Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 26, No. 3, pp. 277-285, May 31, 2020, ISSN 1229-3431(Print) / ISSN 2287-3341(Online) https://doi.org/10.7837/kosomes.2020.26.3.277

Performance Evaluation of Seismic Stopper using Structural Analysis and AC156 Test Method

Hyun-su Ryu*†
* Professor, School of Industrial Engineering and Naval Architecture, Changwon National University, Changwon, 51140, Korea

Abstract : *Recently, studies have been actively conducted on seismic design and improvement of the seismic performance of bridges, buildings, factories, and plants. In particular, heavy items that are being manufactured or waiting to be shipped from factories (such as generators, engines, and boilers) must be equipped with seismic stoppers to prevent them from moving or falling during an earthquake. Seismic stoppers should be suitably determined by the size and weight of these heavy items; however, they have no general design standard. In this study, structural analyses and seismic tests were conducted to evaluate the performance of newly designed seismic stoppers. Structural analysis was performed on three stopper models to estimate the external load at which the yield stress of the material was not exceeded. Based on the analysis results, a seismic test of the stopper was carried out in accordance with the AC156 test method. Finally, product specifications for all three seismic stopper models were determined and their static/dynamic load performance was evaluated.*

Key Words : *Seismic stopper, Seismic performance, Structural analysis, Structural safety, AC156 test method*

1. Introduction

Recently, studies have been actively conducted on seismic design and improvement of the seismic performance of bridges, buildings, factories, and plants. In the case of bridges, studies on seismic reinforcement methods using ductile reinforcement materials are being actively performed. Cho et al. (2017), through dynamic tests on columns reinforced with PolyUrea, confirmed that their seismic performance is improved and proposed a new method for seismic reinforcement. Studies on the seismic design and performance of buildings are mainly conducted for the establishment of design criteria, application of new materials and performance evaluation. The seismic design standards for domestic and Japanese building facilities have been compared, and a study on the application of seismic designs has been conducted (Jeon and Jang, 2005). Kim et al. (2015) verified the performance improvement effect in seismic members made of high strength steel through numerical analysis of two-dimensional and three-dimensional steel structural models. Additionally, to evaluate the seismic performance the dynamic response characteristics of riser pipes installed in a building was analyzed using the AC156 shake table test method (Jeon et al., 2017). Lee et al. (2017) improved the seismic design method of pipes by comparing the Cook method and the static system analysis method based on the seismic design criteria of fire-fighting facilities. Extensive studies to improve the seismic performance of plants are being conducted on various elements such as cranes, storage tanks, valves, and manifolds. Lee et al. (2011) analyzed the natural frequency and vibration phenomena through modal analysis of polar cranes installed in nuclear power plants and evaluated their seismic safety based on the analysis results. They also evaluated the seismic performance of a liquid storage tank through sloshing analysis. A seismic analysis study was carried out to evaluate whether butterfly valves for nuclear power plants were structurally safe under earthquake loads (Han et al., 2012). Lee and Kwak (2019) assessed the seismic strength of offshore subsea manifolds through the response spectrum analysis (RSA) and time history analysis (THA). Further, a number of studies have been conducted regarding the application of stoppers, which is one of the methods for improving the seismic performance. Studies on the stopper have been conducted in various fields. An ultimate strength assessment for foundations of bow chain stoppers (Chen, 2010), the design of a floating slab system equipped with stoppers (Park et al., 2011), and a structural analysis of the damper stoppers of a lock-up clutch (Oh et al., 2014) are representative examples. Research and developments related to seismic stoppers include mechanical stopper development, development of the double-stage yield

† hsryu@changwon.ac.kr, 055-213-3682

buckling restrained brace (DYB), and a study on an active mounting system. Dechant et al. (2017) proposed a new concept for low-frequency broadband with two mechanical stoppers, and Sun et al. (2018) experimentally studied the DYB, which is a reliable and practical alternatives to the conventional framing systems, to enhance the earthquake resistance of structures. Hong (2018) modeled an active mounting system for vibration reduction of the plate structure and confirmed the effective vibration reduction through simulations and experiments. Meanwhile, heavy items that are being manufactured or waiting to be shipped from the factory (such as generators, engines, and boilers) must be equipped with seismic stoppers to prevent them from moving or falling during an earthquake. Seismic stoppers should be suitably determined by the size and weight of these heavy items; however, there is no general design standard for them. In this study, structural analyses and seismic tests were conducted to evaluate the performance of newly designed seismic stoppers. The structural analysis was performed on three stopper models to estimate the external load with which the yield stress of the material was not exceeded. Based on the analysis results, a seismic test of the stopper was carried out in accordance with the AC156 test method. Finally, product specifications for all three seismic stopper models were determined and their static/dynamic load performance was evaluated.

2. Seismic stopper models

Seismic stoppers are installed with the vibration-proof system of heavy machines to prevent movement and falling of the equipment due to seismic loads as shown in Fig. 1. The seismic stopper covered in this study consists of bracket, stopper, shear bolt and assembly bolts as shown in Fig. 2, and the dimensions are listed in Table 1. In this study, three seismic stopper types were proposed so that the user could select the appropriate seismic stopper type according to the weight of the machine. The bracket and stopper are made of SS400 carbon steel plate. The bottom surface of the bracket of the seismic stopper is bolted to the pad and the vertical surface of the bracket prevents the machine from moving horizontally. The stopper is bolted to the vertical face of the bracket and serves to limit the vertical movement of the machine. In addition, the stopper is designed so that its position can be adjusted according to the height of the vibration-proof foundation.

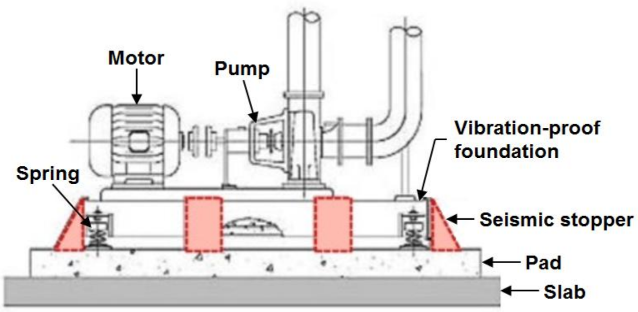
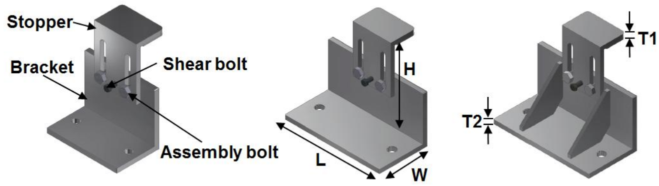


Fig. 1. Example of seismic stopper installation.



(a) BTST-1000 (b) BTST-2200 (c) BTST-5600

Fig. 2. Seismic stopper configuration.

Table 1. Types and dimensions of seismic stoppers

Type	Height (mm)	Length (mm)	Width (mm)	Thickness (mm)	
				T1	T2
BTST-1000	225	200	176	10	10
BTST-2200	225	300	206	10	12
BTST-5600	225	300	206	10	12

3. Structural analysis of seismic stopper

3.1 Purpose of structural analysis

In this study, a series of structural analyses were performed to pre-estimate the static and dynamic test loads of the proposed seismic stopper model. Static analyses were performed to calculate the maximum allowable load applicable to each seismic stopper model using a commercial finite-element analysis software (ABAQUS). The maximum allowable load was divided into two cases, horizontal direction and vertical direction. Based on the structural analysis results, the maximum allowable load was determined as the maximum external load with which the yield stress of the material was not exceeded.

3.2 Finite elements model

To verify the efficiency of analysis time, a finite element model of type BTST-5600 was created as shown in Fig. 3, and the preliminary structural analysis was performed. Bracket, stoppers and bolts were generated by creating a part-mesh for each part, and the whole seismic stopper model was created through assembly methods with contact and fixed conditions. As a result, the analysis time was of approximately 150 min, and the solution did not converge for some of the analysis cases owing to the tight mesh size.

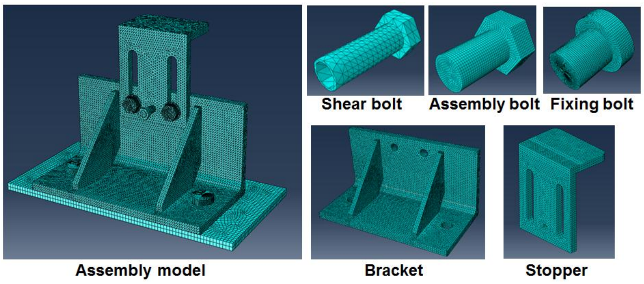
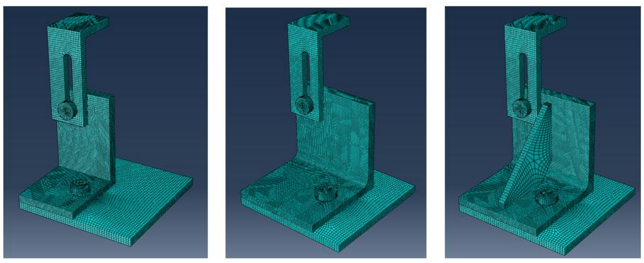


Fig. 3. Finite element model for preliminary analysis.

To solve this problem, a left and right symmetry model was created to significantly reduce the number of finite elements and secure the efficiency of analysis time, as shown in Fig. 4. The symmetric model reduced the number of elements by up to 80 % and reduced the analysis time to approximately 40 min. The material properties were taken from the internal test data provided by the stopper manufacturer, and the values listed in Table 2 were applied to the finite element model.



(a) BTST-1000 (b) BTST-2200 (c) BTST-5600

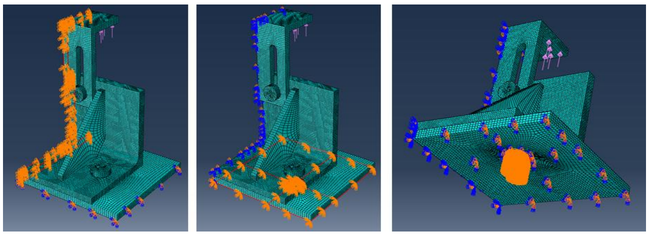
Fig. 4. Finite element symmetric models.

Table 2. Material properties (SS400)

Property	Value	Unit
Young's modulus	210	GPa
Yield stress	215	MPa
Tensile strength	400 ~ 510	MPa
Density	7.86×10^{-6}	kg/mm^3
Poisson's ratio	0.26	-

3.3 Boundary and external load conditions

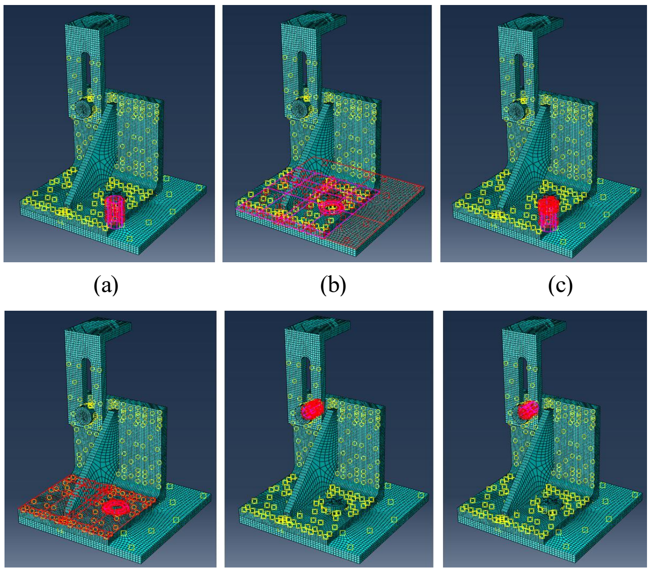
The boundary conditions for the structural analysis were applied considering the symmetry of the model and the coupling state of the base and fixing bolts, as shown in Fig. 5.



(a) Symmetry (b) Base fixed (c) Fixing bolt

Fig. 5. Boundary conditions (BTST-5600).

In addition, to consider the fastening state of the bolts, bracket, and stopper, the contact conditions of each part were applied as shown in Fig. 6. These boundary conditions were also applied to the BTST-1000 and BTST-2200 models.

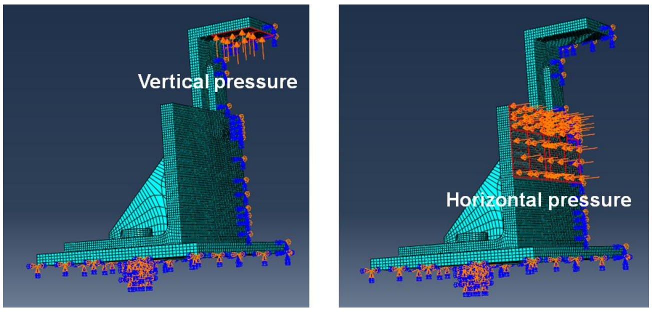


(a) (b) (c)

(d) (e) (f)

Fig. 6. Contact conditions (BTST-5600): (a) Base & fixing bolt, (b) base & bracket, (c) bracket & fixing bolt, (d) bracket & fixing bolthead, (e) bracket & assembly bolt, (f) stopper & assembly bolt.

The load applied to the structural analysis was divided into the case of vertical pressure acting on the stopper and that of horizontal pressure acting on the bracket, as shown in Fig. 7. The area under load was set considering the area where the seismic test equipment can apply an external force to the stopper and bracket. Table 3 presents the load range and area applied to the structural analysis for each seismic stopper type.



(a) Vertical pressure (b) Horizontal pressure

Fig. 7. External load conditions (BTST-5600).

Table 3. Applied loads and area

Stopper type	Vertical		Horizontal	
	Pressure (MPa)	Area (mm^2)	Pressure (MPa)	Area (mm^2)
BTST-1000	0.5-3.2	6000	0.25-2.0	15000
BTST-2200	1.0-3.6	6000	1.0-1.9	22500
BTST-5600	1.3-3.7	6000	1.5-3.8	22500

3.4 Structural analysis results

The structural analysis was performed within the load ranges listed in Table 3. The analysis proceeded by increasing the load gradually, and the load at which the maximum stress did not exceed the allowable stress of the material was determined as the maximum allowable load of the seismic stopper. Figs. 8 and 9 show the analysis results of the maximum stress according to the applied load for each stopper type.

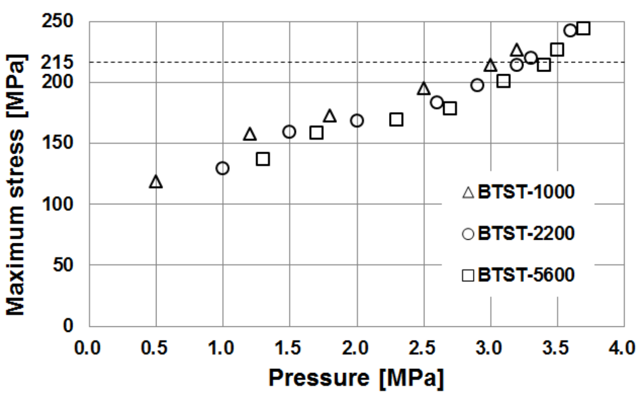


Fig. 8. Analysis results for vertical pressure.

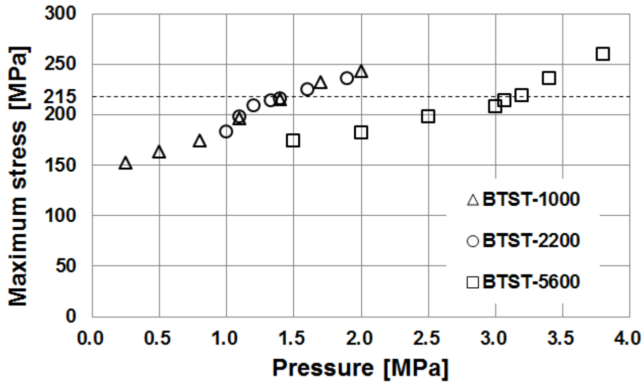


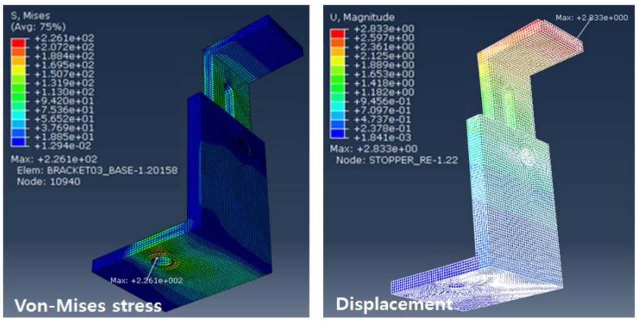
Fig. 9. Analysis results for horizontal pressure.

In the case of vertical loads, the load areas were the same for all three stopper types. As shown in Fig. 8, the larger the stiffness of the bracket was, the greater the increase in the allowable load. In the case of horizontal loads, the allowable pressures of BTST-1000 and BTST-2200 were calculated in a similar way. It can be observed that the allowable load of BTST-2200 is 43 % larger when the pressure is converted into external force because its pressure area is 50 % larger than that of BTST-1000. In addition, as shown in Fig. 9, the allowable pressure of BTST-5600 was calculated to be 2.2 times larger than that of the other two stopper types. It can be observed that, unlike the case of the vertical load, when the horizontal load is applied, the reinforcement of the bracket can sufficiently support the horizontal load. Table 4 presents the allowable load and the corresponding maximum stress value for each stopper type.

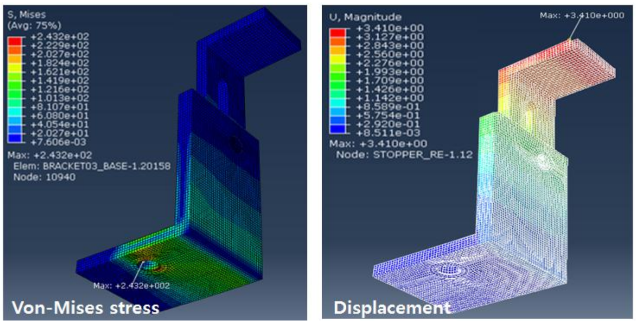
Table 4. Allowable load and maximum stress

Stopper type	Vertical		Horizontal	
	Load (kN)	Max. stress (MPa)	Load (kN)	Max. stress (MPa)
BTST-1000	18.0	213.5	21.0	214.7
BTST-2200	19.2	214.2	29.9	213.9
BTST-5600	20.4	213.9	69.1	214.2

In the case of BTST-1000, the maximum stress occurs at the fastening area of the bracket and fixing bolt when the vertical load is applied, and the maximum stress occurs at this area even when the horizontal load is applied as shown in Fig. 10. However, when the vertical load is applied, it can be observed that a considerable level of stress is distributed in the vertical member of the stopper as shown in Fig. 10(a).



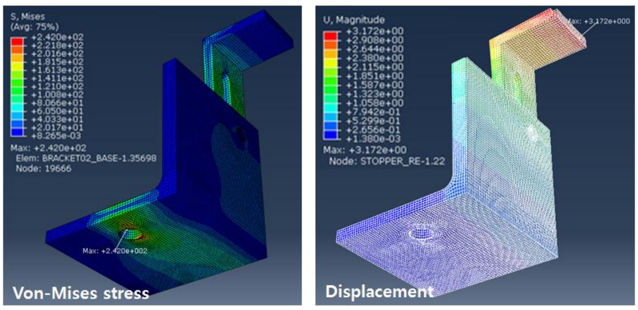
(a) Analysis results with vertical load



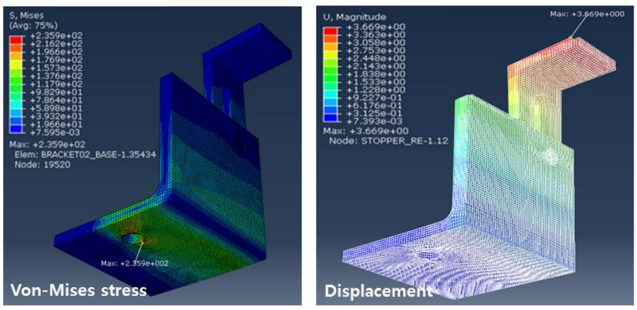
(b) Analysis results with horizontal load

Fig. 10. Structural analysis results of BTST-1000.

In the case of BTST-2200, as shown in Fig. 11, the stress distribution and shape of deformation are similar to those calculated for BTST-1000.



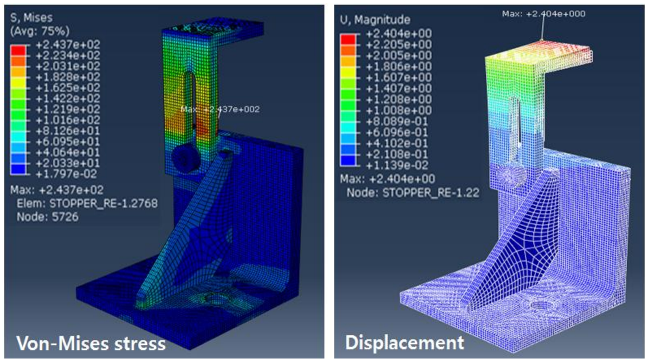
(a) Analysis results with vertical load



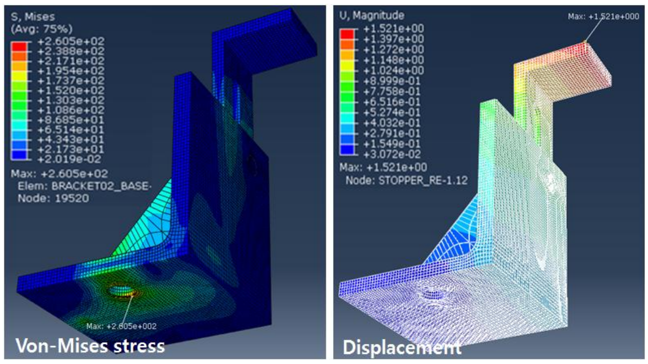
(b) Analysis results with horizontal load

Fig. 11. Structural analysis results of BTST-2200.

Fig. 12 shows analysis results of BTST-5600. When the vertical load was applied, the maximum stress occurred in the lower part of the stopper's vertical plate as shown in Fig. 12(a). In this case, the vertical load is not transmitted to the lower part of the bracket owing to the reinforcement attached to the bracket. Moreover, because most of the vertical load acts on the vertical plate of the stopper, it can be seen that the stress is concentrated. In the case of horizontal load, as shown in Fig. 12(b), most of the load is transmitted through the reinforcement to the bottom of the bracket, and the maximum stress occurs near the bracket's fixing hole.



(a) Analysis results with vertical load



(b) Analysis results with horizontal load

Fig. 12. Structural analysis results of BTST-5600.

The above structural analysis results were used to prepare the static test conditions of the seismic stopper.

4. Seismic test of stopper

4.1 Static test of seismic stopper

Based on the structural analysis results, static tests (Hwang et al., 1997) were performed as shown in Fig. 13 considering the test load for each seismic stopper type. After the seismic stopper was bolted to the test bed, the displacement of the bracket was measured by linear variable differential transformer (LVDT) while applying a static horizontal load to the vertical surface of the bracket using a hydraulic actuator. In the case of the vertical load, the displacement occurring in the horizontal plate of the bracket was measured while applying a load to the horizontal surface of the stopper.

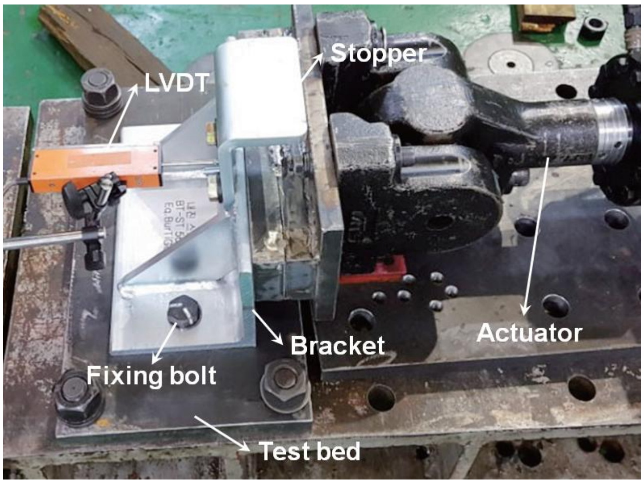


Fig. 13. Configuration of static test.

The static test proceeded up to the allowable load presented in Table 4, and after releasing the load, the dimensions of the seismic stopper were measured to confirm that plastic deformation did not occur. The static test results for the horizontal and vertical loads are shown in Figs. 14 and 15.

As the load increases, the displacement increases almost linearly, and the displacement of BTST-5600 is the smallest under the same load. Based on the static test results, the static performance of the seismic stopper was derived as presented in Table 5.

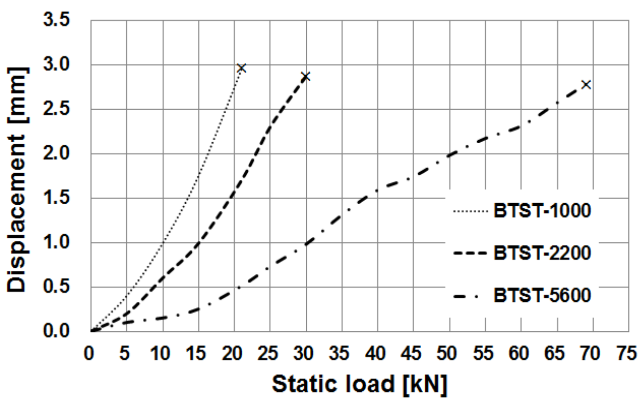


Fig. 14. Static test results with horizontal load.

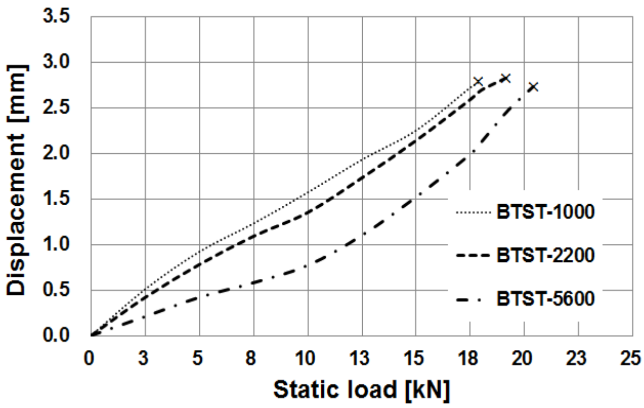


Fig. 15. Static test results with vertical load.

Table 5. Static performance of seismic stoppers

Stopper type	Vertical		Horizontal	
	Load (kgf)	displacement (mm)	Load (kgf)	displacement (mm)
BTST-1000	1800	3	2100	3
BTST-2200	1900	3	3000	3
BTST-5600	2000	3	7000	3

4.2 Dynamic test of seismic stopper

In this study, the seismic test of stoppers was carried out in accordance with the AC156 test method (Kim and Jeong, 2017) to evaluate their dynamic load performance. The test was carried out using the shaking table of the Seismic Simulation Test Center (Busan, Korea). Table 6 lists the specifications of the shaking table and Fig. 16 shows the configuration of the dynamic test.

Table 6. Specification of shaking table

Items	Specification
Control degrees of freedom	6 DOF (X, Y, X, RX, RY, RZ)
Max. loading	30000 kg
Table size	4.0 m × 4.0 m
Max. displacement	H = ±300 mm , V = ±150 mm
Max. velocity	H = 1.5 m/s , V = 1.0 m/s
Max. acceleration	H = ±1.5 g , V = ±1.0 g
Frequency range	0.1-60 Hz
Excitation mechanism	Electro-hydraulic servo
Feedback data acquisition	32 channels

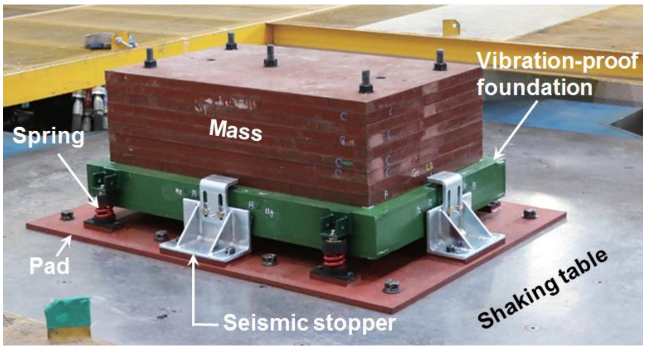


Fig. 16. Configuration of dynamic test.

Table 7 includes the shaking table test parameter according to the AC156 criteria. The shaking table was excited using the values of these parameters to simulate an artificial earthquake.

Table 7. Shaking table test parameter

Test criteria	S_{DS} (m/s^2)	z/h	Horizontal		Vertical	
			A_{FLX-H} (m/s^2)	A_{RIG-H} (m/s^2)	A_{FLX-V} (m/s^2)	A_{RIG-V} (m/s^2)
ICC-ES AC156	9.81	1.00	15.69	11.77	6.57	2.65

The procedure for the shaking table test (Kim and Jeong, 2017) is as follows:

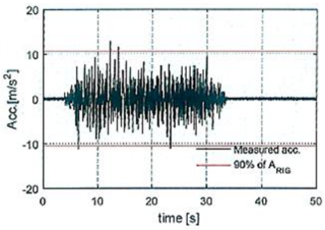
(A) Inspection before test
   (1) Visual inspection
(B) Resonant frequency search test
   (1) Excitation: Low-level amplitude (0.98 m/s^2 peak input) single-axis sinusoidal sweeping from 1.0 to 50.0 Hz
   (2) Direction and sequence: Longitudinal, lateral, and vertical, independently, not simultaneously
   (3) Analysis method: Transfer function estimation using input and output accelerations
(C) Multi-frequency seismic simulation test
   (1) Excitation: Artificial earthquake generated according to the required response spectrum (RRS)
   (2) Direction and sequence: Longitudinal, lateral, and vertical, simultaneously
   (3) Tested response spectrum (TRS) and cross-correlation verification of excitation motion
(D) Inspection after test
   (1) Visual inspection

As a result of the resonant frequency search test, the resonance frequencies of each stopper were determined as presented in Table 8.

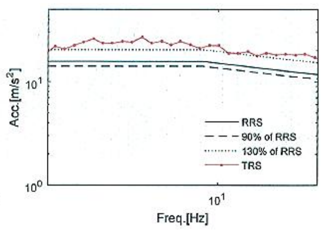
Table 8. Results of resonant frequency search test

Stopper type	Resonance frequency (Hz)		
	Longitudinal, X (Side-to-side)	Lateral, Y (Front-to-back)	Vertical (Z)
BTST-1000	4.50	4.00	6.00
BTST-2200	3.50	2.75	5.00
BTST-5600	3.25	2.50	4.50

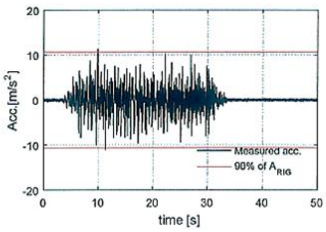
Fig. 17 shows the acceleration time history and test response spectrum as the results of the multi-frequency seismic simulation test for BTST-5600. Fig. 18 shows the result of visual inspections for the four seismic stoppers.



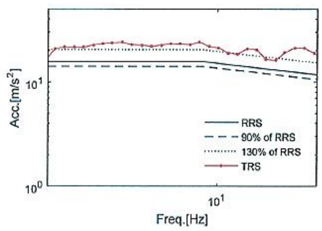
(a) Acceleration time history-X



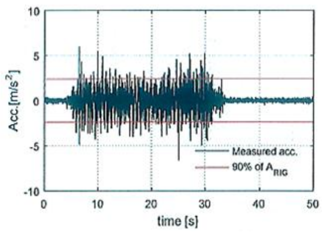
(b) Response spectrum-X



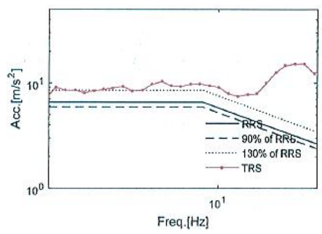
(c) Acceleration time history-Y



(d) Response spectrum-Y



(e) Acceleration time history-Z



(f) Response spectrum-Z

Fig. 17. Acceleration time history and TRS of BTST-5600.

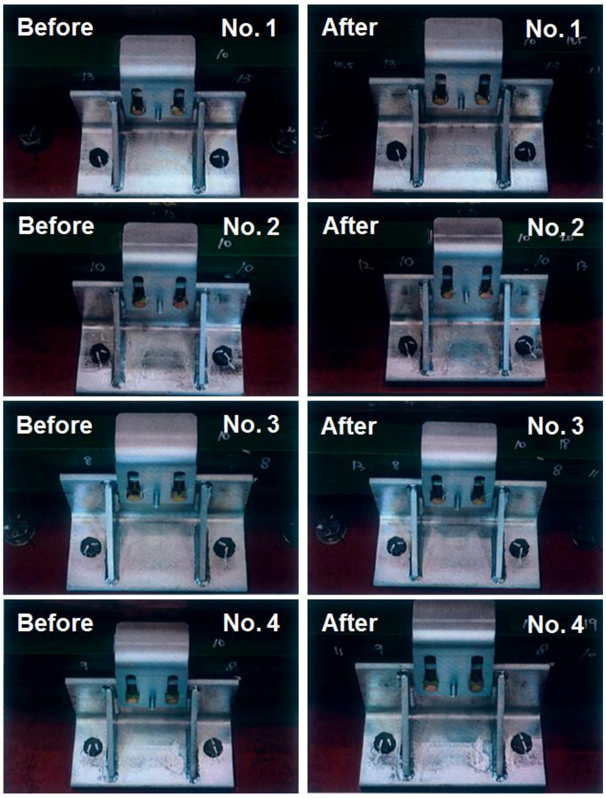


Fig. 18. Visual inspection of BTST-5600.

As a result of verifying TRS and time history of the measured acceleration values in the X, Y, and Z directions, as shown in Fig. 17, it was confirmed that the intended artificial earthquake phenomenon was well simulated. This means that a valid test has been conducted. In addition, as a result of the visual inspection, as shown in Fig. 18, no major structural failure was observed in the installed stoppers. Moreover, major structural failures were not observed in the visual inspection of the BTST-1000 and BTST-2200 models. Based on the above test results, the dynamic load performance of the seismic stoppers was determined as listed in Table 9.

Table 9. Dynamic performance of seismic stoppers

Stopper type	Dynamic load (kgf)	Design spectral response acceleration, z/h=1 (m/s^2)
BTST-1000	2000	4.90
BTST-1000	1000	9.80
BTST-2200	2200	4.90
BTST-2200	1100	9.80
BTST-5600	5600	4.90
BTST-5600	2800	9.80

5. Conclusions

In this study, structural analysis and seismic tests were performed to evaluate the performance of the newly designed seismic stoppers. The major results obtained are as follows:

(1) To increase the efficiency of analysis time, symmetrical finite element models of seismic stoppers were proposed, the number of elements was reduced by 80 %, and the analysis time was reduced to approximately 40 min.
(2) Effective contact conditions and fixed boundary conditions for structural analysis of the seismic stoppers were proposed and the maximum load with which the allowable stress of the material was not exceeded was calculated for each stopper model through a series of structural analyses.
(3) Based on the structural analysis results, static load tests were performed for each seismic stopper model and the structural analysis method was verified. In addition, the static load performance of the seismic stopper was determined based on the static test results.
(4) The resonant frequency of each stopper model was derived by performing the dynamic performance test of the seismic stopper in accordance with the AC156 test procedure, and it was confirmed through visual inspection that there were no major structural failures of the seismic stoppers.
(5) Finally, product specifications for all the newly designed three seismic stopper models were determined and the load performance was evaluated.
(6) The structure analysis method and performance evaluation test method of the seismic stopper proposed in this study could be used in the future as an effective tool in the stage of change or verification of a new stopper design. In addition, further research on the development of a dynamic analysis method that can simulate the seismic stopper dynamic test should be conducted.

Acknowledgements

This research was supported by Changwon National University in 2019~2020.

References

[1] Chen, S. G.(2010), Ultimate Strength Assessment for Foundation of Bow Chain stopper, M.S. Thesis, Ulsan

University, Ulsan, Korea.
[2] Cho, C. M., D. S. Lee, T. K. Kim, and J. H. Kim(2017), Pseudo Dynamic Test Study on Seismic Performance Evaluation of RC Columns Retrofitted by PolyUrea, Journal of the Korean Society of Civil Engineers, Vol. 37, No. 2, pp. 289-301.
[3] Dechant, E., F. Fedulov, D. V. Chashin, L. Y. Fetisov, Y. K. Fetisov, and M. Shamonin(2017), Low-frequency, broadband vibration energy harvester using coupled oscillators and frequency up-conversion by mechanical stoppers, Journal of Smart Materials and Structures, Vol. 26, pp. 1-11.
[4] Han, S. U., J. T. Ahn, K. C. Lee, and S. H. Han(2012), Theoretical Seismic Analysis of Butterfly Valve for Nuclear Power Plant, Transactions of the Korean Society of Mechanical Engineers-A, Vol. 36, No. 9, pp. 1009-1015.
[5] Hong, D. W.(2018), Modeling & Analysis of Plate Structures with Active Mounting System for Vibration Reduction Control, M.S. Thesis, Yeungnam University, Gyeongsan, Korea.
[6] Hwang, C. H., C. Y. Park, S. R. Hah, and C. W. Kim(1997), Static Structural Test and Analysis of Basic Trainer, Journal of The Korean Society for Aeronautical and Space Sciences, Vol. 25, No. 3, pp. 123-130.
[7] Jeon, B. G., Y. S. Jeong, S. W. Kim, M. U. Gim, and J. H. Cheung(2017), Shake Table Tests for Seismic Performance Evaluation of Fire Protection Riser Pipes, Proceedings of the Architectural institute of Korea, Vol. 37, No. 2, pp. 1293-1294.
[8] Jeon, J. H. and C. I. Jang(2005), Seismic Design Standards and Application Examples of Domestic Building Facilities, The magazine of the Society of Air-conditioning and Refrigerating Engineers of Korea, Vol. 34, No. 10, pp. 9-14.
[9] Kim, J. B. and J. H. Jeong(2017), Introduction to Seismic Simulation Test Center and Experimental Cases, Journal of Computational Structural Engineering, Vol. 30, No. 2, pp. 5-10.
[10] Kim, M. J., T. U. Ha, and S. H. Cho(2015), Examination of Seismic Performance for Structure with Seismic Members made by High Strength Steel, Journal of Korean Society of Steel Construction, Vol. 27, No. 3, pp. 281-288.
[11] Lee, E. H. and S. Y. Kwak(2019), Seismic Access of Offshore Subsea Manifold using RSA and THA Seismic Analysis Results for Simplified Model, Journal of Computational Structural Engineering Institute of Korea, Vol. 32, No. 1, pp. 7-16.
[12] Lee, J. O., H. K. Kim, and S. B. Cho(2017), A Study on Performance-based Seismic Design Method of Fire Extinguishing Pipe System, Journal of Fire Science and engineering, Vol. 31, No. 4, pp. 86-94.
[13] Lee, W. H., J. R. Cho, M. S. Roh, and J. H. Ryu(2011), Seismic Analysis of Nuclear Power Equipment Related to Design, Transactions of the Korean Society of Mechanical Engineers-A, Vol. 35, No. 3, pp. 317-323.
[14] Oh, M. S., S. H. Nam, and B. G. Lee(2014), Structure Analysis for Damper stopper of Lock-up Clutch, Journal of the Korea Academia-Industrial cooperation Society, Vol. 15, No. 4, pp. 1865-1870.
[15] Park, S. J., C. N. Ma, M. G. Park, and D. H. Lee(2011), Stopper equipped with a Low Vibration Floating Slab System Design, Proceedings of the Korean Society for Railway, Hoengseong, Korea, May 2011, pp. 753-756.
[16] Sun, J., P. Pan, and H. Wang(2018), Development and experimental validation of an assembled steel double-stage yield buckling restrained brace, Journal of Constructional Steel Research, Vol. 145, pp. 330-340.

Received : 2020. 03. 24.
Revised : 2020. 05. 01.
Accepted : 2020. 05. 28.