Since there is not any previous study on the effect of HCWM on the confinement of RC columns, the results of strength and deformation are compared with similar confinement approaches in the literature. The

**Table 1** Specifications of columns.

Specimen	$f_c$ [MPa]	$\frac{P}{f_c A_g}$	Longitudinal Reinforcements			Lateral ties			HCWM
			Bars	$f_y$ [MPa]	$\rho$ [%]	Bars	$f_{yt}$ [MPa]	S [mm]	Mesh size [mm]
ODN	82	0.178	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	150	–
OD2	82	0.188	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	150	25
OD4	82	0.178	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	150	40
IDN	81	0.189	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	100	–
ID2	81	0.186	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	100	25
ID4	81	0.179	8 $\phi$ 14	510	3.08	2 $\phi$ 8	505	100	40
SDN	75	0.180	8 $\phi$ 14	510	3.08	3 $\phi$ 8	505	50	–
SD4	75	0.182	8 $\phi$ 14	510	3.08	3 $\phi$ 8	505	50	40

increasing of ultimate strength by enhancing the confinement of RC columns by adding the EMM was also reported by Kholly and Danish (2016) and El-Kholly et al. (2018). They also explained that adding EMM to specimens with sufficient transverse rebars resulted in a less increase in ultimate load capacity.

### 3.3 Ductility

Cumulative ductility ratio is defined as (Gupta, 2013; Sheikih & Khoury, 1993):

$$N_k = \sum_{i=1}^{i=m} \frac{u_i}{u_{y1}} \quad (2)$$

In equation  $N_k$  is cumulative ductility ratio until the  $k$  percent of the maximum lateral strength after the peak point,  $u_i$  is the deformation in step number  $i$ ,  $u_{y1}$  is deformation at the yield point and  $m$  is the total steps of the experiment. Based on this definition, the cumulative ductility ratio has been calculated for all eight specimens until the 70 percent of maximum load and it is demonstrated by  $N_{70}$  in Fig. 9a. The yield point of all laboratory specimens varies from 8.84 to 10.32 mm. Slight changes in the yield point indicate that the use of the HCWM does not affect the elastic area of the specimens.

Compared to the reference specimens, the ductility ratio was enhanced for the tested specimens that were wrapped internally using the HCWM to enhance its traditional confinement because it acts as a tensional element which prevents early damage of core concrete and buckling of the longitudinal rebars. Furthermore, the use of the smallest size of the mesh layers presented higher ductility compared to the rest of the tested specimens in the same transverse ties volumetric ratio. The improvements of the cumulative ductility ( $N_{70}$ ) of the specimens OD2 and OD4 were about 50% and 34% more than their control specimen (ODN), respectively, and the ductility

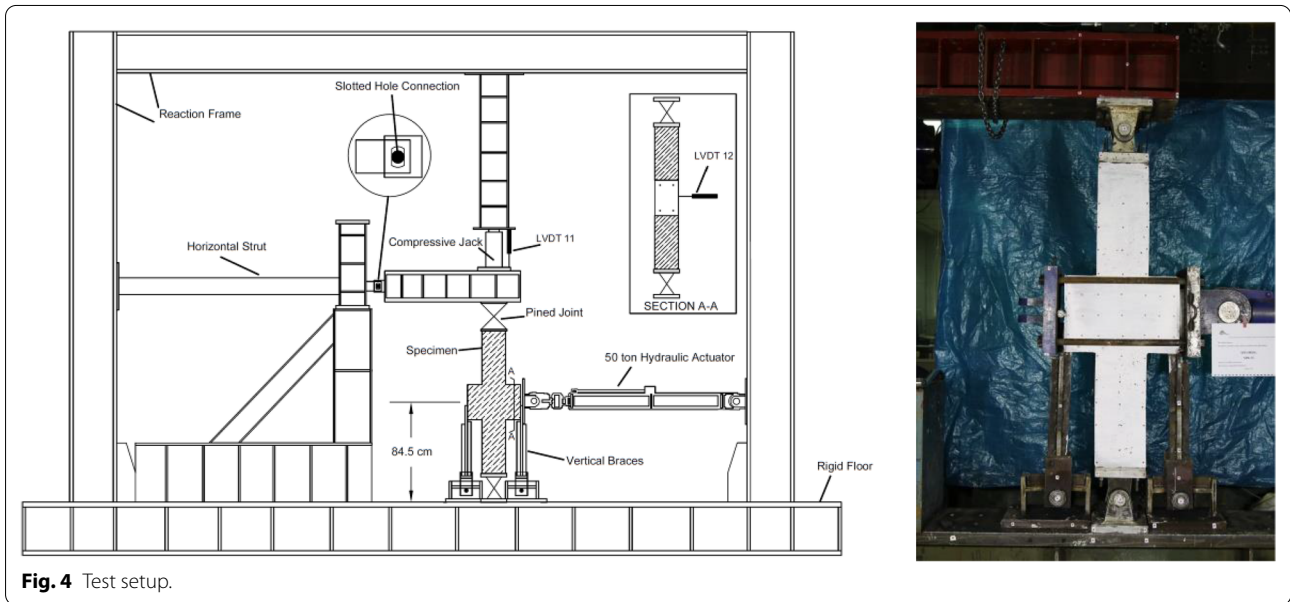
of the specimens ID2 and ID4 increased by 17% and 12% compared to their reference specimen, respectively. The cumulative ductility of the SD4 was increased by 11.88% compared to SDN. See Fig. 9 for more details. These results are consistent with the findings of the studies carried out by El-Kholly and Danish (2016), El-Kholly et al. (2018) and Emara et al. (2021).

### 3.4 Energy Dissipation

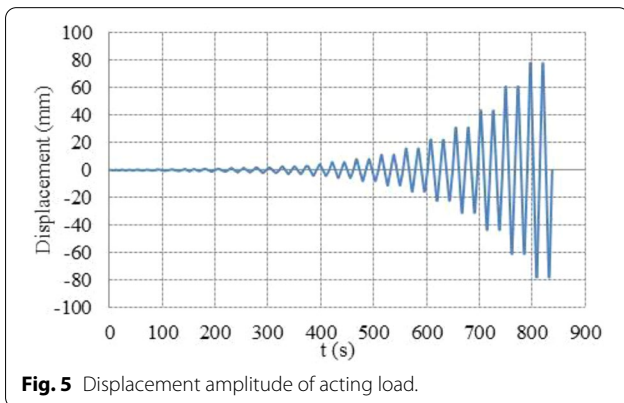
The energy dissipation capacity of the specimens under the cyclic loading is calculated from the area under the hysteresis loop in a cycle. The cumulative energy dissipation ( $E$ ) of the RC columns was obtained by summing the energy dissipation in each cycle. The cumulative energy dissipation was calculated where the ultimate load was considered to be 70 percent of maximum load and it is named  $E_{70}$ . As shown in Fig. 9b, the confinement of reinforced concrete by HCWM increased energy absorption due to the improvement in the confinement of the core concrete because of the presence of HCWM, thus helping the arching action. Confinement of specimens by HCWM improved the specimens' final deflection, and the cracks were formed uniformly across the specimens. The maximum amount of energy absorption is obtained in SD specimens. In OD4 and OD2,  $E_{70}$  absorption increased to 10 kJ and 10.2 kJ, respectively, compared to 3.7 kJ for ODN and this indicates an enhancement in seismic behavior of columns because of the use of HCWM. Also, in ID4 and ID2 specimens, energy absorption increased by 59% and 65.8%, respectively, compared to the IDN. According to Fig. 9b, OD2 and OD4 specimens which were designed with less transverse rebars than ID specimens can absorb equal energy to IDN specimen due to the core confinement of RC columns by HCWM. In SD4, the energy absorption has been increased by 9.05% compared to SDN column. So, it can be noticed that confining by HCWM is an appropriate

**Table 2** Four initial mix designs with compression and slump flow tests results.

No.	Cement [g]	W/C	Superplasticizer (% of cement)	Sand [g]	Gravel [g]	Fly ash [g]	slump flow [cm]	Compression strength [MPa]
A	520	0.347	0.921	900	500	200	51.30	78.80
B	520	0.435	0.512	900	500	200	82.30	47.80
C	520	0.395	0.854	1000	470	220	68.50	64.20
D	520	0.410	0.675	1000	470	220	79.50	54.50



**Fig. 4** Test setup.



**Fig. 5** Displacement amplitude of acting load.

of the RC specimens compared to the traditional RC columns. El-khoy and Dahish (2016) also stated that EMM confinement can reveal the transverse rebar reduction by absorbing the energy up to 227% of controlled specimens.

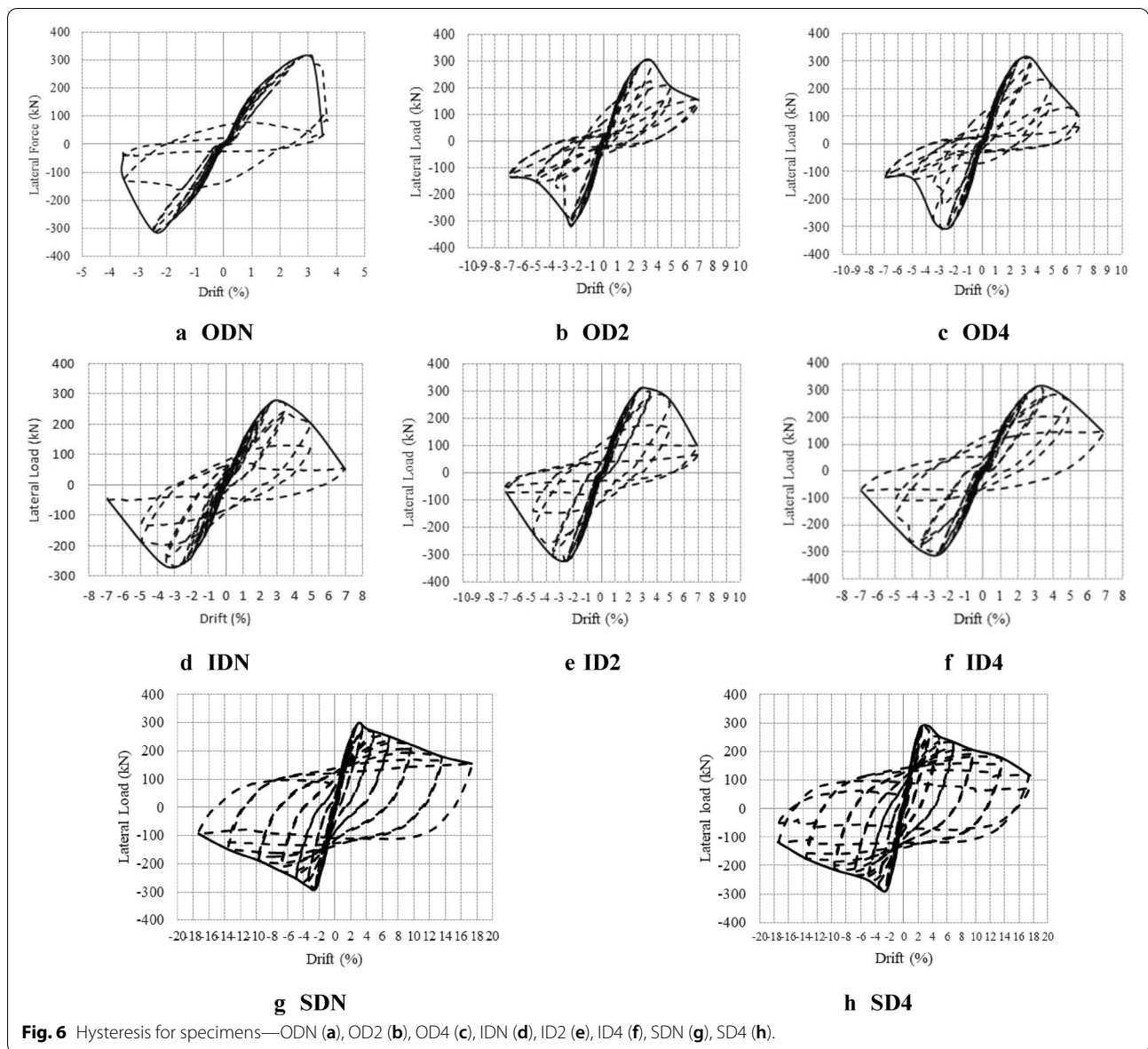
**3.5 Failure Modes of Specimens**

Generally, confining the columns by HCWM increases the number of cracks and reduces their depth as can be seen in Fig. 10. Confinement by HCWM encloses the core concrete and prevents the sudden collapse of specimens and buckling of the longitude bars. In confined columns, fewer damages have been observed in the core of concrete.

**3.5.1 OD Specimens**

Due to the lower volumetric ratio of transverse reinforcement incorporated in the predicted plastic hinge area, these columns are more brittle than other specimens. By increasing the lateral displacement in the control specimens (ODN), some shallow cracks were seen in the upper half of the specimen. The specimen then failed abruptly with a large, deep diagonal crack in the bottom

way to increase the energy absorption of the ordinary and intermediate moment frame columns while it has little effect on SD members. These results are in accordance with the derived conclusions of available studies (El-Kholy & Dahish, 2016; El-Kholy et al., 2018; Emara et al., 2021; Krishnapriya et al., 2017) which mentioned that EMM or SWM confining improves the absorbed energy



**Fig. 6** Hysteresis for specimens—ODN (a), OD2 (b), OD4 (c), IDN (d), ID2 (e), ID4 (f), SDN (g), SD4 (h).

section of specimens (Figs. 10 and 11). The core concrete was collapsed and crushed as a result of the development of deep cracks. Because of the long distance between the lateral bars, significant buckling occurred in the longitudinal rebars.

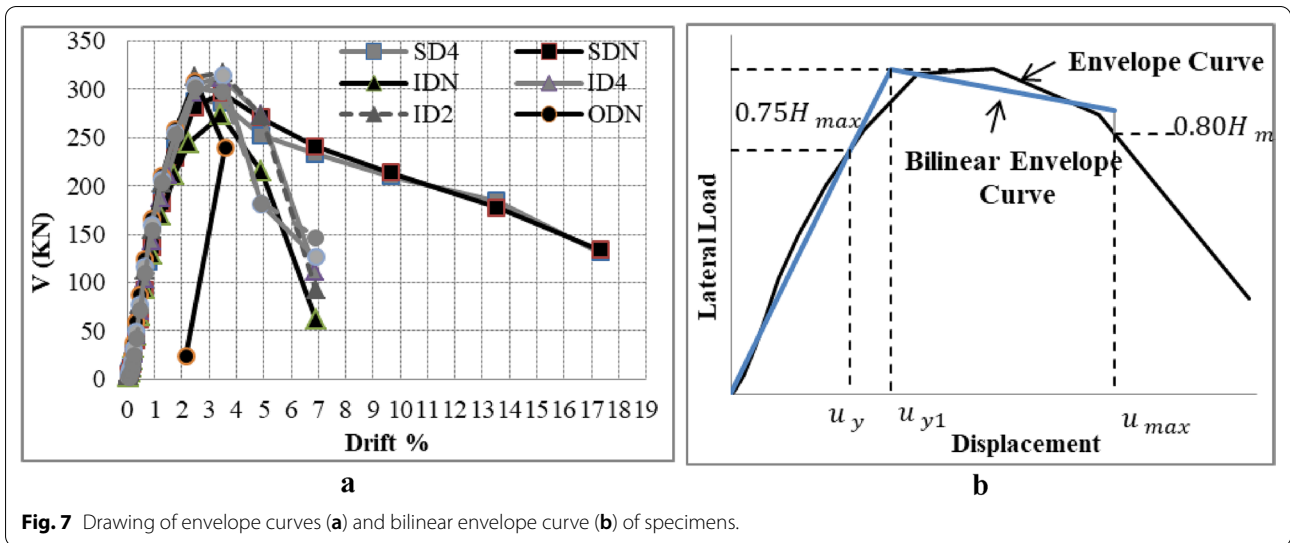
OD2 and OD4 demonstrated different behavior in terms of failure. By increasing the lateral displacement in these specimens, small cracks appeared more vastly throughout the specimens rather than the control specimen (ODN). Therefore, it can be observed that the confinement of the specimens by HCWM reduces the depth of cracks and increases the number of propagated cracks throughout the specimen in comparison with the reference specimen. Similar to the ODN specimen, large

diagonal cracks formed but their depth was lower than ODN specimens (Figs. 10 and 11). Also, the presence of HCWM helps to improve the confining of the concrete core and prevents the obvious buckling of the longitudinal bars after the formation of the plastic hinge in OD2 and OD4 specimens.

### 3.5.2 ID Specimens

In all three columns with intermediate ductility detailing, the collapse occurred in the bottom half of the columns. By increasing the lateral displacement in IDN specimen, first fine cracks have been observed initially in the top and bottom halves of the specimen. Then the width of the cracks increased and spalling of the cover concrete





occurred. Finally, longitudinal bars buckled and the concrete core collapsed (Figs. 12 and 13).

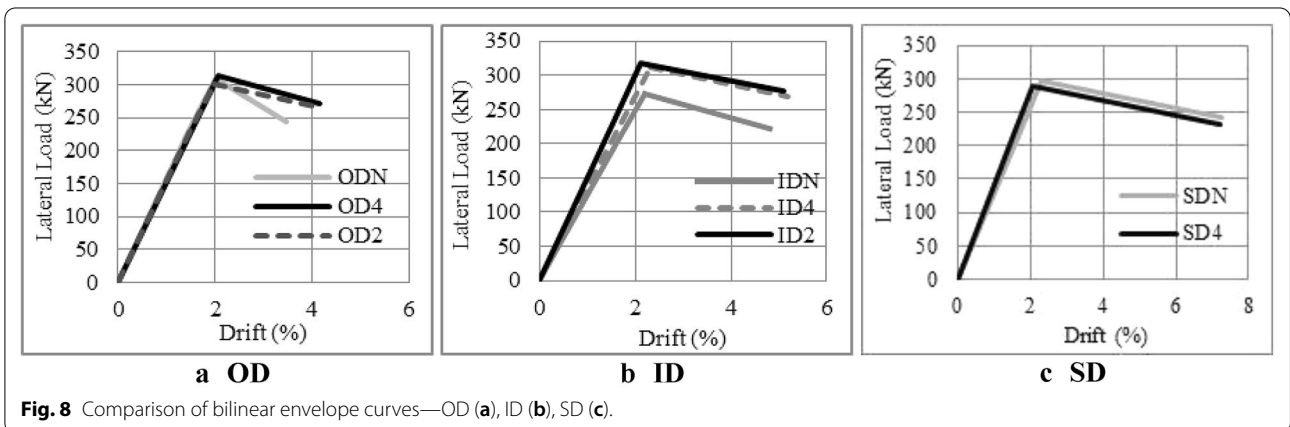
In ID2 and ID4, the collapse occurred slower and columns exhibited fine cracks with short cracks spacing, rather than the focused enormous crack in the reference column. This behavior indicates more energy absorption in the confined specimens. The failure of HCWM specimens began with the creation of fine cracks on the concrete surface, which continues with the propagation of the cracks and the separation of the concrete cover from the concrete core. By formation of the plastic hinge, the HCWM stretched and prevented the fracture of the longitudinal rebar (Fig. 13). Buckling has been detected in longitudinal bars and a number of them have been broken (Figs. 14 and 15). Using HCWM as a confiner reduces the depth of the cracks while more of them have been created during the

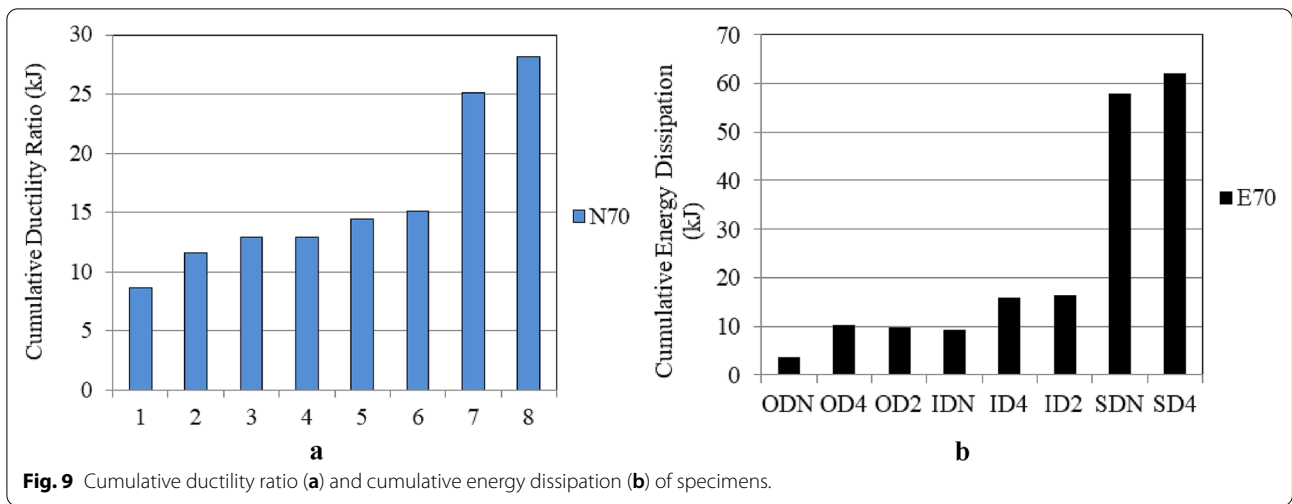
loading. It also delayed the failure of cover concrete and consequently the buckling of longitudinal bars.

### 3.5.3 SD Specimens

In the SD4 specimen, the concrete cover was not completely separated from the specimen, and the number of buckled longitudinal rebar decreased even in large drifts. But more longitudinal bars were broken compared to the SDN sample (Figs. 14 and 15).

As mentioned before, using the HCWM improves the ductility of the specimens and increases the final deformation of the columns. So it prevents the collapse of the specimens in the early steps of loading. The use of HCWM improves the performance of the structure at the level of collapse prevention. This leads to a reduction in human and economic losses during an earthquake. Fig. 8 compares the bilinear envelope curve of specimens in

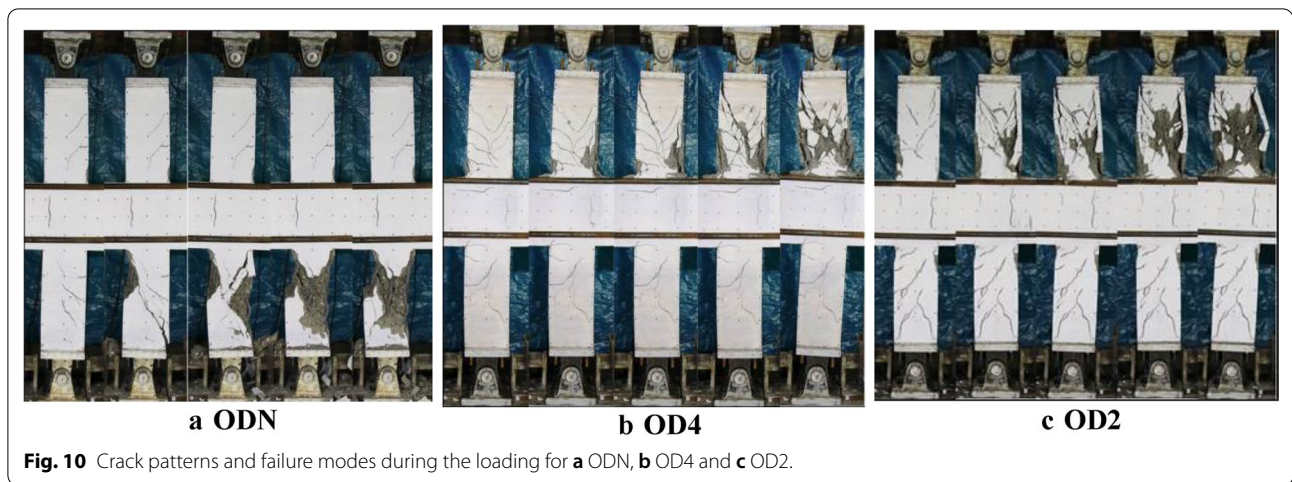




each level of ductility. As could be noticed, the improvement of the ultimate drift ratio is more evident in the ordinary level of ductility.

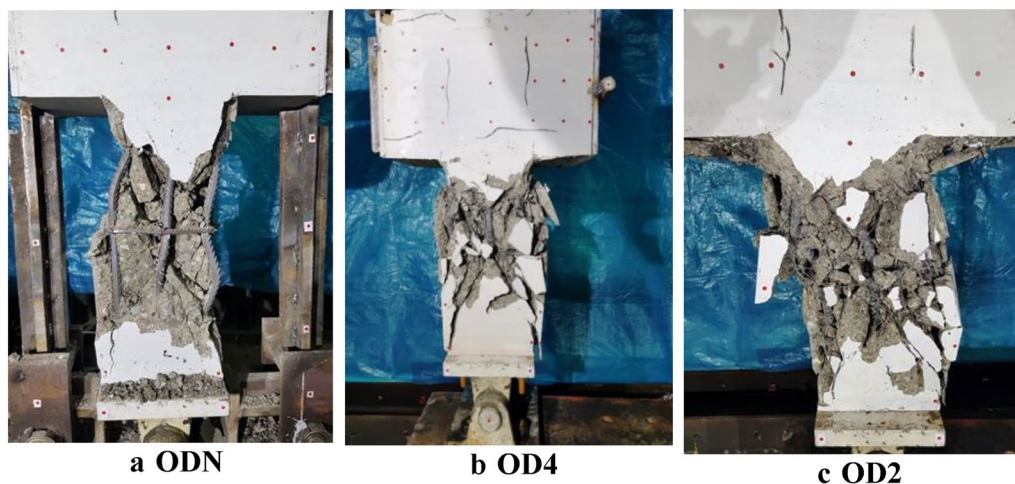
Similar to the current investigation, El-Kholy and Danish (2016) and El-Kholy et al. (2018) stated that the failure of column specimens which confined with only ties was sudden and brittle unlike the failure of confined

specimens with EMM which exhibited significant plastic deformation. While the crashed part of the concrete core was large and the buckling of vertical bars was excessive for controlled column specimens, the confining of EMM layer limited the crushing of the concrete core and reduced the buckling of vertical bars as observed in the current study.



**Table 3** Results of T50, J-Ring and L-Box tests for mixture C.

Slump flow		J-Ring				L-Box		
Slump flow [mm]	T50 (sec)	Slump flow [mm]	T50 (s)	Concrete average height [mm]	Difference of slump flow in J-Ring test and slump test [mm]	H1 [mm]	H2 [mm]	(H2/H1)
685	3.21	655	3.88	9.2	30	94.33	76.44	0.813



**Fig. 11** Final failure modes of: **a** ODN, **b** OD4 and **c** OD2.

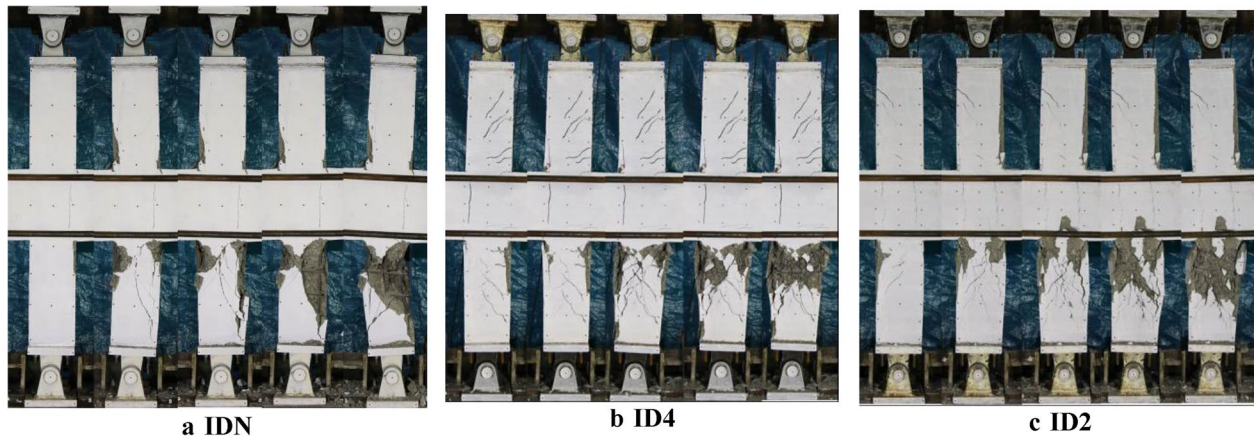
#### 4 Conclusions

In this study, HCWM has been used as the confining element of the high-strength self-consolidating reinforced concrete columns to investigate its effect on the strength, ductility, and energy dissipations of RC columns. Eight tests have been conducted under deformation–control cyclic loading and the following major results have been obtained:

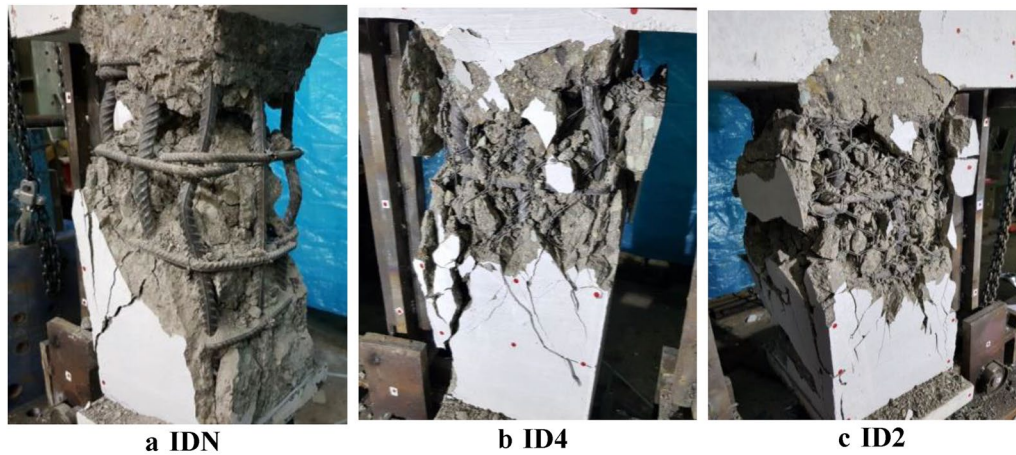
- Implementation of HCWM enhances the ductility and energy absorption of the columns in all specimens by enhancing the number of loading cycles and preventing the abrupt failure of columns and buckling of longitudinal rebars in the final steps of loading. More cracks developed along with the specimens in

the damaged region in the specimens which HCWM was wrapped around the transverse rebars, although the depths of the cracks were diminished. The OD4 demonstrates more increase in ductility among the other specimens. In ODs specimens, HCWM confinement provides three times more energy dissipation compared to the controlling specimen. Ductility was observed to increase as much as 65% in ODs specimens compared to the specimen confined only by transverse rebars.

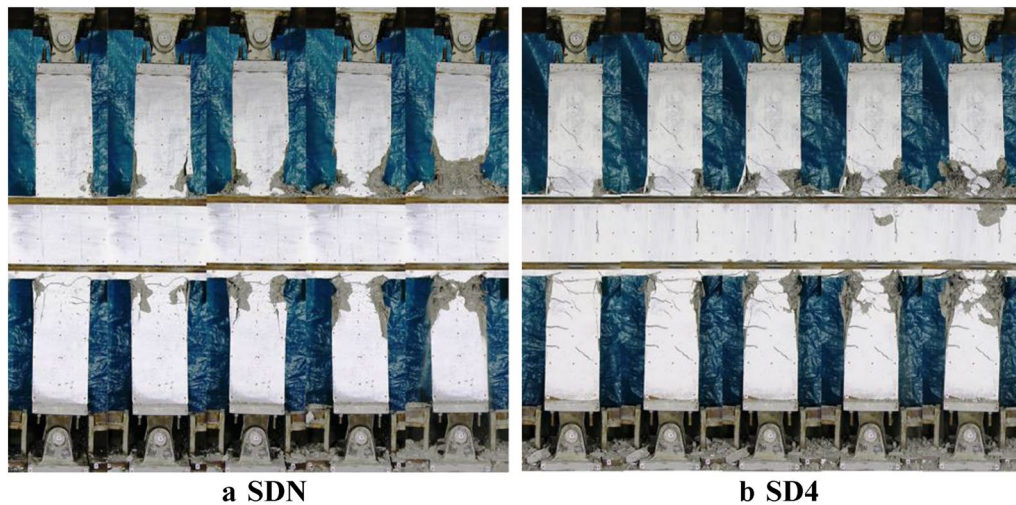
- The ultimate deformations of OD4 and ID4 specimens are increased by 21% and 8.3% compared to their control specimens (ODN and IDN, respectively). Confining of SD members by HCWM has a neglecting effect on the ultimate strain. Moreover,



**Fig. 12** Crack patterns and failure modes during the loading for: **a** IDN, **b** ID4 and **c** ID2.



**Fig. 13** Final failure modes of: **a** IDN, **b** ID4 and **c** ID2.



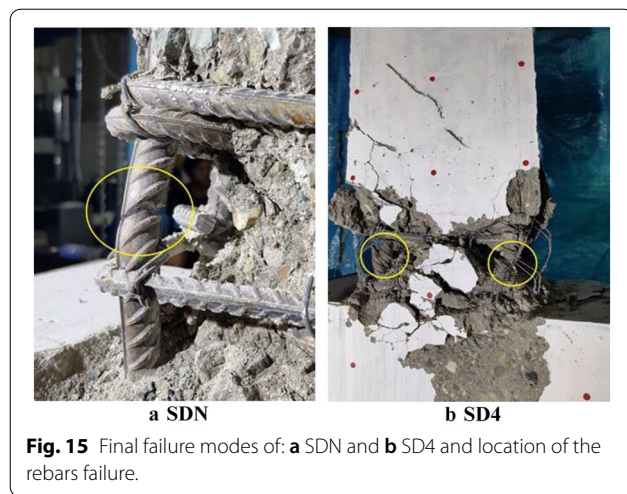
**Fig. 14** Crack patterns and failure modes during the loading for: **a** SDN and **b** SD4.

the ultimate strength of ODs and IDs specimens were increased 15% and 22% compared to ODN and IDN specimens, respectively, while ultimate strength did not change for SD4 compared to the specimen without HCWM.

- HCWM prevents sudden failure of the specimens by enclosing the longitudinal bars and damaged core concrete. So the specimens could endure more deformation and this can be considered as a merit of using HCWM in improving the performance level of buildings.

- With regard to the construction costs, HCWM only increases 2% of the cost of the construction in comparison to the specimens without HCWM. Therefore, HCWM can be proposed as an economically feasible option for retrofitting of the existing RC columns.

- Finally, it could be concluded that the use of HCWM improves the performance of the structure at the collapse prevention level, leading to a reduction in human and economic losses in earthquake events.



### Abbreviations

$A_g$ : Gross cross-sectional area of concrete;  $f'_c$ : Concrete cylinder strength;  $f_y$ : Yield strength of longitudinal reinforcement;  $f_{yt}$ : Yield strength of transverse reinforcement;  $\Delta$ : Lateral displacement;  $P$ : Axial compressive force;  $s$ : Spacing of transverse reinforcement;  $\epsilon$ : Strain;  $\rho$ : Longitudinal reinforcement ratio;  $\rho_s$ : Volumetric ratio of transverse reinforcement;  $N_{70}$ : Cumulative ductility ratio;  $E_{70}$ : Cumulative energy dissipation.

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### Authors' contributions

MB: conceptualization, methodology, validation, writing—review and editing, supervision, project administration, funding acquisition. AEM: specimen fabrication and testing, conceptualization, validation, investigation, data curation, writing—original draft. MA: conceptualization, investigation, formal analysis, resources, writing—original draft. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets generated during analyzed during the current study are available from the corresponding author on reasonable request.

### Declarations

#### Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

#### Consent for publication

Not applicable.

#### Competing interests

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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