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Seismic performance of reinforced concrete columns with intermediate height-to-depth ratio failed in shear

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ABSTRACT

According to the previous earthquake reconnaissance, existing reinforced concrete buildings with intermediate short columns are vulnerable to shear failure. Thus a simulation of the behavior of intermediate short columns has a significant influence on the seismic evaluation. This paper tests eight intermediate short column in shear failure cases with different combinations of structural parameters, such as height-to-depth ratio, transverse reinforcement ratio, and axial load ratio, which are designed to explore how different structural parameters influence the seismic behavior of intermediate short columns failed in shear. According to the test results, this paper proposes a lateral load displacement curve for the intermediate short column failed in shear with a height-to-depth ratio of between 2 and 4. This study also uses the shear force transfer mechanism of intermediate short columns and a strut-and-tie model to propose an evaluation method for shear strength. Using the method, this paper further predicts the shear deformation induced by the shear cracks in intermediate short columns. In addition to comparing the proposed curve with the test data in this paper, data from other literature are also used for verification. Test verification indicates that the proposed curve possesses a reasonable prediction, which is helpful for seismic evaluation of existing buildings.

1 INTRODUCTION

Generally, the reinforced concrete short column refers to columns with a height-to-depth ratio lower than 2, their seismic behavior is always dominated by shear. According to the research of Li and Hwang (2017), the

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shear strength of short columns can be predicted with a strut-and-tie model, and the shear deformation induced by shear cracks also leads the lateral displacement of short columns. Similarly, columns with a height-to-depth ratio of between 2 and 4 are called intermediate short columns, their seismic behavior can be greatly influenced by shear, which is also the research objective of this paper.

In general building, columns are usually connected with infilled walls with openings, thus intermediate short columns are easily created. According to previous earthquake reconnaissance, since existing buildings were constructed in era which was lack of seismic design, their intermediate short columns are very sensitive to shear failure, which makes the seismic capability of the structure insufficient. As intermediate short columns have a high stiffness, when an earthquake occurs, the columns usually fail at an early stage. Therefore, when evaluating the seismic performance of a building, the lateral load deformation behavior of intermediate short columns failed in shear is always the critical structural member. To this regard, a thorough understanding of the seismic behavior of intermediate short columns in shear failure is beneficial to the evaluation of the seismic performance of buildings.

To evaluate the seismic performance of reinforced concrete columns failed in shear, engineers in the USA usually use the ASCE/SEI 41-13 (2014) evaluation method. ASCE/SEI 41-13 (2014) adopts empirical formula to evaluate shear strength, thus, many tests are required for comparison with data of shear strength from intermediate short column. ASCE/SEI 41-13 (2014) does not include the shear deformation induced by shear cracking expansion when evaluating the lateral displacement of the strength point, so experimental verification is also needed.

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 complete experiment designed to compare an intermediate short column lateral load displacement curve in shear failure is rarely seen. As the number of experiments was limited, experimental data of intermediate short columns failed in shear is still desired.

This paper describes and discusses the seismic behavior of intermediate short columns failed in shear by conducting experiments (Weng 2007) on eight different intermediate short columns with height-to-depth ratios of between 2 and 4. Secondly, based on experimental observation, this paper proposes a lateral load displacement curve in order to simulate the seismic behavior of intermediate short columns failed in shear under earthquake loadings. 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.

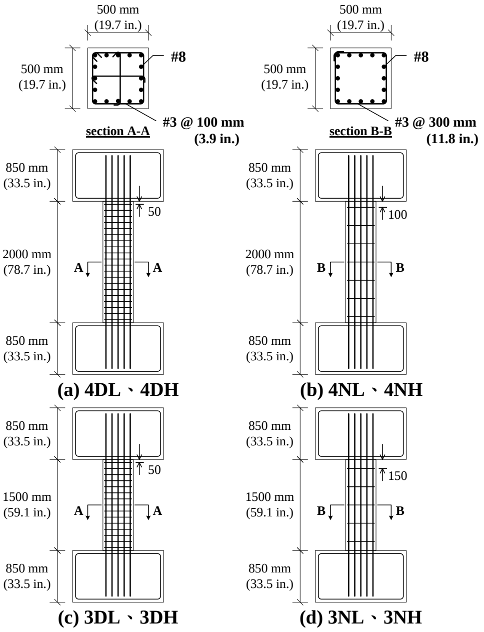
2 EXPERIMENTAL INVESTIGATION

2.1 Specimens and design

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 intermediate short columns failed in shear with height-to-depth ratios within the range 2 to 4, how different parameters influence the seismic behavior of intermediate short columns under a constant axial load (Weng 2007). This study picks three parameters, height-to-depth ratio, transverse reinforcement ratio, and axial load ratio, which have significant influence on intermediate short column seismic behavior. Three different parameters are examined in a total of eight different specimens. Conducting these eight columns under double curvature deformation allows an understanding of the influence of different parameters on the seismic behavior of intermediate short columns with height-to-depth ratios between 2 and 4. Thus, the experiments are named in order, based on different parameters. For example, a specimen with height-to-depth ratio of 4, equipped with high hoop ratio (D), and low axial load is named 4DL. Detailed specimen specifications are shown in Figure 1 and Table 1.

Table 1: Test parameters and material properties

					Reinforcement			
Specimens	Aspect Ratio	Hoop Ratio, ρ_s	$\frac{N}{A_g f'_c}$	f'_c, MPa	Longitudinal		Transverse	
					size	$f_{y\ell}$, MPa	size	f_{yt}, MPa
4DL	4	0.43%	0.08	30.7	#8	472	#3	448
4DH			0.22	34.0				
4NL		0.10%	0.08	29.7				
4NH			0.24	30.8				
3DL	3	0.43%	0.07	34.5				
3DH			0.22	33.8				
3NL		0.10%	0.07	33.5				
3NH			0.23	32.4				



(a) 4DL、4DH (b) 4NL、4NH (c) 3DL、3DH (d) 3NL、3NH

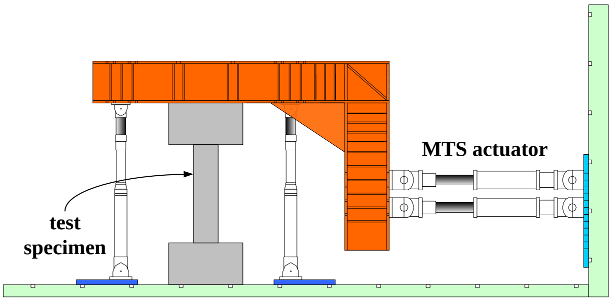


Figure 1: Specimen elevation and sectional detailing *Figure 2: Test setup*

2.2 Test program and instrumentation

This experiment is designed to understand the seismic behavior of intermediate short columns 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 2. 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 intermediate short column's seismic behavior under cyclic loading and constant axial load. T As for cyclic loading input, the loading protocol follows ACI 374.1-05 (2006), and the drift ratio works as the control parameter. 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 3.

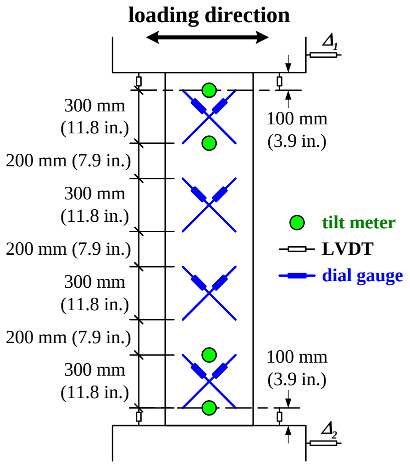


Figure 3: Instrumentation arrangement for Series 4

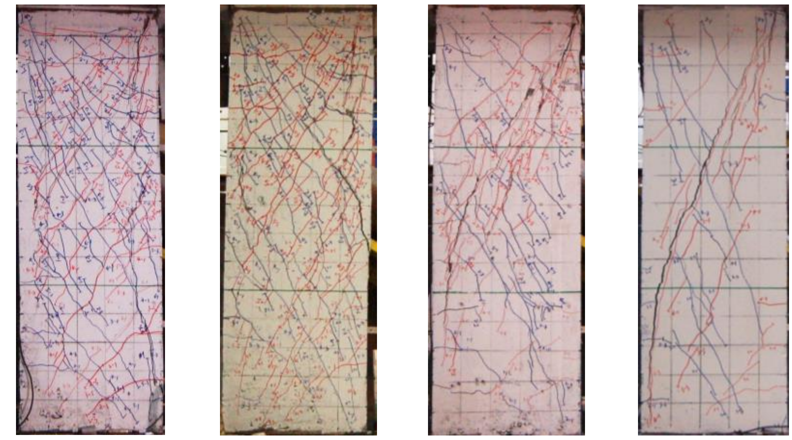
3 TEST OBSERVATIONS

Shear failure is designed as the primary failure mode of all specimens observed in this experiment. Figure 4 shows the crack patterns of all specimens at the peak strength. According to Figure 4, the main cracks on all specimens in this experiment are inclined cracks, but the development of inclined cracks cannot be directly connected from the loading end to the reaction end, which indicates that concrete struts within inclined cracks cannot be directly linked the loading end to reaction end of the column, and the concrete strut of the nodes on the total length of the column needs to be balanced by the transverse reinforcement. This observation indicates that transverse reinforcement plays a key role in the force transfer mechanism of intermediate short columns.

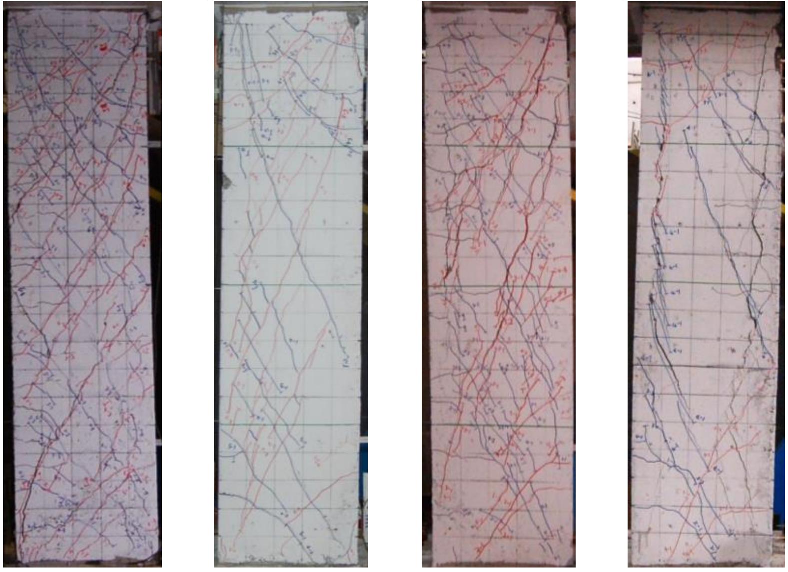
The hysteretic loops of all specimens are shown in Figure 5. According to the lateral load displacement curve of specimens, before the maximum strength of a specimen is reached, abundant shear cracks develop, and the phenomenon of stiffness softening is also evident. Moreover, after specimens reach their maximum strengths, although lateral strength decays very fast, the deterioration behavior is a negative gradient. This type of lateral load displacement curve is very common in structural members failed in shear. In this experiment, the maximum lateral load and lateral displacement at the maximum load are listed in Table 2.

Table 2: Comparison of test and analysis results

Specimens	Test data			Evaluation						
				Strength point						Collapse point
				Existing model			Proposed			
	V_{test} kN	$\Delta_{n,test}$ mm	Δ_a mm	$\frac{V_{test}}{V_{n,ACI}}$	$\frac{V_{test}}{V_{n,ASCE}}$	$\frac{\Delta_{n,test}}{\Delta_{n,ASCE}}$	θ	$\frac{V_{test}}{V_{n,prop.}}$	$\frac{\Delta_{n,test}}{\Delta_{n,prop.}}$	$\frac{\Delta_a}{\Delta_{a,prop.}}$
4DL	717	34.5	136.0	1.08	0.95	2.64	63.4	0.95	1.65	1.27
4DH	772	24.4	80.1	1.03	0.86	2.27	63.4	0.86	1.32	0.92
4NL	467	16.7	93.6	1.41	1.10	2.25	63.4	1.10	1.08	2.57
4NH	661	14.8	60.0	1.61	1.18	2.21	63.4	1.18	1.01	2.00
3DL	766	15.4	67.9	1.13	0.94	2.63	63.4	0.94	1.23	0.88
3DH	845	17.6	59.4	1.12	0.87	3.42	63.4	0.87	1.50	0.95
3NL	471	7.3	68.6	1.36	0.96	2.06	63.4	0.96	0.70	2.63
3NH	699	6.2	38.0	1.67	1.10	1.83	63.4	1.10	0.61	1.73
Average (AVG)				1.30	1.00	2.41	-	1.00	1.14	1.62
Coefficient of Variation (COV)				0.18	0.11	0.19	-	0.11	0.30	0.42



(a) 3DL @ 1.0% (b) 3DH @ 1.2% (c) 3NL @ 0.5% (d) 3NH @ 0.4%



(e) 4DL @ 1.7% (f) 4DH @ 1.2% (g) 4NL @ 0.8% (h) 4NH @ 0.7%

Figure 4: Crack patterns of specimens at peak lateral load

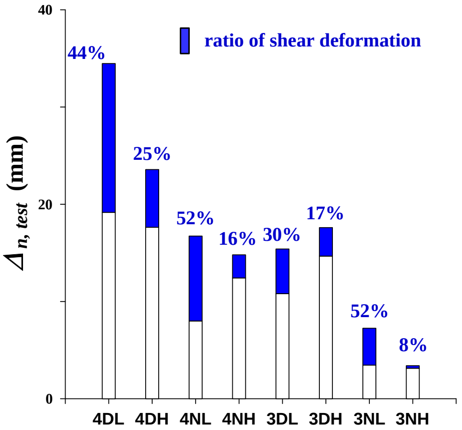


Figure 6: Shear deformation ratio at peak load

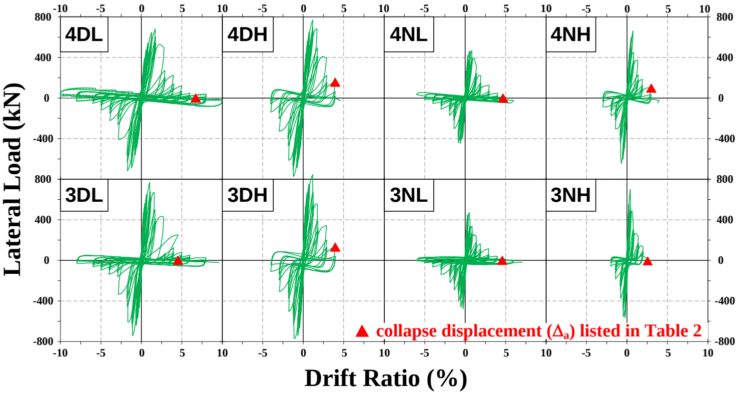


Figure 5: Hysteretic loops

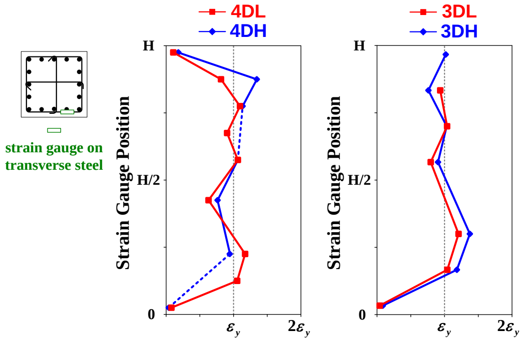


Figure 7: Strain distribution of shear reinforcement along the column height

This paper compared the deformation to understand the contribution of shear deformation in lateral displacement of intermediate short columns. The paper adopts the deformation analytical method by Li et al.

(2014) to measure and calculate shear deformation. However, there is an interruption in instrument configuration in this experiment (Figure 3). Therefore, the measurement and analysis of shear deformation in this paper uses an average value of two areas, before and after the interruption, to estimate the shear deformation.

Figure 6 shows the contribution of shear deformation in lateral displacement in all specimens. It can be seen from Figure 6 that shear deformation has a high contribution, which is too high to be ignored. For the low axial load specimen (Series L), the contribution of shear deformation is 30%~52%; for the high axial load specimen (Series H), shear deformation has a lower contribution of 8%~25%.

Figure 7 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 for the equilibrium on the node. In addition, the tensile strain of transverse reinforcement near the column end is extremely small, which indicates that transverse reinforcement has a low force transfer efficiency. This is because the equilibrium on the column end is provided by interface shear force. 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.

4 PROPOSED LOAD DISPLACEMENT CURVE

This paper compares experimental data with the existing analytical model, and based on those results, suggests a lateral load displacement curve for intermediate short columns failed in shear with height-to-depth ratios of between 2 and 4. The existing analytical model refers to the evaluation method in ASCE/SEI 41-13 (2014) and ACI 318-14 (2014) and the comparison results were listed in Table 2.

According to the experimental results in Figure 5, for intermediate short columns failed in shear with a height-to-depth ratio of between 2 and 4, 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 8.

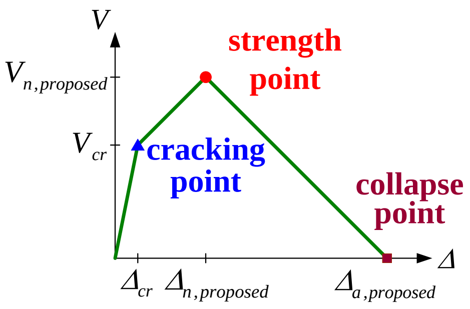


Figure 8: Proposed load displacement curve of intermediate short column failed in shear

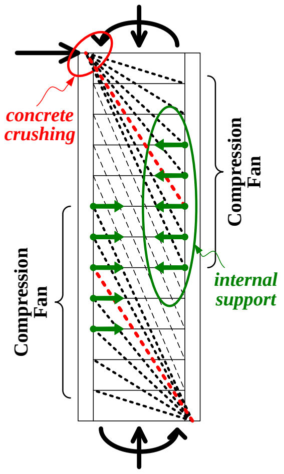


Figure 9: Force transfer mechanism (MacGregor 1997)

According to the observations on cracking in Figure 4, the concrete struts between the inclined cracking of intermediate short columns failed in shear cannot be directly connected from the loading end to the reaction end, so its force transfer mechanism is exactly the same as MacGregor (1997) suggested, as shown in Figure 9. In Figure 9, there are two strengths in the compression fan, one is the concrete crushing strength ($V_{n,c}$) in the compression zone in the column end of the compression fan, the other is the tensile strength ($V_{n,t}$) induced by the insufficient internal support at the node, which is dispersed along the whole column.

The concrete crush strength ($V_{n,c}$) in the compression zone of the column end can be predicted by the softened strut-and-tie model (Li and Hwang 2017). As for the tensile strength ($V_{n,t}$) of internal support of the compression fan dispersed on the column, it can be predicted by the shear strength of inclined cracking. This paper suggests using the shear strength formula in ASCE/SEI 41-13 (2014). Therefore, the shear strength ($V_{n,proposed}$) of intermediate short columns failed in shear with a height-to-depth ratio of between 2 and 4 should use following equation:

$$V_{n,proposed} = \text{smaller of } \left(V_{n,c}, V_{n,t}\right) \tag{1}$$

Figure 10 shows the comparison of envelope curves of specimens in the experimental and proposed lateral load displacement curve, the envelope curves of the experiments can be seen in Figure 10. Before intermediate short columns reach their shear strength, stiffness softening can occur as the expansion of shear cracks, this indicates the requirement to consider shear deformation induced by shear cracking. After intermediate short columns reaching their shear strength, the lateral strength decreases rapidly, and the straight line of negative stiffness of the proposed curves matches the results of experiments. The prediction of the proposed curve is rational and conservative.

Table 2 also indicates the prediction of lateral displacement at the strength point in the proposed curves and compares it with experimental values, the average value of the test-analytical displacement ratio is 1.14, and the coefficient of variation is 0.30. Since the proposed curve comprehensively takes consideration of shear deformation induced by shear cracks, it can rationally predict the lateral displacement at the strength point in intermediate short columns failed in shear. As for the comparison of the collapse point on proposed curves (Table 2), the average value of the test-analytical displacement is 1.62, and the coefficient of variation is 0.42. After comparing with experimental results, the prediction of the proposed curves on the behavior of the collapse point is rational.

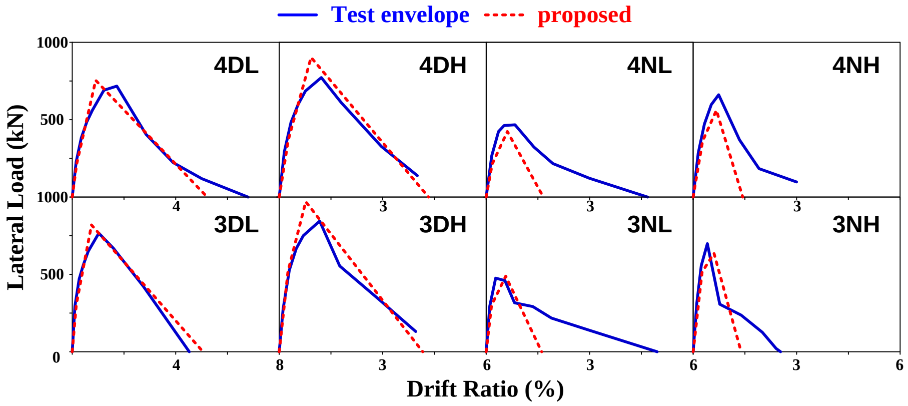


Figure 10: Comparison of test envelope and proposed curve

5 CONCLUSION

This paper conducts cyclic load experiments on eight intermediate short column specimens failed in shear with height-to-depth ratios of 3 and 4, 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 intermediate short columns failed in shear with height-to-depth ratios of between 2 and 4.

Experimental observation shows that, before the intermediate short columns failed in shear reached their shear 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 an intermediate short column, 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 intermediate short columns failed in shear with a height-to-depth ratio of between 2 and 4. 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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