PERFORMANCE VERIFICATION TESTS OF SPRING DAMPER FOR A CURVED CABLE-STAYED BRIDGE

Kazuo Endo[1] and Shigeki Unjoh[2]

Abstract

A spring damper with trigger function and self-restoration function is going to be installed at a curved cable-stayed bridge to raise the seismic performance. Since this type of devise has never been used for a bridge so far, two types of loading tests of the spring damper were performed to verify the performance under the conditions in the actual bridge; one was a cyclic loading test and the other was a long-term constant loading test. The cyclic loading test was to identify the force-displacement relationship, and its temperature and loading-speed dependencies, verifying the performance in case of a large-scale earthquake. The long-term constant loading test was to identify the durability of the spring damper, verifying the performance in case of a dead load condition. As a result, it was verified that the spring damper could meet the specified performance criteria under the conditions in the actual bridge although a minor temperature dependency in the force-displacement relationship was found.

Introduction

The Yabegawa Bridge (provisional name) is a PC cable-stayed bridge being constructed in Kyushu, Japan. Since the bridge is designed to have a curved girder in horizontal alignment as shown in Figure 1, constant horizontal force is always applied to the girder at the tower supports due to the transverse components of the stay cable tension forces. Accordingly, in case of a dead load condition, the tower supports need to resist the constant horizontal force acting from the girder. On the other hand, in case of a large-scale earthquake, it is desirable for the tower supports and the girder to allow the displacement of the girder in order to mitigate the seismic force. Therefore, a spring damper with trigger function and self-restoration function installed at the tower supports is going to be adopted in the design. Expected behavior of the girder at the tower supports is illustrated in Figure 2.

The designed spring damper is schematized in Figure 3. The spring damper is mainly composed of a steel annular cylinder, a steel piston, and silicon resign filling pressed into the cylinder. The mechanism of the spring damper utilizes the compressibility of the filling. The spring damper is expected to behave in the following manner; the piston-rod of the spring damper does not move until a certain force level (trigger force) during a dead load condition, then, the piston moves into the cylinder when the force

---

[1] Senior Research Engineer, Earthquake Engineering Research Team, Public Works Research Institute
[2] Team Leader, ditto

increases beyond the trigger level during a large-scale earthquake, and finally, the piston returns to its original position after the earthquake subsides. The expected force-displacement relationship is described in Figure 4.

Since this type of devise has never been used for a bridge so far, two types of loading tests of the spring damper were performed to verify the performance under the conditions in the actual bridge; one was a cyclic loading test and the other was a long-term constant loading test. The cyclic loading test was to identify the force-displacement relationship, its temperature and loading-speed dependencies and the durability, verifying the performance in case of a large-scale earthquake. The long-term constant loading test was to identify the durability of the spring damper, verifying the performance in case of a dead load condition (Yokomine et al., 2004).

Performance Criteria

For application of the spring damper to the bridge, the following four performance criteria were specified.

(1) Force-displacement relationship should be the one with trigger function and self-restoration function.
(2) Temperature and loading-speed dependencies of the force-displacement relationship should be small enough to be manageable for the bridge design.
(3) Force-displacement relationship should be stable in case of large-scale earthquakes.
(4) The damper should be durable under the cyclic loading condition in case of a large-scale earthquake as well as under the constant loading condition in case of a dead load condition.

Mechanism of Resisting Force Generation

Mechanism of resisting force generation of the spring damper is described in Figure 5. The resisting force acting on the piston (F) can be expressed as

$$F = P(A_1 - A_2) = PA_r \qquad (1)$$

where P is the filling pressure, A_1 is the section area of the piston-head, A_2 is the rod-side pressurized area of the piston-head, and A_r is the section area of the piston-rod. Based on equation (1), the change of the resisting force (ΔF) is

$$\Delta F = \Delta P A_r \qquad (2)$$

where the change of the resisting force (ΔP) is given by

$$\Delta P = R_{\Delta V} K = \frac{\Delta V}{V_s} K = \frac{A_r S}{V_s} K \qquad (3)$$

where $R_{\Delta V}$ is the volume change rate of the filling, K is the volume elastic modulus of the filling, ΔV is the rod ingression volume, S is the stroke of the piston, and V_S is the volume of the filling when S=0.

Scaling of Specimen

As mentioned earlier, the spring damper utilizes the compressibility of the filling and the resisting force is dominated by the filling pressure. Therefore, scaling of a scaled-down specimen focused on the filling pressure so that the pressure equaled between the specimen and the actual bridge. Scale factors of the specimen are tabulated in Table 1. The pressure of the specimen adjusted based on the scaling would equal to the one of the actual bridge, while the displacement of the specimen would be scaled down, as schematized in Figure 6. Scaling factor (N) was set as five due to the loading machine's capability. Properties of the spring damper and overview of the specimen are shown in Table 2 and Figure 7, respectively.

Cyclic Loading Test

Basic Characteristic Verification Test

20 cases of basic characteristic verification tests were performed with the specimen temperature and the loading speed being varied in each repetition case. Figure 8 shows the overall view of the testing apparatuses. The objectives of the tests were to identify the force-displacement relationship, and its temperature and loading-speed dependencies, verifying the performance in case of a large-scale earthquake. The loading displacement was 60mm in every case. The specimen temperature was set to be four patterns; +30, +15, -10 degrees C and room temperature. The loading speed was set to be five patterns; 0.5, 1mm/sec as static loading tests and 0.1, 0.3, 0.65Hz as dynamic loading tests. The number of loading cycles was one in the static loading tests whereas three in the dynamic loading tests. In the dynamic loading tests, only a compression force was applied to the specimen assuming actual behavior of the spring damper in the bridge as illustrated in Figure 9: the actuator was once away from the spring damper after pushing in the damper, then pushed in the damper again. Above experimental program was determined by the analysis results in case of a large-scale earthquake, temperature observation data at the bridge site, and the air-conditioner's capability. The specimen had been left in the air-conditioner's room for approximately 48 hours before the loading tests in order to stabilize its temperature. Besides, the specimen was installed in a heat-retention box with circulating the conditioned air during the loading tests. Figure 10 shows the cyclic loading tests overview.

Durability Verification Test Under 50-Cycle Loading

A durability verification test under 50-cycle loading was performed by using the same apparatuses as the basic characteristic verification test. The objectives of the test were to identify the stability of the force-displacement relationship and the durability of the spring damper under a 50-cycle loading condition, verifying the performance in case of a large-scale earthquake. The testing program was as follows; specimen temperature: room temperature, loading speed: 0.65Hz, loading displacement: 60mm, number of loading cycles: 50. The number of loading cycles, 50, was pursuant to the provision regarding the isolation bearing in the Japanese seismic design code for a highway bridge (Japan Road

Association, 2002).

Long-Term Constant Loading Test

A long-term constant loading test is being performed after completing the cyclic loading tests. The objective of the test was to identify the durability of the damper under a constant loading condition, verifying the performance in case of a dead load condition. Figure 11 shows the overall view of the testing apparatuses. The loading apparatus is mainly composed of two hydraulic jacks with different pressure receiving area and a hydraulic hose which connects the two jacks. Applied force to the specimen is dominated by steel weight and pressure receiving area ratio of two hydraulic jacks as illustrated in Figure 12. In order to obtain 230kN (see Table 2) as the applied force to the specimen, the steel weight and the area ratio of two hydraulic jacks were set to be about 8.8kN and 1/26 (Pressure Generation Jack /Loading Jack), respectively. Displacement of the spring damper, the applied load and the specimen temperature are being continuously recorded at five-minute intervals. The long-term constant loading test overview is shown in Figure 13.

Test Results

Results for Basic Characteristic Verification Test

Figure 14 indicates some results of the basic characteristic verification tests in terms of force-displacement relationship. Legends in the diagrams are defined as follows; *Trigger Force*: Force at the intersection of the first gradient line with the second gradient line. Average value is taken over three cycles for the dynamic loading tests. *Maximum Force*: The maximum force measured by the load cell. The maximum value is taken from the dynamic loading tests. *2nd Gradient*: Linear gradient derived from two points of 10% and 90% of the maximum displacement. *Disp. at Trigger Force*: Displacement at the trigger force. These diagrams reveal the following findings;

- ✓ All results with the specimen temperature and the loading speed being varied indicated the force-displacement relationship with trigger function and self-restoration function.
- ✓ The force-displacement relationship showed hysteresis loop: the second gradient lines during unloading were somewhat below the lines during loading. It is likely that primary reasons of this energy dissipation are the surface friction at sealing devises of the damper and viscous internal friction of the filling.
- ✓ There were some rises in the force just before the large displacement generated. It seems that this is because of the surface frictions at sealing devises of the damper and the inertial force of the cylinder. Nevertheless, the force itself was not so large; about 1.4 times of the trigger force and 0.5 times of the maximum force at the largest.
- ✓ The force-displacement in each cycle during dynamic loading was the almost same. It can be stated that the force-displacement relationship is stable under cyclic loading.

Temperature and loading-speed dependencies in terms of the trigger force and the maximum force are shown in Figure 15. Data at around eight degree C in the diagram (a) correspond to the results at room temperature. These diagrams suggest the following findings;

- ✓ Temperature dependency in the trigger force and the maximum force was found: the forces increased as the specimen temperature did. Since the spring damper utilizes the compressibility of the filling as mentioned above, it seems that this is due to the change in the filling pressure associated with the change in the temperature. The change rate (about 3kN/degree C), however, was stable and within the manageable range for the bridge design.
- ✓ Although the forces slightly increased as the loading speed did, the rate of increase was not significant: 8% at the largest. It can be said that loading-speed dependency in the trigger force and the maximum force is trivial.

Results for Durability Verification Test Under 50-Cycle Loading

Force-displacement relationship during the first (1-10) and the last (41-50) ten cycles and trigger force, the maximum force-number of cycles relationship of the durability verification test under 50-cycle loading are shown in Figure 16 and Figure 17, respectively. These figures suggest the following findings;

- ✓ The force-displacement relationship under 50-cycle dynamic loading was stable. It should be noted that, although the displacement looks unstable especially in the first 10 cycles, this instability is responsible for the loading machine's characteristic, not for the damper's characteristic.
- ✓ Although the trigger force and the maximum force slightly increased in proportion to the number of loading cycles, the increase rate was not significant: 5% at the largest. It is likely that this is due to the increased temperature of the filling associated with the cyclic loading.
- ✓ After completing the test under 50-cycle loading, no malfunction in the appearance of the damper, such as filling leak, was seen.

Results for Long-Term Constant Loading Test

Figure 18 shows about five-month's results for the long-term loading test still in progress; fluctuations of the applied force to the specimen, the specimen temperature and the displacement. Legends in the diagrams are defined as follows; *Daily Mean*: Mean value of daily five-minute interval data. *Daily Maximum*: The maximum value of daily five-minute interval data. *Daily Minimum*: The minimum value of daily five-minute interval data. Based on the Figure 18, the following findings were obtained;

- ✓ The displacement has been stable and no creep has been seen under long-term constant loading.
- ✓ The applied force to the specimen decreased as the specimen temperature did. This decrease in the force seems to be attributable to the oil pressure decrease of the jack associated with the surface friction at sealing devises and the oil volume decrease due to the temperature change. The change of the applied force, however, is not so significant, approximately 10 kN and can be controlled by steel weight.
- ✓ No malfunction in the appearance of the damper, such as filling leak, has been observed so far.

Conclusions

This paper presented performance verification tests of the spring damper with trigger function and self-restoration function for a curved cable-stayed bridge under the conditions in the actual bridge. After performing two types of loading tests; cyclic loading tests verifying the performance in case of a large-scale earthquake and a long-term constant loading test verifying the performance in case of a dead load condition, the following major conclusions were obtained;

- ✓ All results by the cyclic loading tests with the specimen temperature and the loading speed being varied indicated the force-displacement relationship with trigger function and self-restoration function.
- ✓ Although minor temperature dependency in the trigger force and the maximum force was found, the change rate was stable and within the manageable range for the bridge design.
- ✓ The force-displacement relationship under the 50-cycle loading test was stable.
- ✓ The displacement has been stable and no creep has been seen under long-term constant loading.
- ✓ It seems reasonable to state that the spring damper can meet the specified performance criteria under the conditions in the actual bridge.

Acknowledgments

The Kyushu Regional Development Bureau, the Ministry of Land, Infrastructure and Transport Government, developed the spring damper and funded the tests presented in this paper. The authors wish to appreciate the Government, especially extend thanks to Mr. Masaji Yokomine, General Manager, the Government's Ariakekai-engan-doro Branch Office, and Mr. Yuuki Kishi, engineer, the Japan Bridge Engineering Center, for their assistance in performing the tests.

References

Yokomine, M., Unjoh, S., Endo, K., Kishi T.(2004), "Performance Verification Tests of Spring Damper for a Curved Cable-Stayed Bridge." *Civil Engineering Journal*, Vol. 48, Public Works Research Center, Japan, (in Japanese).

Japan Road Association (ed.) (2002). *Specifications for Highway Bridges Part V Seismic Design*, Maruzen Co., Ltd., Tokyo

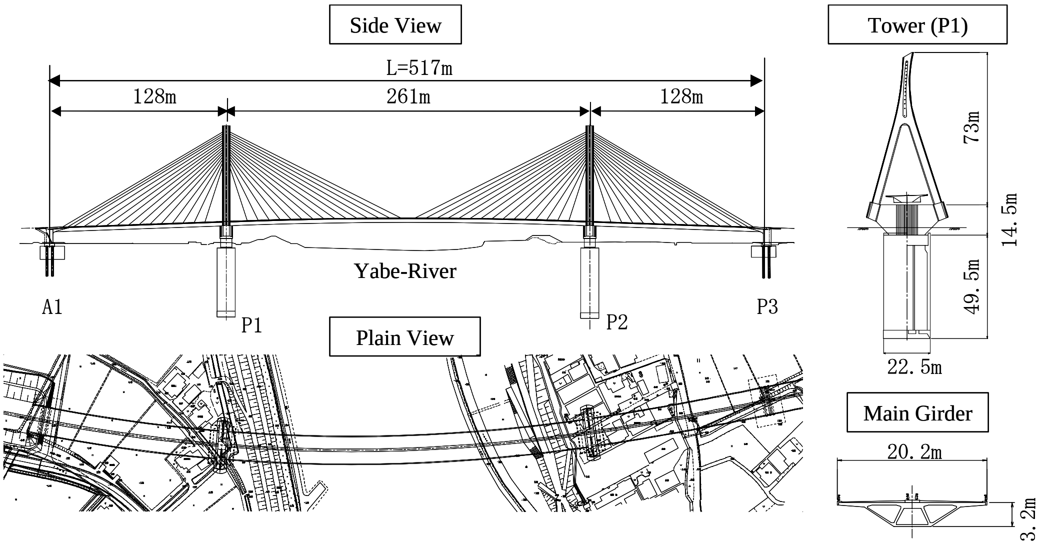
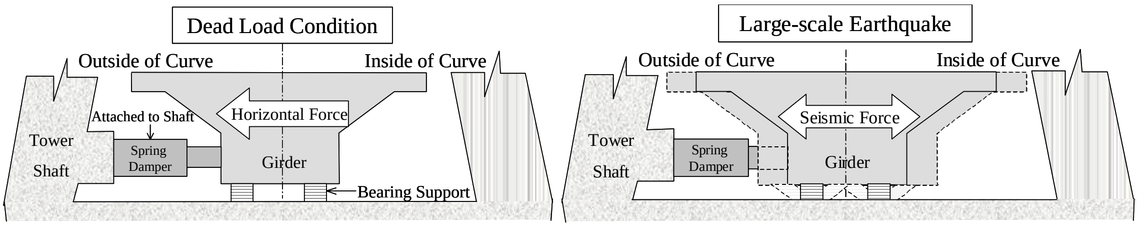


Fig.1 Overview, Yabegawa Bridge



- Resist Horizontal Force
- Don't Allow Displacement of Girder

- Allow Displacement of Girder to Mitigate Seismic Force
- Restore Girder to its Original Position after E.Q.

Fig.2 Expected Behavior of Girder at Tower Support

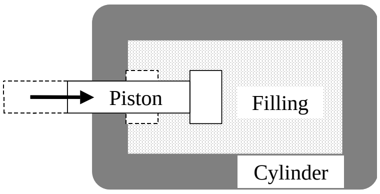


Fig.3 Schema of Spring Damper

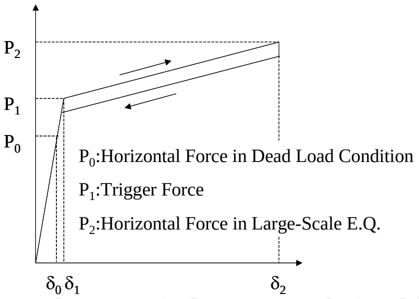


Fig.4 Expected Force-Displacement Relationship

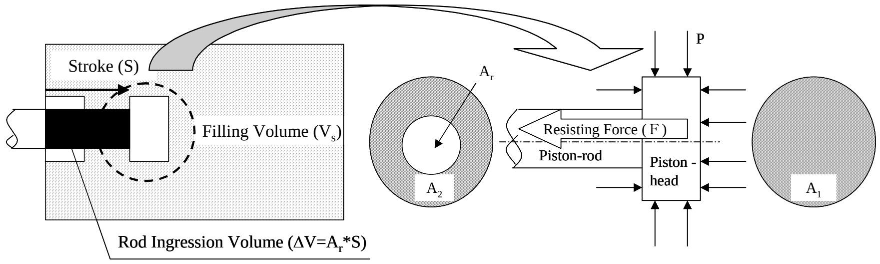


Fig.5 Mechanism of Resisting Force Generation

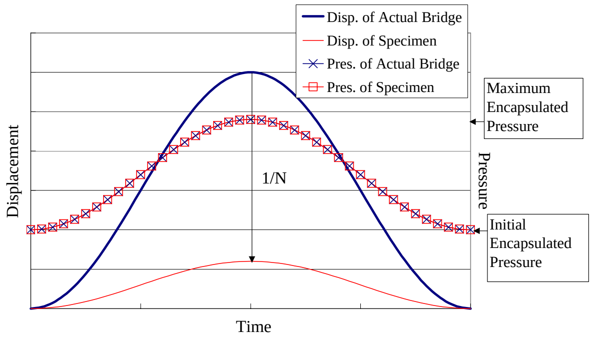


Fig.6 Pressure and Displacement Change of Spring Damper

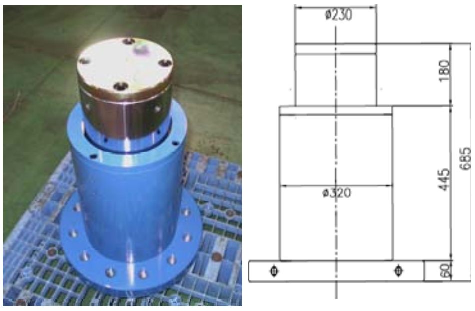
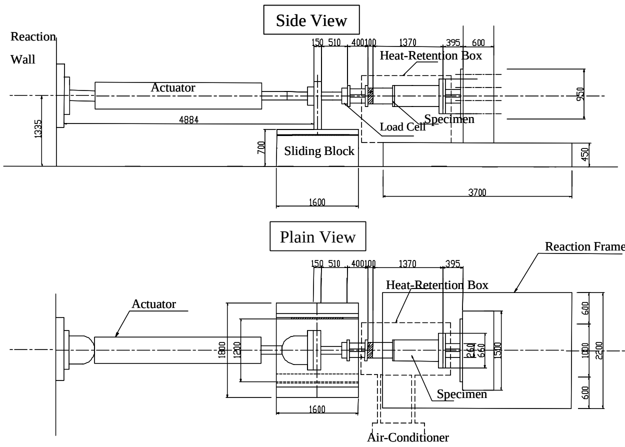


Fig.7 Specimen Overview



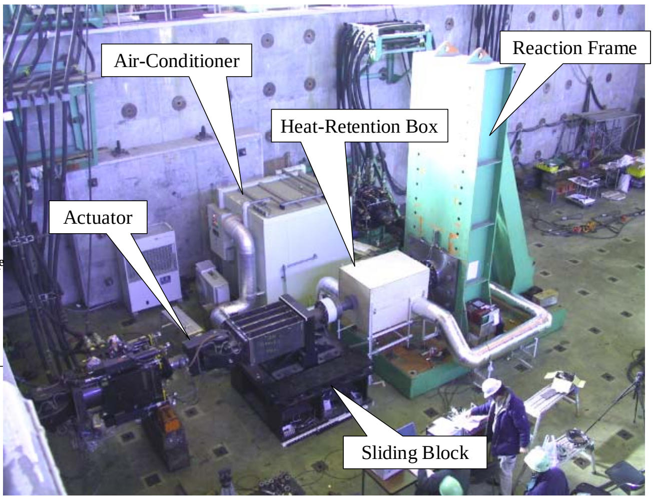
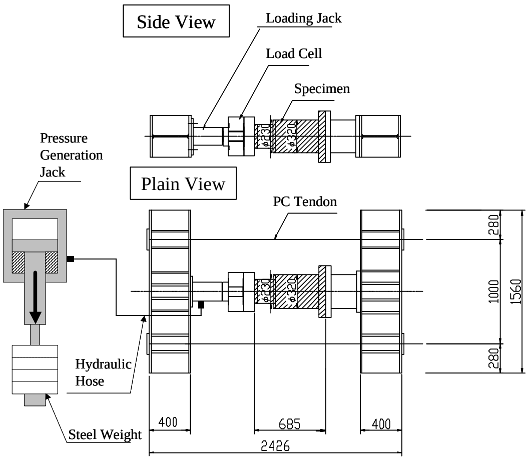


Fig.8 Testing Apparatuses for Cyclic Loading Test

Fig.10 Cyclic Loading Test Overview



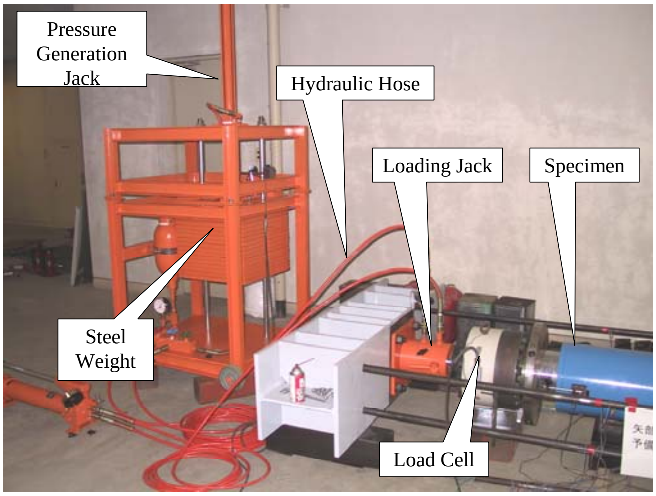


Fig.11 Testing Apparatuses for Long-Term Constant Loading Test

Fig.13 Long-Term Constant Loading Test Overview

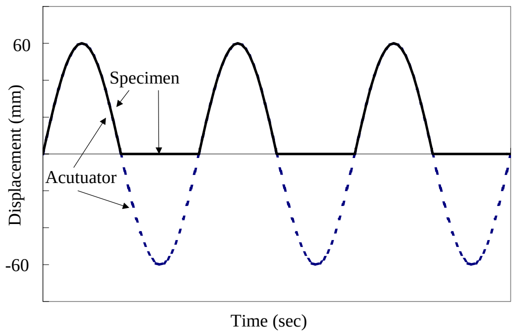


Fig.9 Displacement of Dynamic Loading Test

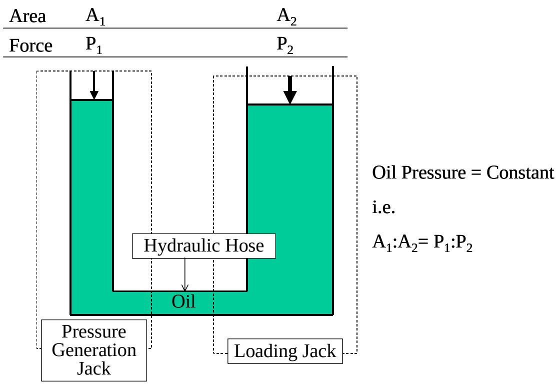
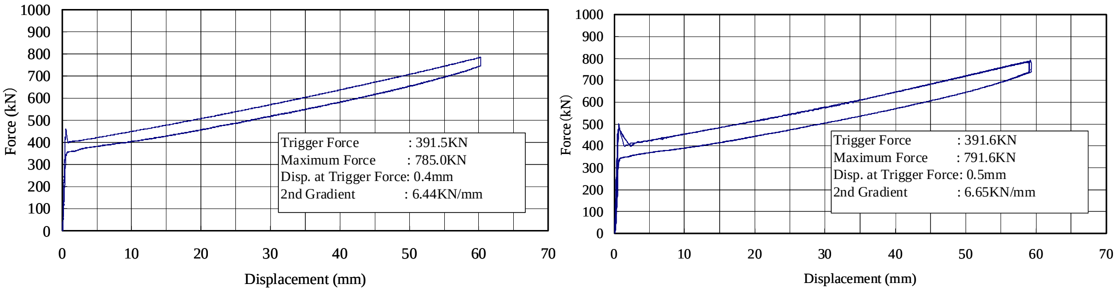
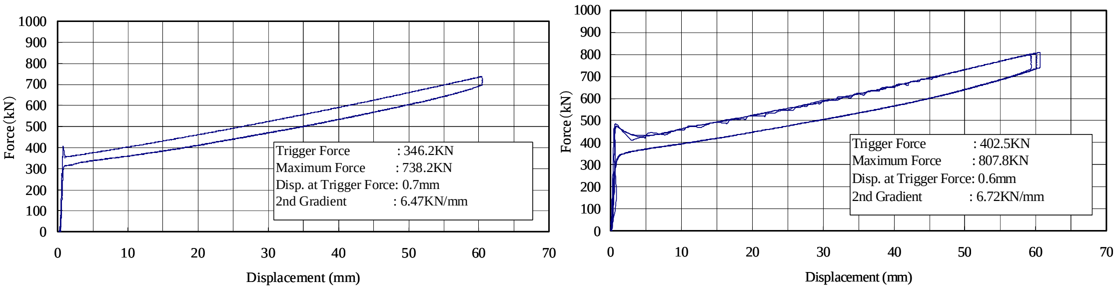


Fig.12 Schema of Loading Apparatus



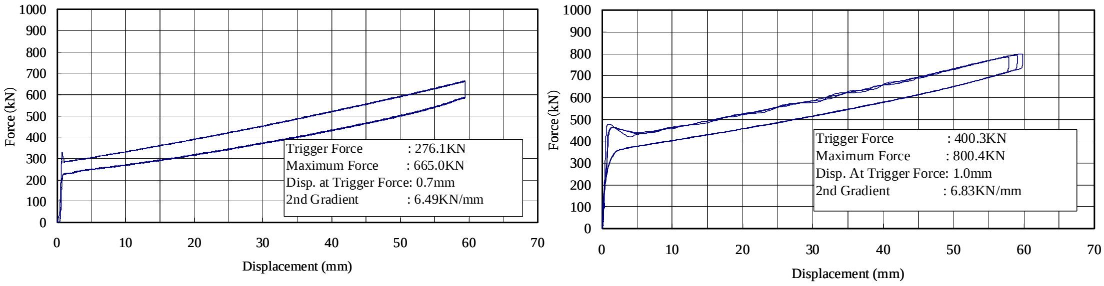
(a) Static Loading Test (Temp.: +30 degree C, Speed: 0.5mm/s)

(d) Dynamic Loading Test (Temp.: +30 degree C, Freq.: 0.1Hz)



(b) Static Loading Test (Temp.: +15 degree C, Speed: 0.5mm/s)

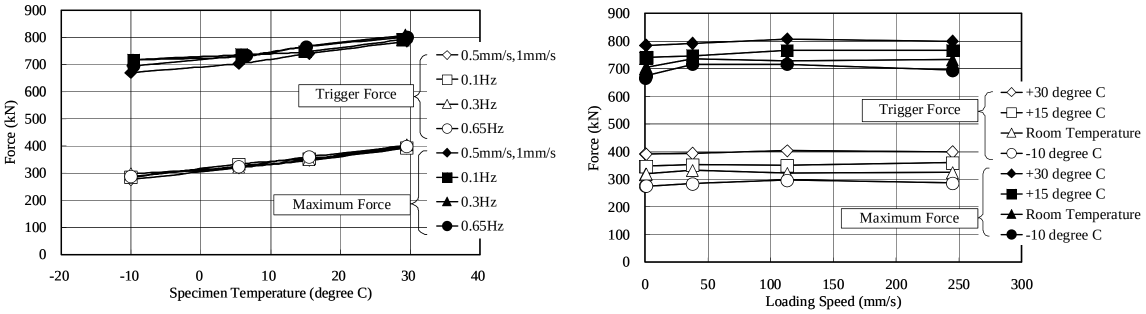
(e) Dynamic Loading Test (Temp.: +30 degree C, Freq.: 0.3Hz)



(c) Static Loading Test (Temp.: -10 degree C, Speed: 0.5mm/s)

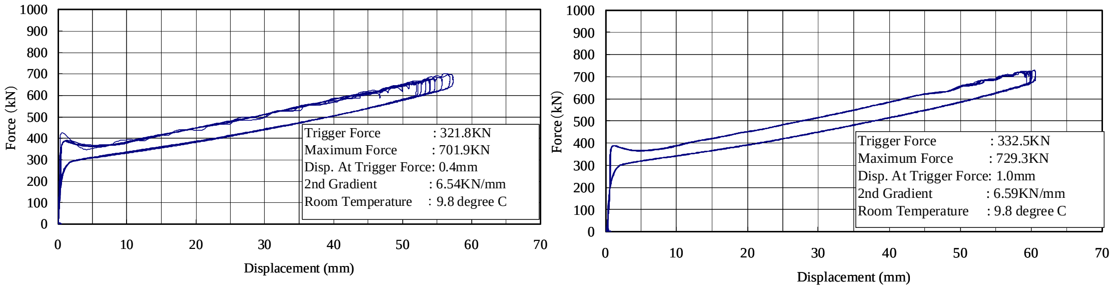
(f) Dynamic Loading Test (Temp.: +30 degree C, Freq.: 0.65Hz)

Fig.14 Force-Displacement Relationship for Basic Characteristic Verification Tests



(a) Temperature Dependency (b) Loading-Speed Dependency

Fig.15 Temperature and Loading-Speed Dependencies



(a) Temp: Room Temperature, Freq.: 0.65Hz、1-10 cycles (b) Temp: Room Temperature, Freq.: 0.65Hz、41-50 cycles

Fig.16 Force-Displacement Relationship for Durability Verification Test Under 50-Cycle Loading

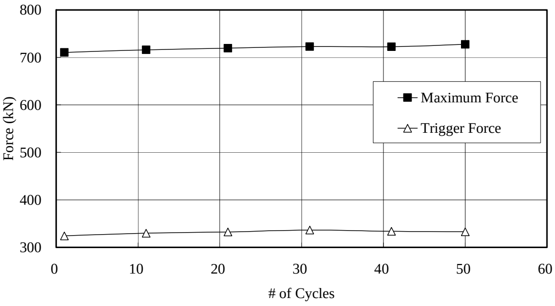


Fig.17 Force-Number of Cycles Relationship for Durability Verification Test Under 50-Cycle Loading

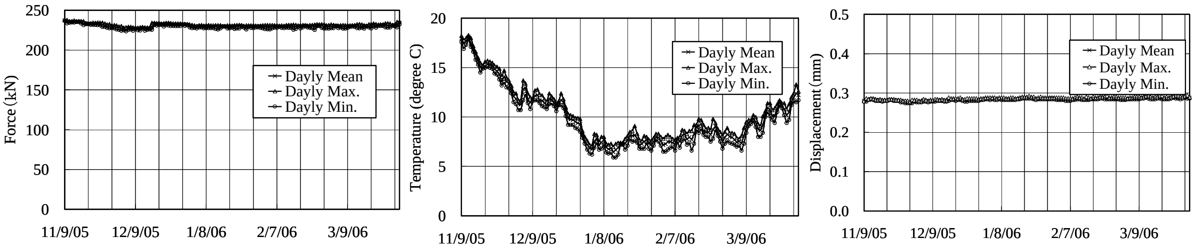


Fig.18 Fluctuations of Applied Force, Temperature and Displacement

Table 1 Scale Factors

Variable	Scale Factor	Remarks
Pressure of Filling (P)	1	
Volume Elastic Modulus (K)	1	
Resisting Force (F)	1/N	Dominated by a loading machine’s capability
Section Area of Piston-Rod (A_r)	1/N	See Eq. (1)
Stroke (S)	1/N	Conform to scale factor of resting force in order to suppress V_s
Volume of Filling (V_s)	$1/N^2$	See Eq. (3)
Loading Frequency	1	

Table 2 Properties of Spring Damper

Quantity	Values	
	Actual Bridge	Specimen
Horizontal Force in Dead Load Condition (P_0)	1,150kN	230kN
Trigger Force (P_1)	1,650kN	330kN
Horizontal Force in Large-Scale E.Q. (P_2)	3,300kN	660kN
Displacement in Large-Scale E.Q. (δ_2)	300mm	60mm