FLEXURAL-SHEAR BEHAVIOR OF EXISTING REINFORCED CONCRETE COLUMNS UNDER HIGH AXIAL LOAD AND VARYING AXIAL LOAD

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SUMMARY

There is usually insufficient transverse reinforcement in vertical structural members of elder existing reinforced concrete buildings in Taiwan. Due to this phenomenon, the flexural strength would reach first and fail by shear in the damaged columns, that is flexural-shear failure. The seismic behavior of these columns was well known in many studies, especially for low-rise buildings. However, the columns on the lower story of mid- and high-rise buildings usually suffered high axial load and varying axial load which was caused by overturning moment. It becomes very important to understand the flexural-shear behavior of RC columns with high axial load and varying axial load for seismic evaluation of elder existing reinforced concrete buildings.

To investigate the seismic behavior of flexural-shear behavior of RC columns with high axial load and varying axial load, this study tested six reinforced concrete columns. Test parameters are included as axial load ratio, transverse reinforcement ratio, and varying axial load. The test results in constant high axial load showed that the columns with the higher axial load will have higher stiffness, cracking strength, peak strength, and degradation beyond the peak strength. The analytical curves in varying axial load tests should be taken into more consideration and further studies to develop.

Keywords*: reinforced concrete columns; seismic behavior; high axial load; varing axial load; flexural-shear failure.*

INTRODUCTION

According to previous seismic investigation experience, some old buildings made of reinforced concrete are vulnerable to shear failure, not only because of they were constructed many years ago when there was a lack of seismic design or insufficient transverse reinforcement, but also because of the formation of intermediate short columns in normal columns due to the connection of infilled walls with openings. Due to the requirements of open space, there are almost no walls on the ground floor of soft story buildings. The stiffness and strength of the ground floors are weak compared to other levels. The buildings collapse in past earthquake due to damage in the weak and soft stories is common situation (Pujol et al. 2017). If the vertical members of the soft stories are only shear-critical columns, the problem becomes even more severe(in Figure 1).There is usually insufficient transverse reinforcement in vertical structural members of elder existing reinforced concrete buildings in Taiwan. Due to this phenomenon, the flexural strength would reach first and fail by shear in the damaged columns, that is flexural-shear failure. The seismic behavior of these columns was well known in many studies, especially for low-rise buildings. However, the columns on the lower story of mid- and high-rise buildings usually suffered high axial load and varying axial load which was caused by overturning moment. It becomes very important to understand the flexural-shear behavior of RC columns with high axial load and varying axial load for seismic evaluation of

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elder existing reinforced concrete buildings.

If a comprehensive description of the seismic behavior of vertical members in a structure is desired, the optimum method is to propose a lateral load displacement curve accredited by experiments, however, a comprehensive experiment designed to compare a reinforced concrete column lateral load displacement curve under high axial load and varying axial load is rarely seen. This paper discusses and describes the seismic behavior of reinforced concrete columns under high axial load and varying axial load by conducting experiments on six different reinforced concrete columns with different transverse steel ratio. Secondly, based on experimental observation, this paper proposes a lateral load displacement curve analysis model in order to simulate the lateral load displacement curve of intermediate short columns failed in shear under seismic forces. In addition, this paper demonstrates the force transfer mechanism and strength behavior of intermediate short columns when they reach the shear strength point in shear failure and a comprehensive comparison is made with the collected experimental data of intermediate short columns, in order to verify the feasibility and accuracy of the method for engineering application in practice.

Figure 1 Damage buildings in Hualien Earthquake 2018

EXPERIMENTAL INVESTIGATION

According to statistical data of the PEER Center (Berry et al. 2004) Column Database, the parameters that affect column's seismic behavior include height-to-depth ratio, axial load ratio, longitudinal reinforcement ratio, and transverse reinforcement ratio. Therefore, this experiment is designed to clearly understand, in reinforced concrete columns under high axial load and varying axial load, how different parameters influence the seismic behavior of reinforced concrete columns under high axial load and varying axial load. This study picks two parameters, transverse reinforcement ratio, and axial load ratio, which have significant influence on reinforced concrete columns under high axial load and varying axial load seismic behavior. Two different parameters are examined in a total of four different specimens and the another two specimens with varying axial load. Conducting these six columns under double curvature deformation allows an understanding of the influence of different parameters on the seismic behavior of reinforced concrete columns under high axial load and varying axial load. Thus, the experiments are named in order, based on different parameters. For example, a specimen equipped with high hoop ratio (D), and low axial load is named RD4. Detailed specimen specifications are shown in Figure 2 and Table 1.

The cross-section of all intermediate short column specimens in this experiment is a 500×500 mm rectangle. As the purpose of experiment is to observe the seismic behavior of reinforced concrete columns under high axial load and varying axial load for seismic forces, the bar configuration for the columns is: 12 #8 reinforcement, longitudinal reinforcement ratio 2.24%, yield strength 467 MPa. Columns have two different types of hoop ratios, the high hoop ratio specimen adopts #3 reinforcement and a spacing of 100 mm, and its hoop area ratio is 0.54%. The specimens with a low hoop ratio adopt #3 reinforcement and a spacing of 200 mm, and their hoop area ratio is 0.27%. The yield strength of #3 reinforcement is 456 MPa. The reinforcement detailing of this experiment is shown in Figure 2. The design strength of concrete used in this experiment is 20.6 MPa, and in practice the compressive strength of concrete is within the range 22.0 to 25.2 MPa, the concrete strength of specimens is shown in Table 1. The deployment of axial load has two different values, $0.4A_g f_c'$ and $0.6A_g f_c'$, the axial load for different specimens is shown in Table 1.

Table 1 Test parameters and material properties

Specimens	$\frac{N}{A_g f_c'}$	f_c', MPa	Reinforcement				
			Longitudinal		Transverse		
			size	$f_{y\ell}$, MPa	size	f_{yt}, MPa	spacing, mm
RN4	0.4	22.0	#8	467	#3+#4	#3-456 #4-468	200
RD4	0.4	24.8					100
RN6	0.6	24.4					200
RD6	0.6	25.2					100
VN	varying	24.9					200
VD	varying	24.6					100

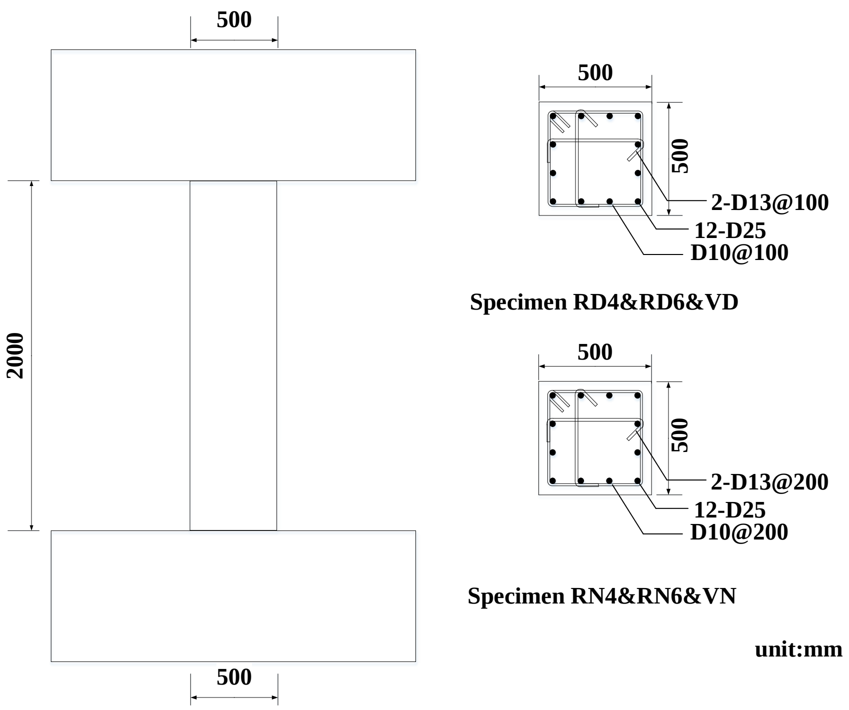


Figure 2 Specimen elevation and sectional detailing

This experiment is designed to understand the seismic behavior of reinforced concrete columns under high axial load and varying axial load in buildings. According to the features of double curvature deformation, the loading system of this test setup comprises of two horizontal actuators and two vertical actuators, as shown in Figure 3. The horizontal resultant force passes through the center point of column, which is the inflection point of double curvature bending. Vertical actuators apply a constant axial load on the specimens, and the vertical deformation of the two vertical actuators is the same, which guarantees that specimens can be tested under double curvature deformation. This experiment is designed to simulate the seismic behavior of the reinforced concrete columns under high axial load and varying axial load. As for lateral cyclic load, the loading time follows ACI 374.1-05(2006), and the inter-layer deflection angle works as the controlling parameter; the load is deployed in order. Each inter-layer deflection angle includes three loops and the detailed load cycle is shown in Figure 4. The external instruments used in this experiment include a linear variable differential transducer (LVDT), dial gauge, and tiltmeter that are used to measure the deformation during the loading; the installation locations of the instruments are shown in Figure 5.

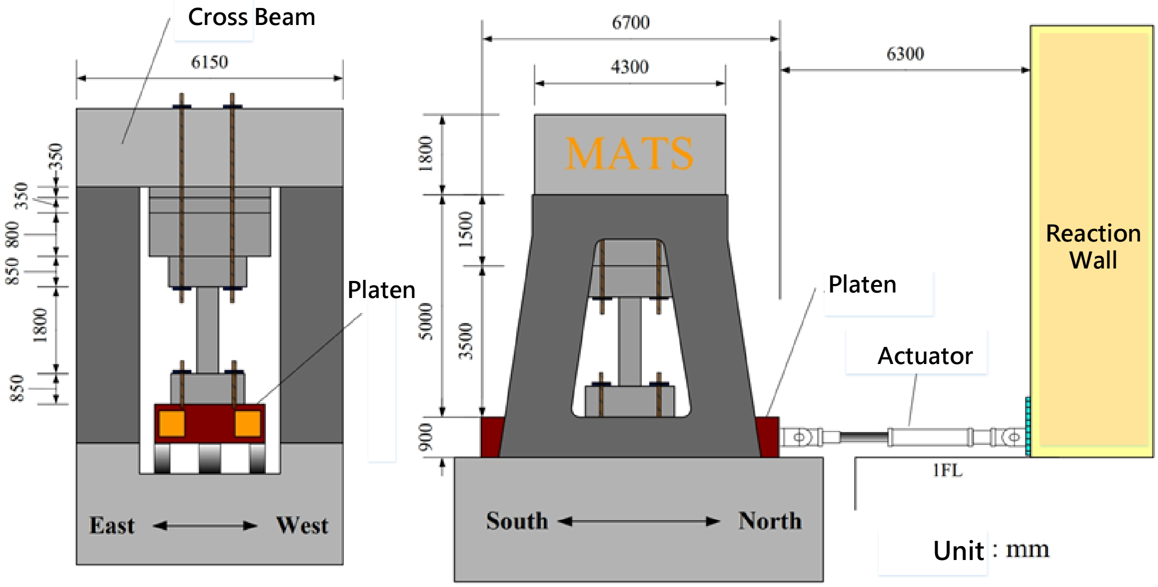


Figure 3 Test setup (Multi-Axial Testing System)

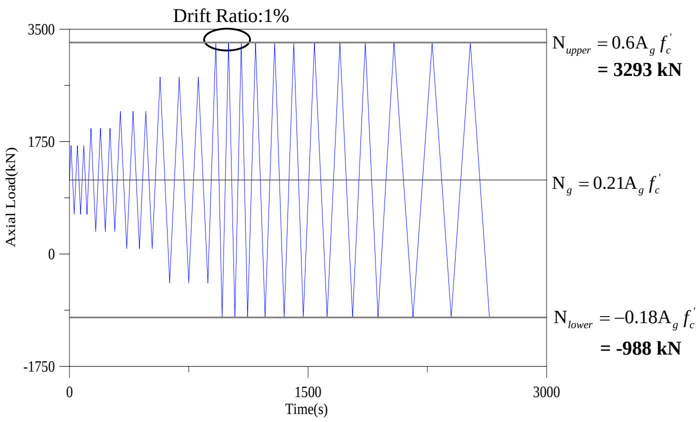


Figure 4 Loading protocol for varying axial load

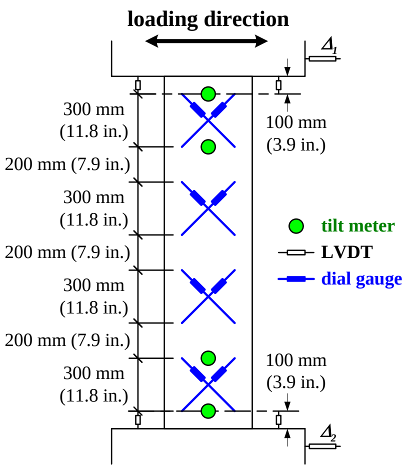
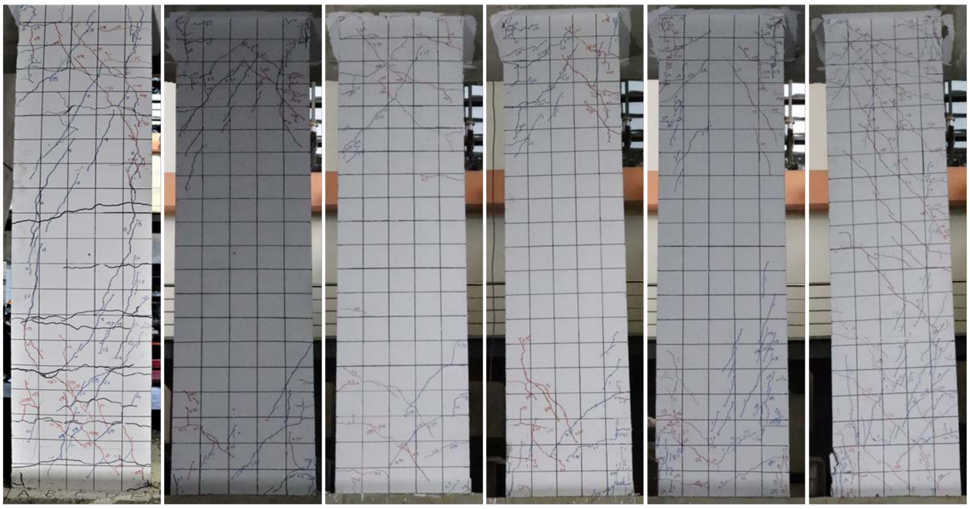


Figure 5 Instrumentation arrangement

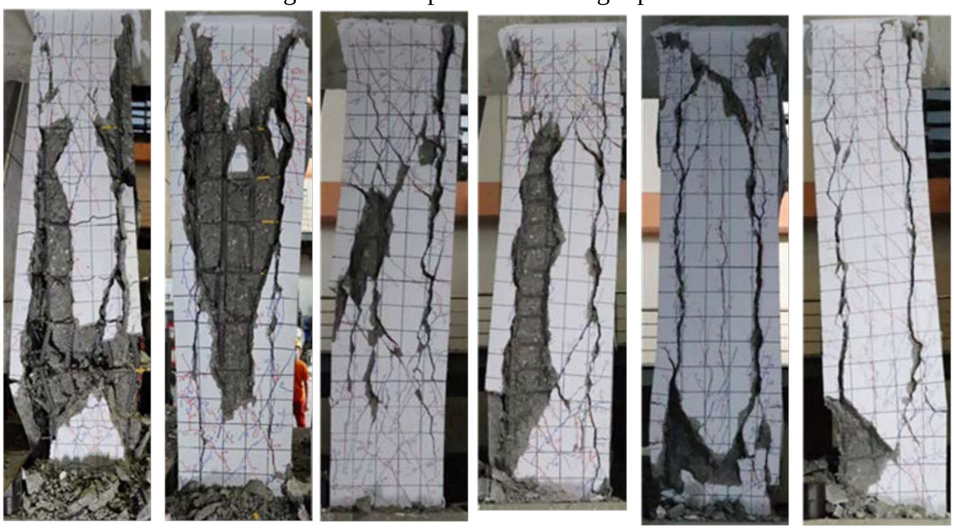
TEST RESULTS

Flexural-Shear failure is designed as the primary failure mode of all specimens observed in this experiment. Figure 6 shows the crack patterns of all specimens at the strength point. According to Figure 6, the primary cracks on all specimens in this experiment are mainly oblique cracks, but the development of oblique cracks cannot be directly connected from the force-deploying side to the force-reaction side, which indicates that concrete struts with oblique cracks cannot be directly fixed on the force-deploying side and force-reaction side of the column, and the equivalent point of the concrete strut on the total length of the column needs to be balanced by the transverse reinforcement force. This observation indicates that transverse reinforcement plays a key role in the force transfer mechanism of reinforced concrete columns under high axial load and varying axial load. In addition, according to the observation of the cracks, specimens with high transverse reinforcement (Series D) develop more cracks compared to specimens with low transverse reinforcement (Series N). In Series V, it can be clearly observed that the primary cracking angle (angle to horizontal axis) increases as the axial force increases, as shown in Figure 6 and Figure 7.



RN4	RN6	VN	RD4	RD6	VD
@1.50%	@1.00%	@0.75%	@1.00%	@1.00%	@1.50%

Figure 6 Crack patterns at strength point



(a)RN4 (b)RN6 (c)VN (d)RD4 (e)RD6 (f)VD

Figure 7 Failure stage

The lateral load displacement hysteretic loops of all specimens are shown in Figure 8. According to the lateral load displacement curve of specimens, before the maximum strength of a specimen is reached, abundant cracks develop due to shear failure, and the phenomenon of stiffness turning is also evident. Moreover, after specimens reach their maximum strengths, although lateral strength decays very fast, the slope of the decaying behavior is still negative. This type of lateral load displacement curve is very common in structural struts failed in shear. In this experiment, when all specimens are deployed with positive or negative loads, the maximum lateral load V_n and the lateral displacement at the maximum load Δ_n are listed in Table 2 in order.

According to experimental observation and the hysteretic loop (Figure 8), when peak strength occurs in reinforced concrete columns under high axial load and varying axial load, the majority of the vertical force is supported by concrete. As the lateral displacement increases, the concrete crushes constantly, so its lateral strength decays rapidly. However, for the RN4 and RD4 specimens deployed with low axial force, since the bar configuration in this experiment is high, the axial force can be supported by the bar. Therefore, a small slope in a section of the strength decaying curve can be seen in the low axial force experiment, which facilitates the double curvature of lateral load strength decaying. In the high axial force experiment, depression occurs in the reinforcement, which eliminates the decaying section with a small slope. Since the bar in this experiment is over-configured, which is not normal, the bar's contribution to the collapse point displacement of the short column will not be included. Therefore, in Figure 8, the displacement of the collapse point is decided as follows: for the low axial force experiment, the decaying section with small slope is removed and the intersection point between the zero lateral load strength line (X axis) and the negative slope line of the inter-layer drift angle just before the removed point is chosen. For high axial force experiments, the point when 20% of its axial force is lost is judged as the collapse point of losing vertical bearing force. The displacement of the collapse point is decided in the same way as the literature (Li et al., 2014).

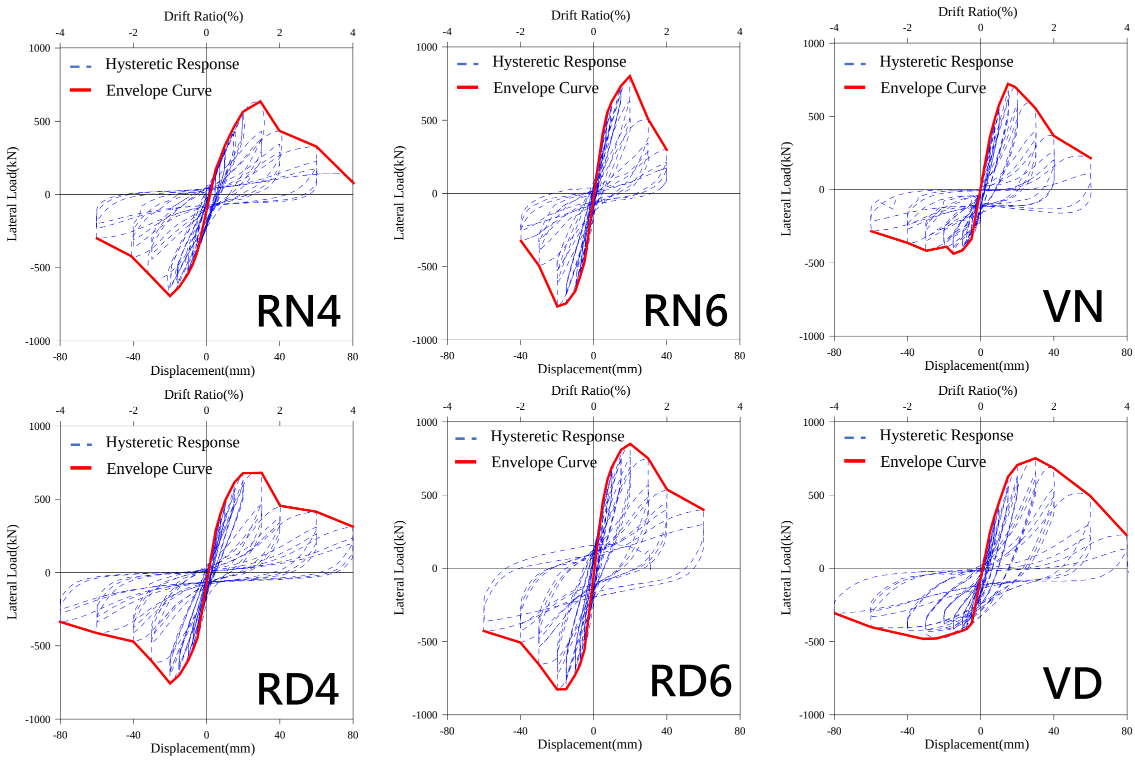


Figure 8 Hysteretic loops and envelope curve

Table 2 Test data

Specimens	Axial Load Mode	P,kN	Δ_{cr},mm	Δ_{n},mm	Δ_{s},mm	Δ_{a},mm	V_{cr},kN	V_{n},kN
RD4	Regular	2195	7.53	19.82	36.17	79.78	400	678
RN4	Regular	2195	14.94	29.48	36.04	80.36	458	635
RD6	Regular	3293	9.90	19.93	33.18	59.96	690	849
RN6	Regular	3293	10.00	19.85	25.29	39.98	627	800
VD	Varying	3293	10.00	29.94	48.58	79.63	449	751
		-988	-4.89	-24.10	-63.31	-79.47	-375	-480
VN	Varying	3293	7.45	14.94	28.26	60.10	472	721
		-988	-4.98	-14.87	-43.34	-59.72	-337	-438

The primary parameters in this experiment, based on the experimental results in Table 2 and Figure 8, are compared and discussed independently. For axial force, the specimen with a high axial force, has a comparatively higher maximum lateral load but its lateral displacement corresponding to the maximum lateral load is small (Table 2). As for strength decaying, due to the influence of the high axial force, concrete experiences a stressful deterioration after it reaches the strength point, and this is the cause of the large decaying slope. Therefore, in terms of collapse point displacement, the high axial force specimen has a small collapse point displacement (Figure 8). As for the hoop ratio, the specimen in Series D with a high hoop ratio has a comparatively higher maximum lateral load (Table 2). In terms of strength decaying, since the high hoop specimen has a high horizontal hoop ratio, which effectively constrains the width of cracks, the concrete strength decay is quite slow and the slope of the strength decay is also small. Therefore, a high hoop ratio specimen has a higher collapse point displacement(Figure 8). As for height-to-depth ratio, the maximum lateral load of the specimen with a ratio of 0.4 is slightly higher than the specimen with a ratio of 0.6, and the lateral displacement corresponding to the maximum lateral load of ratio 3 is comparatively smaller (Table 2). In terms of comparison between strength decaying and collapse point displacement, the specimen with a height-to-depth ratio of 0.6 has bigger collapse point displacement because its column height is higher (Figure 8).

This paper will measure the deformation to understand the contribution of shear deformation in lateral displacement of intermediate short columns. The paper adopts the deformation analytic method (Li et al., 2014) to measure and calculate shear deformation. However, there is a break in instrument configuration in this experiment (Figure 5). Therefore, the measurement and analysis of shear deformation in this paper uses an average value of two areas, before and after the break, to estimate the shear deformation in the break.

Figure 9 shows the contribution of shear deformation in lateral displacement in all specimens. It can be seen from Figure 9 that shear deformation has a high contribution, which is too high to be ignored. For the low axial force specimen Series L, the contribution of shear deformation is 15%~30%; for the high axial force specimen Series H, shear deformation has a lower contribution of 15%~20%.

Figure 9 shows the strain of transverse reinforcement in high hoop ratio specimen Series D. According to the figure, both specimens with height-to-depth ratios 3 and 4 have significant yielding in their transverse reinforcement. The experimental results show that transverse reinforcement does transfer shear force in intermediate short columns, and it also provides the tensile force used to achieve force balance on the strut. In addition, the tensile strain of transverse reinforcement on the column side is extremely small, which indicates that transverse reinforcement has a low force transfer efficiency on the strut ends. This is because the force balance on the strut end is provided by shear force on that interface. Therefore, accompanied with the observation results of crack patterns, transverse reinforcement plays a key role in the force transfer mechanism of intermediate short columns, and has a significant contribution to shear strength of intermediate short columns with a height-to-depth ratio of between 2 and 4 failed in shear.

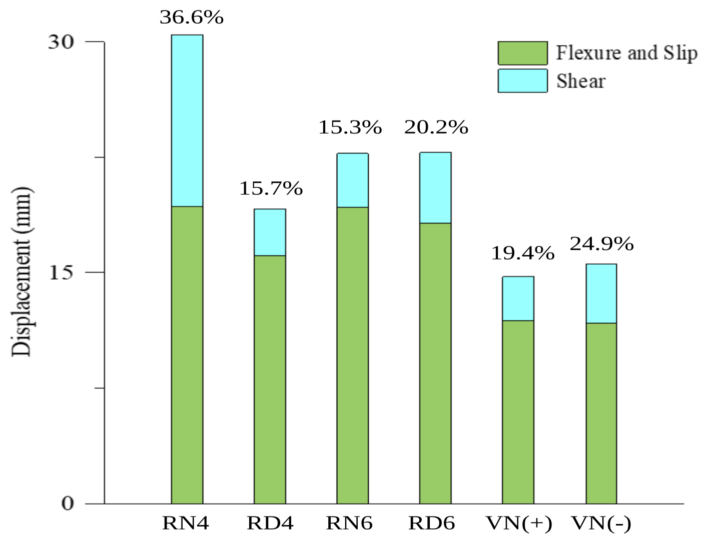


Figure 9 Shear deformation ratio at peak load

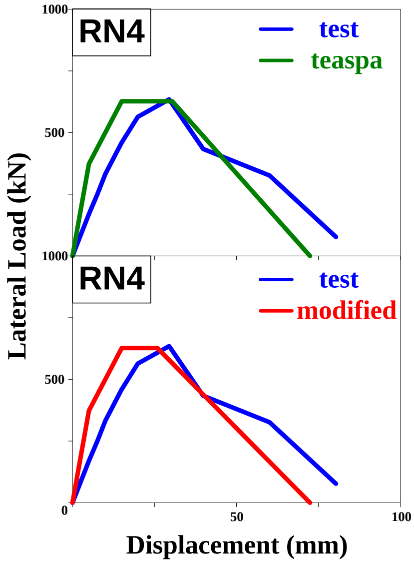
COMPARISON WITH EXISTING EVALUATION MODELS

This paper compares experimental data with the existing analytic model, and based on those results, suggests a lateral load displacement curve for reinforced concrete columns under high axial load and varying axial load. The existing analytical model refers to the evaluation method in ASCE/SEI 41-13 (2014) and ACI 318-19 (2019), but the experimental database follows the experimental results of this paper. According to the experimental results in Figure 8, for reinforced concrete columns under high axial load and varying axial load, the lateral load displacement hysteretic loop is very similar to the experimental results (Li et al., 2014) of short columns, so the lateral load displacement curve of short columns failed in shear (Li and Hwang, 2017) is adopted, as shown in Figure 10.

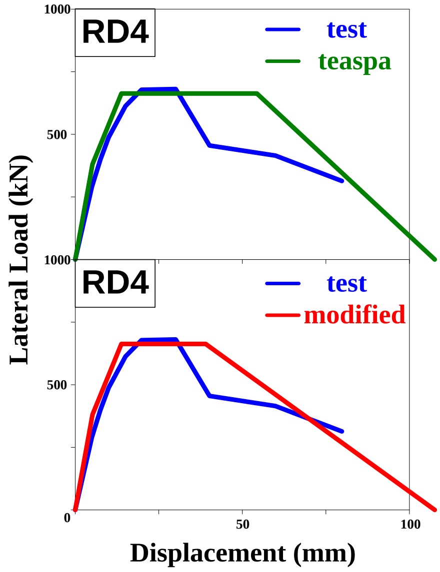
Figure 10 shows the comparison of enveloping lines of specimens in the experimental and proposed lateral load displacement curve, the enveloping lines of the experiments in this paper can be seen in Figure 10. Before reinforced concrete columns under high axial load and varying axial load reach their shear strength, stiffness softening can occur as the expansion of shear cracks, this indicates the necessity to consider shear deformation induced by shear cracking. After reinforced concrete columns under high axial load and varying axial load reach their shear strength, the lateral strength decreases rapidly, and the negative stiffness oblique line of the proposed curves matches the results of experiments. The prediction of the proposed curve is rational and conservative.

Table 2 shows the prediction of shear strength in the proposed curves and compares it with experimental results. The average value of the experimental-analytical strength ratio is 1.18, and the coefficient of variation is 0.18. In terms of the prediction of failure mode in the proposed model, the failure mode of specimen 0-PM of Umehara and Jirsa is a simultaneous shear compressive and shear tensile failure because the axial force is 0 and its concrete strength is low. For other specimens, the predictions are all shear tensile failure, so the prediction complies with the results of ASCE/SEI 41-13 (2014).

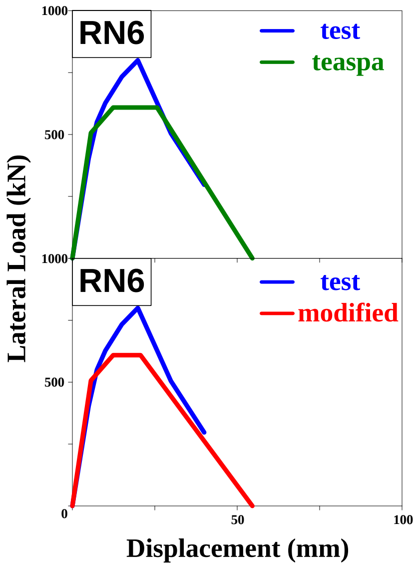
Table 2 also indicates the prediction of the strength point lateral displacement in the proposed curves and compares it with experimental values, the average value of the experimental-analytical displacement ratio is 1.47, and the coefficient of variation is 0.38. Since the proposed curve comprehensively takes consideration of shear deformation induced by shear cracks, it can rationally predict the lateral displacement of the strength point in intermediate short columns failed in shear.



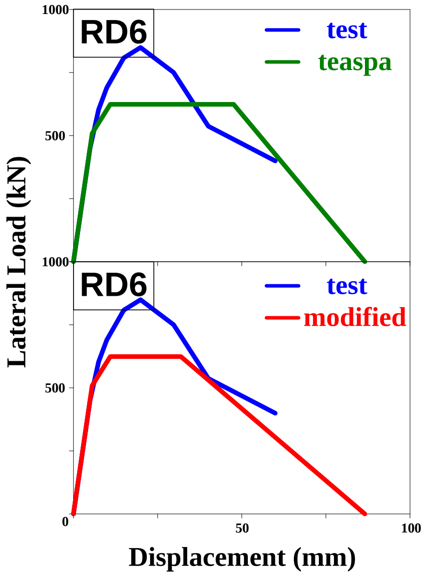
(a)RN4



(b)RD4



(a)RN6



(b)RD6

Figure 10 Comparison of test envelope and proposed curve

CONCLUSIONS

This paper conducts cyclic load experiments on six reinforced concrete columns under high axial load and varying axial load, with the objective of understanding their seismic behavior. By experimental observation, this paper suggests adopting the shear transfer mechanism described by MacGregor (1997), and then proposes a lateral load displacement curve for reinforced concrete columns under high axial load and varying axial load.

Experimental observation shows that, before the reinforced concrete columns under high axial load and varying axial load reached their flexure strength, their stiffness will decline due to the expansion of shear cracks, so the increase rate of lateral displacement of the intermediate short column is improved. This phenomenon indicates that when predicting the lateral displacement at strength points in a reinforced concrete columns under high axial load and varying axial load, shear deformation induced by the expansion of shear cracks should be taken into consideration. In addition, according to the crack development at the strength point in the intermediate short column experiment, one side of the compression fan can be fixed on the compression zone of column end, and the other side requires force from transverse reinforcement to reach an equilibrium. Therefore, it can be known that transverse reinforcement is critical to shear transfer mechanism in intermediate short columns failed in shear. After shear failure, the lateral strength of intermediate short columns decay rapidly, the strength degradation behavior can be simulated with a straight line of negative stiffness.

This paper suggests using the cracking point, strength point, and collapse points tri-linear relationship to simulate the lateral load displacement curves of reinforced concrete columns under high axial load and varying axial load. The strength of intermediate short columns failed in shear can be divided into shear compressive failure and shear tensile failure, shear compressive strength is estimated by the softened strut-and-tie model (Li and Hwang 2017), while shear tensile failure adopts shear strength formula provided by ASCE/SEI 41-13 (2014). The lateral displacement of the strength point includes the shear deformation induced by the expansion of shear cracks. After comparing them with the experimental results of intermediate short columns, the prediction result of the proposed curve is reasonable and conservative.

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