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A STUDY ON ENERGY DISSIPATION AND VISCOUS DAMPING CHARACTERISTICS OF STEEL PLATE CONCRETE WALLS

Ilhwan Moon[1], Sungsoo Kim[2], Kyungkoo Lee[3], Taeil Kim[4], Goeun Han[5]

[1] Professor, Daejin University, Pocheon-si, Korea (ilhwanmoon@gmail.com)
[2] Professor, Daejin University, Pocheon-si, Korea
[3] Professor, Dankook University, Yongin-si, Korea
[4] General Manager, KHNP Co., Ltd, Gyeongju-si, Korea
[5] Senior Manager, KHNP Co., Ltd, Gyeongju-si, Korea

INTRODUCTION

Steel-plate concrete (SC) is a structural system developed for modular design and construction of structures and has been applied to the WEC AP1000 nuclear power plant (NPP) in the United States and Tomari Unit 3 NPP in Japan, and recently to the core structure of Rainier Square Tower. In addition, it is expected to be widely applied as the basic structural system of small modular reactors (SMR) currently under development.

According to existing research results, the characteristics of dynamic behaviour for SC structure are almost same as those of the RC structure before steel plate yields but its damping factor is increased dramatically after the steel plate yielded. The conclusion of these studies can be thought of as meaning that the dynamic characteristics of SC structures are similar to those of RC structures, but the energy dissipation capacity is somewhat superior to that of RC structures.

Based on Japanese test using 1/10-scale SC structure model of NPPs' internal structures, the damping ratio of SC structure was suggested to 5% before the yielding of the steel faceplate and also evaluated that it increases to 20% after yielding (Akiyama et al., 1989). In the study by Siamak Epackachi and Andrew S. Whittaker (2016), the equivalent damping ratio was derived to be more than 6% through repeated cyclic tests and analysis of SC structural shear walls consisting of only web wall. According to the test results on the damping ratio of SC structures by Cho et al. (2013), it has been identified that damping ratios were distributed between 11.2% ~ 13.5% for safe shutdown earthquake (SSE) stress level, and the vibration shaking table test results they performed showed that the damping ratio was slightly over 4% at the operation basis earthquake (OBE) stress level (2015). In addition, the damping ratio of the SC shear wall, which reflects the structural characteristics of nuclear power plants performed in Korea through free vibration tests and repeated loading tests, was evaluated to exhibit dynamic characteristics equivalent to those of reinforced concrete structures, and the energy absorption capacity and ductility were evaluated to be excellent as the stress level increased (Moon et al., 2013). Despite these several studies, there is insufficient test data to determine the damping ratio of SC structures in absolute terms. However, the common conclusion from all test results is that the damping ratio of SC structures is equal to or greater than that of RC structures.

Regarding the damping ratio of SC structure, the KEPIC SNG (2015) of Korea suggests 6% at the safe shutdown earthquake (SSE) stress level, whereas the Japanese JEAG 4618 (2005) and the American AISC N690 Appendix N9 (2018) recommend 5%. However, the common conclusion from each country was that the dynamic behavior characteristics of SC walls were similar to those of RC walls, and the SC structure had a higher energy dissipation capacity according to stress level increase. Despite similar tests and similar conclusions, the damping ratio is being defined differently in the codes. As reference, JEAG 4618 (2005) specifies that the damping constant value of SC buildings and structures shall be used as values commonly applicable to RC structures, because the damping mechanism of SC buildings and structures is basically not different from that of RC structures. JEAG 4618 (2005) also requires the application of nonlinear dynamic analysis method with restoring force characteristics as the seismic analysis method of SC and RC structures for design basis earthquakes. According to ASCE 43, the damping values for linear seismic analysis of RC structures are specified as 5% for operation basis earthquake (OBE) stress levels and 7% for safe shutdown earthquake (SSE) stress levels. These differences between design criteria for seismic design methods or application of damping ratios may be seen as leaving room for future review.

In this paper, the dynamic characteristic tests of SC structure performed in Korea are introduced, and the evaluation results of structural damping ratio using these tests are presented.

CYCLIC TESTS OF SC WALL AND RC WALLS

Six cyclic tests are performed to investigate seismic performances of SC wall specimens with various parameters, and two cyclic tests for reinforce concrete (RC) wall are also carried out to compare with the energy dissipation characteristics of SC structure. The key parameters are the aspect ratio of wall and the thickness of faceplate, and the details are summarized in Table 1.

Table 1: SC and RC wall specimens

Structure	Identification	Faceplate Thick (mm)	Web Size (W×H×T) (mm)	Aspect ratio	Expected Failure Modes[<1>]
SC	R24/400F4.5W3.2S71	3.2	1670×950×230	0.5	SC – SY - MY
	R27/400F6.0W3.2S71	3.2	1670×950×230	0.5	SC – SY – SF
	R27/400F4.5W3.2S71	3.2	1670×950×230	0.5	SC – SY - MY
	R27/400F3.2W3.2S79	3.2	1670×1100×230	0.6	SC – MY - SY
	R27/400F3.2W6.0S87	6.0	1670×1250×230	0.7	SC – MY – MF
	R27/400F6.0W6.0S71	6.0	1670×950×230	0.5	SC – SY – SF
RC	RC27/400S71	-	1220×1860×130	0.5	SC – SY – SF
	RC27/400S87	-	1220×2860×130	0.6	SC – MY – MF

<1> SC (Concrete Shear Cracking), SY (Steel Plate Shear Yielding), SF (Shear Ultimate State), MY (Moment Yielding), MF (Moment Ultimate State)

Cyclic tests with increasing amplitude are performed by applying concentrated loads to the wall of specimen in a quasi-static manner as shown in Fig. 1. As a result of the test, the force-displacement relationships of the SC structure and RC structure are obtained as shown in Figure 2, and the equivalent viscous damping ratio are calculated from each cycle curve of experimental data. The test results of the two structural systems shown in Figure 2 represent that the energy dissipation capacity of the SC structure is significantly superior to that of the RC structure. It can be explained that the energy absorption capacity of SC structures is relatively superior to that of RC structures, and that they have higher seismic performance than RC structures.

Figure 3 shows the distribution of damping ratios of SC and RC structures calculated from above test data. The x-axis represents the drift ratio, and the allowable drift limit for a low shear wall is 0.4% in ASCE 43 (2019), while JEAC 4601 (2015) applies a more conservative value of 0.2%. In the figure, the minimum equivalent viscous damping ratios are 3.6% for the RC specimen and 4.1% for the SC specimen respectively, and at the SSE stress level, it is in the range of 6 to 10% for the SC structures. In particular, in the case of the SC structure, it is calculated that the equivalent damping ratio dramatically increases when the drift ratio exceeds 0.4%, whereas in the case of the RC structure, it does not increase. Therefore, it can be judged that the energy dissipation capacity of the SC structure calculated from these test data is superior to that of the RC structure.

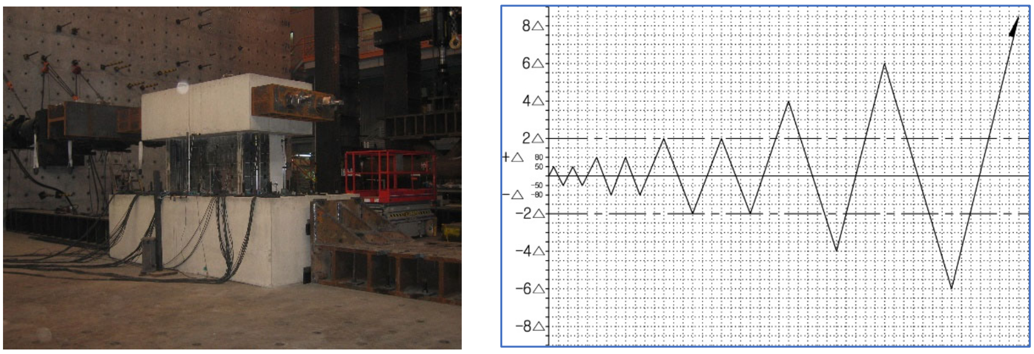


Figure 1. Cyclic test scene and loading methods for SC and RC walls

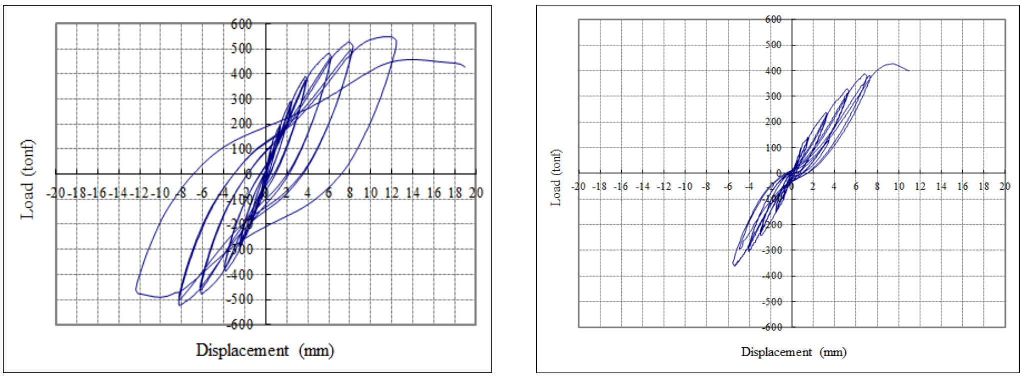


Figure 2. Typical cyclic test results: SC wall on the left and RC wall on the right

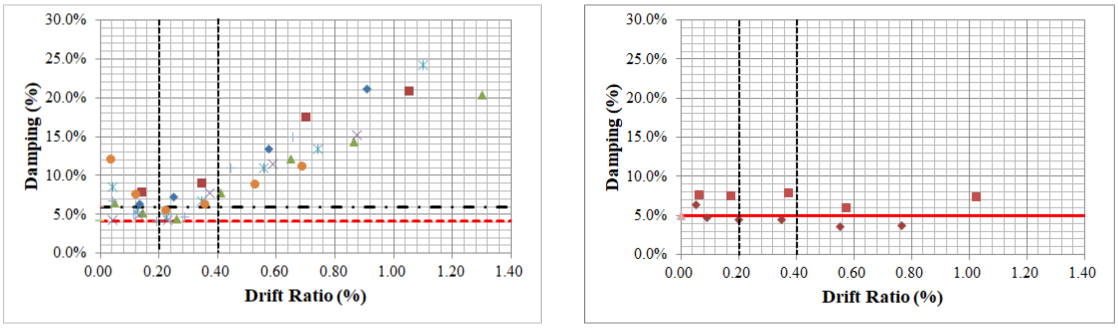


Figure 3. Equivalent viscous damping ratio distributions: SC wall on the left and RC wall on the right

Cho et al. (2013) perform a static cyclic loading test to obtain the force-displacement relationship for SC structure, and the equivalent viscous damping ratios is calculated from the test data. The test specimen is designed according to KEPIC SNG (2015) to consist of double web walls reflecting the characteristics of nuclear power plant structures. It is idealized to exhibit only horizontal in-plane shear without torsion, and the specimen consisted of wall thickness of 300 mm, height of 1,500 mm, and width of 1,500 mm. The rigid RC bottom slab is anchored to the floor of the laboratory with pretension anchors, and horizontal cyclic loads are statically applied through the rigid RC upper slab. The cyclic test is carried out as a quasi-static manner as shown in Fig. 4.

The equivalent viscous damping ratios calculated from the test results are summarized in Fig. 5, and the results are found to be in the range of 11.2% to 13.5%. This calculation result shows a relatively high damping ratio compared to the previously summarized damping ratio for SC structure.

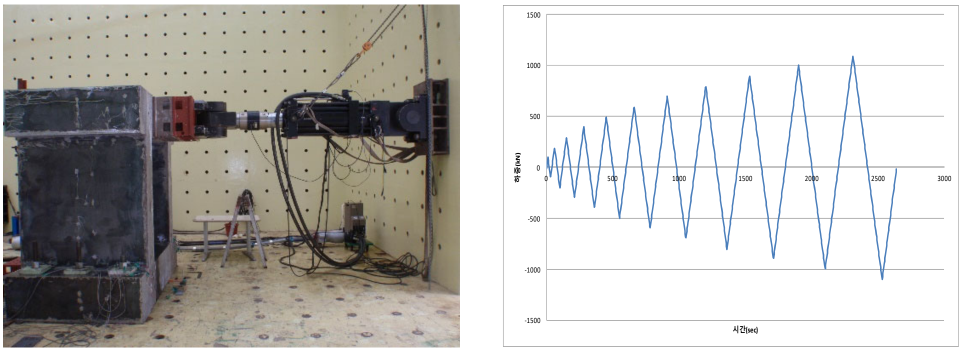
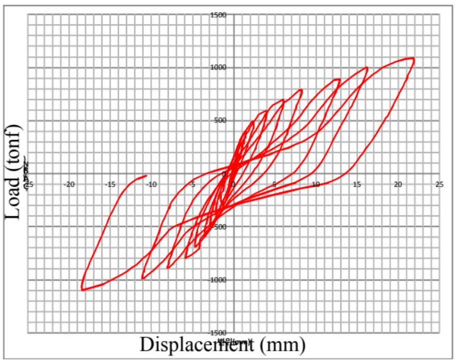


Figure 4. Cyclic test scene and loading methods for SC wall



Cycles	Calculated damping ratio (%)
2	11.2
4	12.3
5	11.9
6	13.1
7	13.5
8	12.1
9	12.6
10	12.4

Figure 5. Hysteresis roof and calculated equivalent viscous damping ratios for SC wall

FREE VIBRATION TESTS OF SC WALL AND RC WALLS

A series of free vibration tests is performed to comparatively evaluate the damping ratio of SC wall comparing with one of RC wall. And two types of specimens such as bending and shear-behaved specimen are designed for SC and RC walls as summarized in Table 2 (Moon et al., 2013).

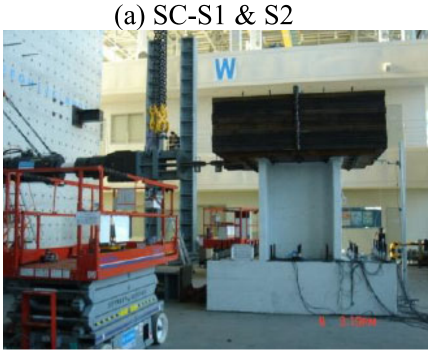
Table 2: SC and RC wall specimens

Structure	Name	Steel Plate Thick	Web Size (W×H×T) (Unit: mm)	Base Slab Size (W×L×T) (Unit: mm)	Remark (Behavior)
SC	SC-S1	1.6 mm	1220×1860×130	2300×3300×900	Shear
	SC-S2	1.6 mm	1220×1860×130	2300×3300×900	Shear
	SC-M	1.6 mm	1220×2860×130	2300×3300×900	Bending
RC	RC-S1	-	1220×1860×130	2300×3300×900	Shear
	RC-S2	-	1220×1860×130	2300×3300×900	Shear
	RC-M	-	1220×2860×130	2300×3300×900	Bending

Free vibration testing method considering step relaxation is adapted for the measurement of vibration decay data. For this test, a notched plate is used as a pulling lug which its notch size is decided based on the static tensile test result to verify the loading level. The SC structure specimen is designed in accordance with KEPIC SNG (2015) and the loading level is decided based on design shear or bending capacity and the nonlinear static push-over analysis results. The bottom slab is anchored to laboratory floor using pretension anchors and steel frame is also added to prevent the lateral movement. The test setup including the pulling lug is as shown in Fig. 6. Impact hammer excitation test is also performed to measure the natural frequency of that before each loading step is started.


(a) SC-S1 & S2

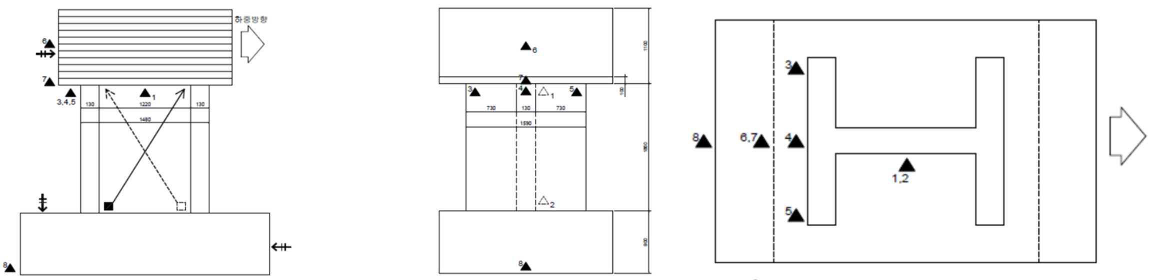

(b) SC-M


(c) RC-S1 & S2


(d) RC-M

Figure 6. Test setup for free vibration test

Displacement and acceleration time histories are measured by using attached LVDTs and acceleration censors as shown in Fig.7. The LVDTs are installed at three locations to measure lateral and vertical movement at base slab and lateral displacement at the middle of top slab or added mass. Acceleration time histories are also measured at eight locations as shown in Fig. 7.



(Note: ▲ Acceleration Censor, LVDT, Wire Gauge)

Figure 7. Measuring locations of displacement and acceleration time histories

Figure 8 shows the frequency distribution of the specimen measured at each load step. The frequencies of the specimen represent a gradual decreasing characteristic as the stress and damage level increased. These values can be obtained from the Power Spectral Density (PSD) function based on ratio of ultimate strength to loading. Bandwidth of the frequencies is similarly placed between 6 and 13 Hz for both SC and RC bending-behaved specimens and between 7.5 and 13 Hz for both SC and RC wall shear-behaved specimens.

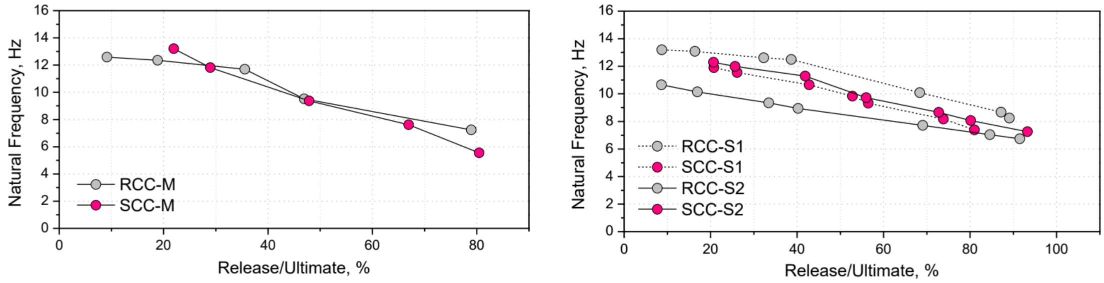


Figure 8. Measured natural frequencies for bending-behaved and shear-behaved specimens

Logarithmic decrement, half-power bandwidth, and exponential curve fitting are adopted to evaluate the damping ratios for SC and RC walls, and then the trend of damping ratio of SC structure is compared with that of RC structure as shown in Fig. 9. It is concluded that the damping ratio of SC wall specimen under SSE stress level is almost the same as that of RC structure.

Fig. 10 shows the comparison results of the damping ratios between SC walls and RC walls evaluated form test data. The damping ratios of SC structures are almost same as those of RC structure under SSE stress level, and the values are dramatically increased according to the stress level increment. Based on these test results, it is believed that the damping ratio of the SC structure can be used similarly to that of the RC structure. However, this conclusion is based on limited test data, therefore considering the high variability due to lack of data, the damping ratio of the SC structure needs to be set lower than that of the RC structure. Therefore, KEPIC SNG (2015) proposed a damping ratio of 6% for the SSE stress level of the SC structure.

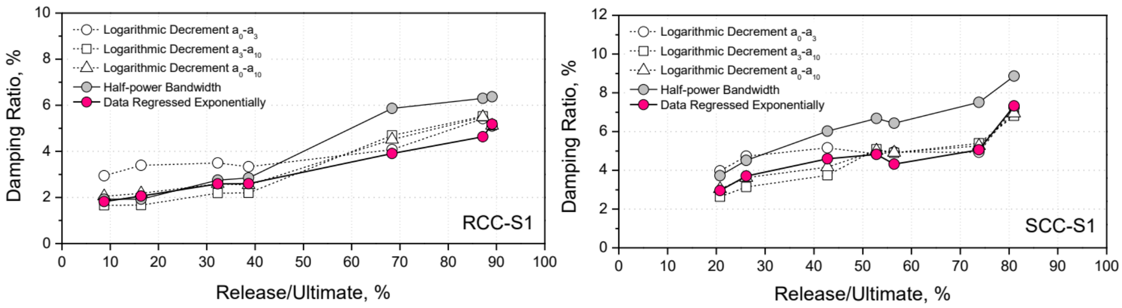


Figure 9. Damping ratio evaluation using various methods for RC and SC specimens

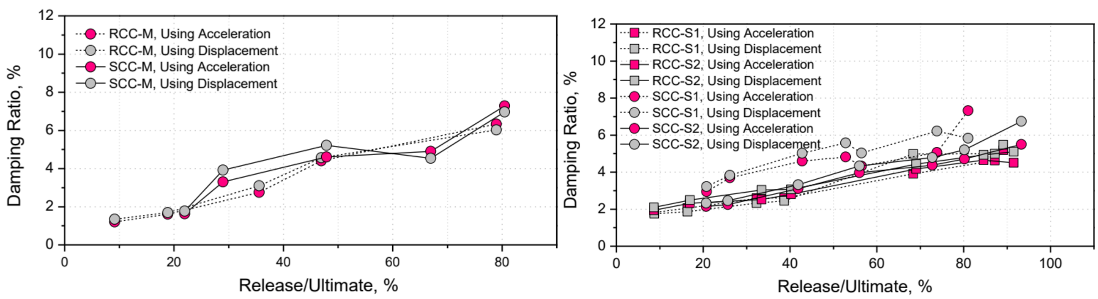


Figure 10. Calculated damping ratios for bending-behaved and shear-behaved specimens

SHAKING TABLE TESTS OF SC WALL

In the test by Cho et al. (2015), a test specimen as shown in Figure 11 is manufactured and a dynamic test is performed on a shaking table. No additional mass is applied to the upper slab of the test specimen, which implies that despite the high acceleration amplitude, the stress level in the web wall may appear low.

Measured acceleration time histories are converted to the transfer functions and then evaluated by using experimental modal analysis technique. As a result, the damping ratio of the specimen is evaluated to be more than 4%, and the overall stress level of the test specimen was found to be elastic. Therefore, they propose a value of 4% as the damping ratio of the SC structure for the OBE stress level.

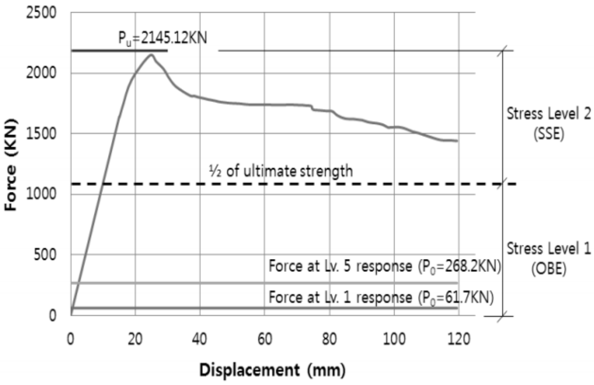


Figure 11. Dynamic test set-up and damping ratios according to stress level

CONCLUSION

Multiple Experimental investigations including cyclic tests, free vibration tests, and shaking table tests, are carried out to identify the equivalent viscous damping ratio for SC structure. Although the test data may not be sufficient to draw a definitive conclusion about the damping ratio, it can still serve as a basis for the damping ratio of SSE and OBE stress levels from the test results conducted so far.

Based on the test results, the dynamic characteristics of the SC structure, including the damping ratio, are almost the same as those of the RC structure, and shows superior results in terms of energy dissipation capacity. Therefore, the Korean SC modular structure design standard, KEPIC SNG, suggests 6% and 4% as damping ratios for the SSE stress level and the OBE stress level, respectively. This requirement differs from the specification of AISC N690 Appendix N9 and JEAG 4618. The best way to resolve the gap between the specification of these codes is to secure more test data and then comprehensively analysis it. Future experimental investigations on the damping ratio of SC structure is planned through an international collaborative research among Korea Hydro & Nuclear Power Co. (KHNP), Korea Society of Steel Construction (KSSC) and Purdue University, with the objective of achieving a more precise and comprehensive understanding of their damping characteristics.

Acknowledgement

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