Full Scale Experimental Evaluation for Cable Dampers

Liang Dong, Tian Jingxian, Du Chuang, Ma Jinlong

Abstract — **One of the key techniques for building long span cable-stayed bridge is the mitigation of stay cable vibration. Mechanical dampers are widely used to mitigate in-plane and out-plane vibrations of long stay cables. In this study, two types of oil dampers were tested by a full scale model. Two types of tests were carried out. Test 1 is the damper performance test for evaluating the damping performance of dampers when they were installed on stay cables. The tested dampers were connected to the cable model via a full scale damper socket; and for one cable there were 2 dampers installed in perpendicular. The test results showed that both types of dampers have nonlinear damping characteristics. Test 2 is the durability test for evaluating the deterioration of dampers. Both two types of dampers were tested by using a fatigue testing machine until 4 million cycles with a frequency of 4 Hz and amplitude of 1 mm. The performance tests of damper were also carried out after every 1 million cycles. According to the durability test results, a formula for performance deterioration of damper was established to predict the lifetime of damper. The test results were very helpful to design the dampers and their sockets for long cable-stayed bridges.**

***Index Terms*—Cable vibration, damping evaluation, durability test, full scale test, oil dampers**

I. Introduction

VIBRATION mitigation of stay is a significant concern to engineers in the design of long span cable-stayed bridge (Hongwei Huang, Limin Sun et al., 2012). Stay cables have low levels of inherent mechanical damping, rendering them susceptible to multiple types of excitation. To suppress the problematic vibrations, viscous dampers are often attached to the stays near the anchorages (F.Weber, 2009). For example, the main span of Stonecutters Bridge reaches 1018m, and the length of the longest cable is 540.425m (Xu Z.H & Huang J.B. 2006). The flexibility of whole structure is considerable large and the scope of natural frequencies is wide, so the stay is more easy to be excited to vibrate. The mechanisms that induce the observed vibrations are still not fully understood, some uncertain factors, such as gap at joints and installation error of dampers, cannot be assessed by accurate calculations. On the other hand, the leakage of oil damper is another concern (Sun L.M., Zhou H.J. & Chen A.R., 2001). Therefore, experiments are necessary to confirm the damping effectiveness of the dampers. In this study, a full scale experiment of dampers was conducted in SRIM (Shanghai Research Institute of Materials) and a durability test of the dampers was carried out in Shanghai Jiaotong University.

So, the valuable test data were gotten to evaluate the oil damper's mitigation effect and to estimate the lifetime of the test oil damper. On the other hand, there are very few reports relative to the durability of oil damper.

Liang Dong is with Department of Civil Engineering, Hebei University of Technology, Tianjin 300130, China, (Phone: +86-22-60202014; fax: +86-22-60202014; e-mail: ldhebut@gmail.com).

Tian Jingxian is with Campus Planning Office, Hebei University of Technology, Tianjin, 300401, China (e-mail: 798071923@qq.com).

Du Chuang is with Department of Civil Engineering, Hebei University of Technology, Tianjin 300130, China, (e-mail: 1229204169@qq.com).

Ma Jinlong is with Department of Civil Engineering, Hebei University of Technology, Tianjin 300130, China, (e-mail: 765710462@qq.com).

II. EXPERIMENTS

A. Set-up for performance test

To simulate the actual vibration situation, a steel tube was used to substitute for a stay. The anchorage socket was fixed on the test bed, and the steel tube was connected with the actuator through joint accessories. The steel tube is subjected to a harmonically varying load in sine-wave form imposed by the actuator. Figs.2 and 3 show the set-up of internal dampers of long cable-stayed bridge.

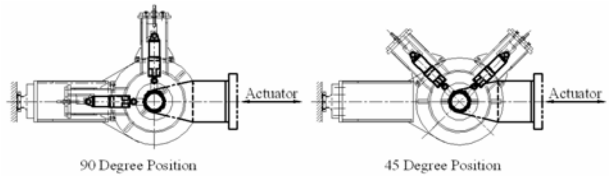

Fig. 2. Damper performance tests (test positions: 0-90 degrees and 45-135 degrees)

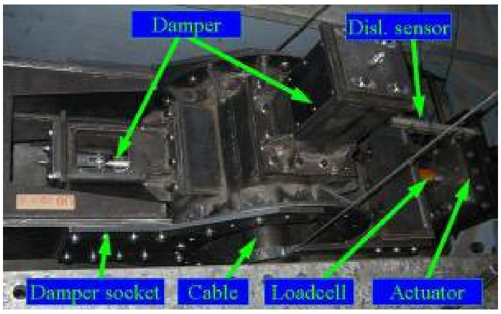

Fig. 3. Set-up of damper performance test in SRIM

Two companies, S-company and H-company, fabricated two dampers (noted as S-damper and H-damper respectively) of each for the longest cable of middle span (Cable No.228). In the experiments, these two groups of oil dampers were tested by using full scale models of dampers and sockets. The tested dampers were connected to a cable model via a full scale damper socket; and there were 2 dampers in- stalled in perpendicular (Fig.2). The cable model was oscillated by an actuator with a certain frequency and amplitude (Table I) which is determined according to the vibration modes and amplitude of stay vibration considered for design. The dampers were tested at two positions, i.e., the dampers have angles of 0-90 degree and 45-135 degree with the direction of oscillation (Fig.2).

TABLE I
THE TEST AMPLITUDES AND FREQUENCIES OF BOTH TESTS

Amplitude (mm)	Frequency (Hz) of performance tests					Cycle tests
	0.245	0.490	0.735	0.980	1.225	4.000
±1	○	○	○	○	○	○
±2	○	○	○	○	○	—
±5	○	○	○	○	○	—
±10	○	○	○	○	○	—
±20	○	○	○	○	○	—
±30	○	○	—	—	—	—

B. *Set-up for durability test*

One damper made by each company was selected for durability test. The durability test was done in Shanghai Jiaotong University and the test machine was MTS-880, as shown in Fig.4. This machine has an excellent behavior for fatigue test in the field of mechanical engineering.

Fig. 4. Durability test set-up

The durability test frequency is 4Hz; the single amplitude is 1mm (peak-peak 2mm); the maximum velocity is 25.1 mm/s; and the total load cycles are 4 million. As shown in Fig.5, the dampers are tested in their linear range. During the durability test, the temperature of damper and testing room, the time history of damping force and displacement were measured.

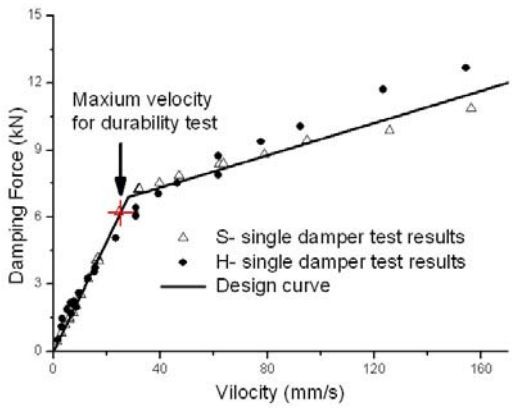

Fig. 5. Single damper performance

III. RESULTS AND DISCUSSIONS

A. *Results of performance test*

In this test, the displacement and damping force history of damper were recorded. From these data, the velocity history can be calculated. As one knows, hysteresis loops of force-displacement and instant velocity-damping force curves can be used for evaluating the damping performance of the damper.

1) Hysteresis loops and instant velocity-force curves of some test cases

Hysteresis loops and instant velocity-force curves of sample cases for S-damper are shown in Fig.6 and Fig.7. A centered finite-divided-difference method is adopted to calculate the instant velocity from displacement data. From these figures, we know that the tested dampers perform well.

The test case of Fig.6 and Fig.7 is with amplitude of 20mm, frequency of 1.225 Hz, and 0-90 degrees position. The hysteresis loops are plump and smooth. At large velocity (corresponding to second phase of design curve with bilinear damping, Fig.4), the hysteresis loops like rectangle (Fig.6) and instant velocity-damping force curves are bilinear (Fig.7). So the damper's nonlinearity maybe modeled as bilinear.

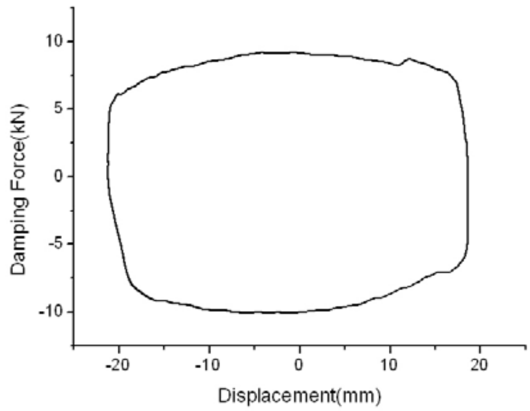

Fig. 6. Hysteresis loop of some test cases with S-damper

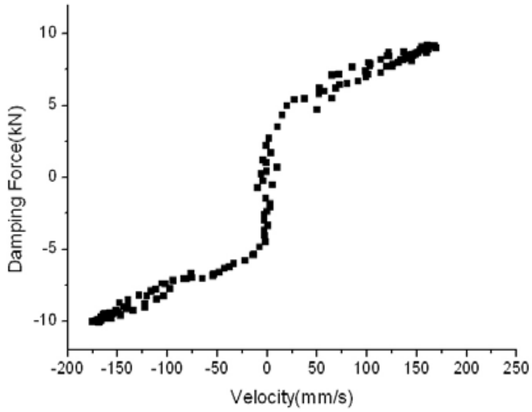

Fig. 7. Instant V-F curves of some test cases with S-damper

The test case of Fig.8 and Fig.9 is with amplitude of 2mm, frequency of 1.225 Hz, and 0-90 degrees position. At small velocity (corresponding to first phase of design curve with bilinear damping, Fig.5), the hysteresis loops like ellipse (Fig.8) and instant velocity-damping force curves like straight line (Fig. 9). So the effect of damper's nonlinearity within this test case is very small.

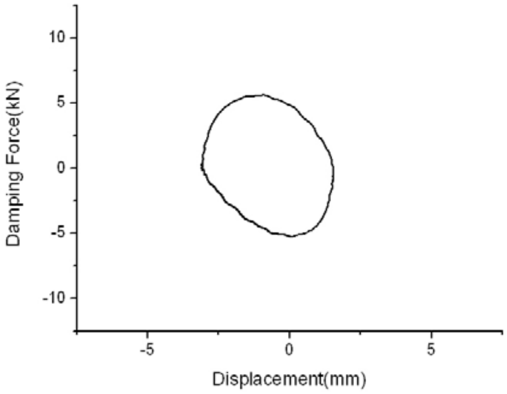

Fig. 8. Hysteresis loop of some test cases with S-damper

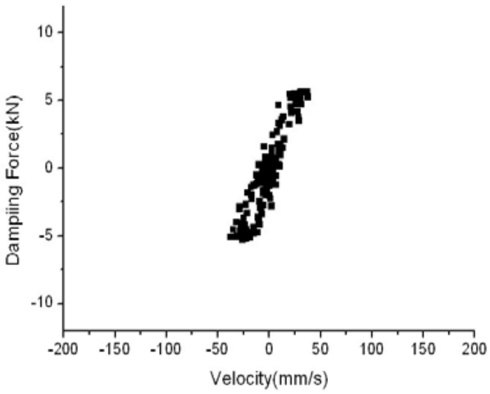

Fig. 9. Instant V-F curves of some test cases with S-damper

From other test cases, including another position of 45-135 degree, other frequencies, amplitudes and H- damper, the same trend and results can be observed.

2) Velocity and Damping force curves (V-F curve):

For each hysteresis loop, we can get the maximum force and amplitude, and corresponding maximum velocity can be calculated by actual test frequency and amplitude conveniently. Then velocity-force curves are given in Fig.10 and Fig.11. The slope of fit line of velocity and force data in these graphs indicates the equivalent damping coefficient.

Following design curves, the experiment data with the maximum velocity fallen in the first design line are used to fit the first line in Fig.10. And the data with the maximum velocity fallen in the second design line are used to fit the second line in Fig.10. Compared to H-damper, the S-damper shows a more pronounced bilinear characteristic. And for H-damper, a fractional power function is more precise than straight line to depict the damping characteristic (as shown in Fig.11).

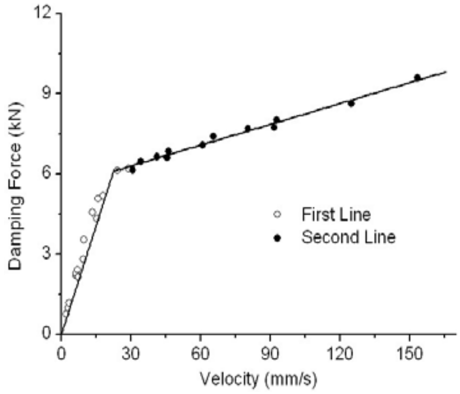

Fig. 10. V-F curve with 90° test case of S-damper

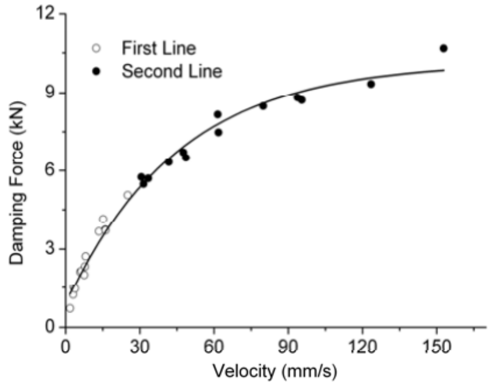

Fig. 11. V-F curve with 90° test case of H-damper

Comparison of two installation positions

As shown in Fig.2, two positions were tested to evaluate the damping performance. The equivalent damping coefficient may depends on evaluation method. The following equivalent damping coefficient used in this paper was computed by the following formula (R.W. Clough & J. Penzien, 1975):

$$c_{eq} = \frac{\Delta W}{\pi \cdot d^2 \cdot \omega} \tag{1}$$

In which, ΔW is the area of displacement-damping force curves; d is amplitude; $\omega=2\pi f$, f is frequency. Fig.12 is the comparison of S-damper's behavior for the two test positions and Fig.13 is the comparison of H-damper's behavior for the two test positions.

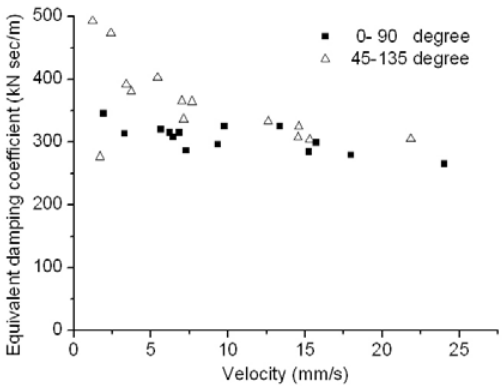

Fig. 12. damper's behavior of two test positions(S-damper)

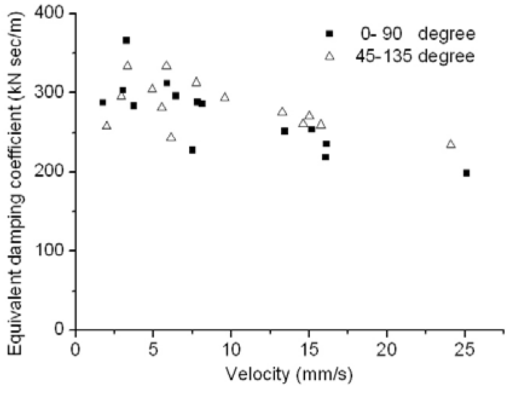

Fig. 13. damper's behavior of two test positions(H-damper)

From these figures, the equivalent damping co- efficient of different positions is a little different. The equivalent damping coefficient average of S-damper with 0-90 degree position fallen in first line in Fig.5 is 305.3 kN×s/m. The counterpart of 45-135 degree is 361.1 kN×s/m, 18.3% higher than 0-90 degree. The equivalent damping coefficient average of H-damper with 0-90 degree position fallen in first line in Fig.5 is 271.7 kN×s/m. The counterpart of 45-135 degree is 282.5.1 kN×s/m, 4.0% higher than 0-90 degree. Although the difference between0-90 degree position and 45-135 degree position of S-damper reaches 18.3%, the minimum equivalent damping coefficient 264.8 kN×s/m is still higher than design value 247 kN×s/m. On the other hand, the minimum equivalent damping coefficient of H-company is 198.4 kN×s/m, lower than design value.

3) Comparison of equivalent damping coefficient in different test cases with the same maximum velocity

Table II and Table III give the comparisons of equivalent damping coefficient of different performance test cases and single damper test cases. These test cases have the same maximum velocity, but the frequencies and amplitudes are different. As shown in Table II and III, the difference is obvious. For S-damper, the max difference is 12.23%, less than 15%. 15% is the ensured error offered by the two companies. For H-damper, the maximum difference is 35.72%, much higher than 15%. And Table II and III show the damping performance of oil damper depended on frequency seriously.

TABLE.II
SOME EQUIVALENT DAMPING COEFFICIENT OF S-CO. DAMPER IN SRIM AND SINGLE DAMPER TESTS

Velocity (mm/s)			3.08	6.16	7.70	15.39
C-eq of single damper tests	Frequency (Hz)	0.245	277.96	—	267.68	244.68
		0.49	280.49	257.16	—	—
		0.98	—	249.7	—	—
		1.225	—	—	234.94	235.32
	Comp.	(%)	0.91	-2.90	-12.23	-3.82
C-eq of performance tests	Frequency (Hz)	0.245	313.22	—	296.13	—
		0.49	320.48	307.46	—	299.12
		0.98	—	314.87	—	—
		1.225	—	—	286.13	278.9
	Comp.	(%)	2.32	2.41	-3.38	-6.76

TABLE.III
SOME EQUIVALENT DAMPING COEFFICIENT OF H-CO. DAMPER IN SRIM AND SINGLE DAMPER TESTS

Velocity (mm/s)			3.08	6.16	7.70	15.39
C-eq of single damper tests	Frequency (Hz)	0.245	326.02	—	299.41	—
		0.49	379.08	348.17	—	247.73
		0.98	—	223.79	—	—
		1.225	—	—	213.15	237.83
	Comp.	(%)	16.28	-35.72	-28.81	-3.99
C-eq of performance tests	Frequency (Hz)	0.245	365.98	—	287.76	—
		0.49	314.09	311.8	—	253.25
		0.98	—	295.7	—	—
		1.225	—	—	227.91	218.21
	Comp.	(%)	-14.18	-5.16	-20.8	-13.83

B. Results of durability test

1) Hysteresis loops and instant velocity-force curves of durability test

In this part, hysteresis loops and instant velocity-force curves of three typical durability test phases are shown in Fig.14 to Fig.17. They show the performance of the two company's damper separately. The three typical phases are after 0.1 million load cycles, after 2.0 million load cycles, and after 4.0 million cycles separately. Fig.14 and Fig.15 are for S-damper and Fig.16 and Fig.17 are for H-damper.

From this figures, we know the hysteresis loops and instant velocity-force curves overlapped very well, indicating that test damper's condition was stable during durability test. The hysteresis loops have little slope and the instant velocity-force curves have some certain areas. All these indicate that the damper's stiffness cannot be ignored in this test condition.

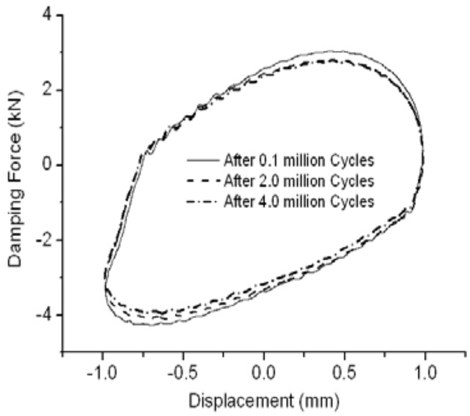

Fig. 14. Hysteresis loops of S-damper in durability test

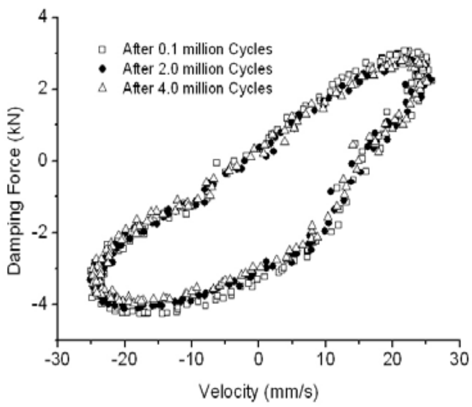

Fig. 15. Instant velocity-force curves of S-damper in durability test

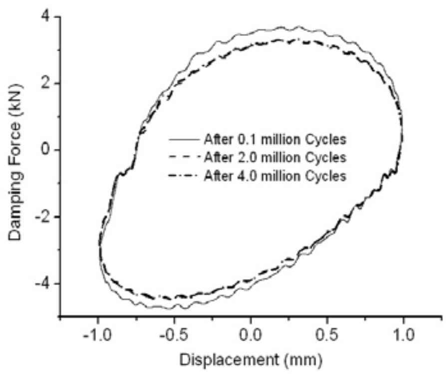

Fig. 16. Hysteresis loops of H-damper in durability test

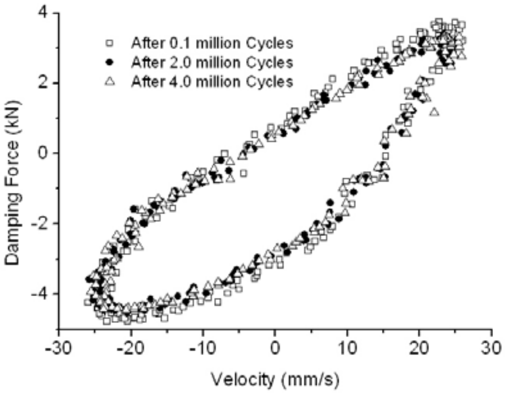

Fig. 17. Instant velocity-force curves of H-damper in durability test

Variety of temperature during durability test

During the process of durability test, the temperature of damper body and testing room were recorded every 6 hours. Fig.18 and Fig.19 show the variety of two company's damper temperature with load cycles increased. In Fig.18 and Fig.19, testing room temperature, damper temperature and the difference between the two temperatures are given.

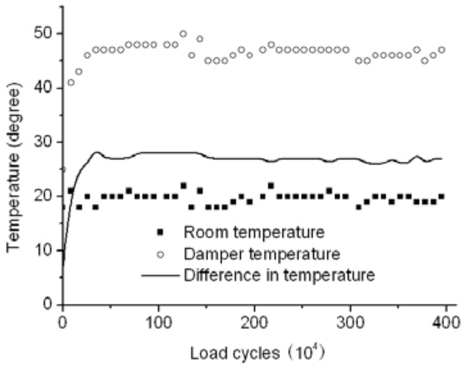

Fig. 18. Variety of temperature of S-damper durability test

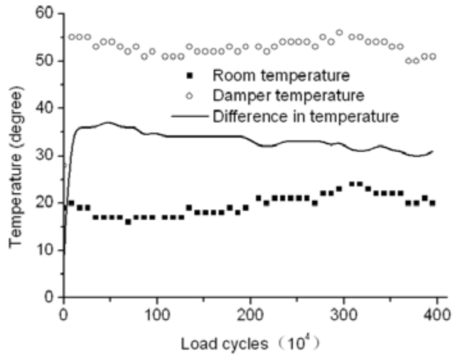

Fig. 19. Variety of temperature of H-damper durability test

From Fig.18 and Fig.19, we can get that the temperature of damper increased quickly at the beginning of durability test. The S-damper's temperature is stable at 47 degrees centigrade, and H-damper is stable at 53 degrees centigrade.

2) Degradation trend of equivalent damping coefficient during cycle test

As we all know, the damper's behavior is different at different frequencies although the maximum velocity is same. Table II lists some test results in SRIM and single damper tests. During the durability test, every 6 hours, the equivalent damping coefficient was calculated by displacement and damping force history. We can see that the equivalent damping coefficients are different in either tests in SRIM or single damper tests. Both types of damper have same conclusion.

The frequency adopted by cycle test is 4Hz. It's about the sixteenth frequency of cable No.228. The equivalent damping coefficient calculated by the data of cycle test is smaller than that in performance test. Therefore we can only get the trend of equivalent damping coefficient degradation.

Fig.20 gives the degradation trend of equivalent damping coefficient during durability test. During durability test, the equivalent damping coefficient of H-damper (calculated by durability test results) is slightly higher than S-damper. Equivalent damping coefficient of H-damper reduced more quickly than S-damper as load cycle increased and the degradation velocity of H-damper is about 4.5 times of S-damper.

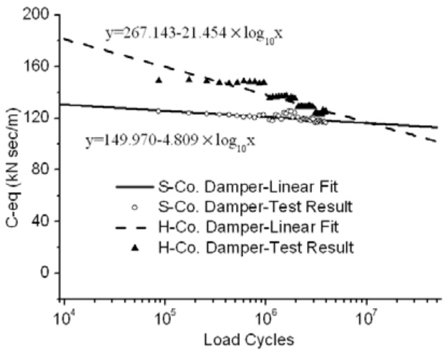

Fig. 20. Degradation trend of equivalent damping coefficient

3) Fluid leakage

During the all durability tests, there was no leakage for the dampers.

IV. ACKNOWLEDGMENTS

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V. CONCLUSIONS

There are many factors affect the quality of damper, such as flexibility of damper supporter, nonlinear character of damper, damper stiffness and gaps of joints etc. The equivalent damping coefficient we got from actual bridge cannot reach theoretic value, and always smaller then theoretic value. So experiment is very important to validate the performance of damper. From tests results discussed above, we can get the following conclusions:

1) The dampers had satisfying performance and attachment of the damper and the socket at the joints was well designed.
2) The design of damper has to cover any a possible uncertainty caused by different damper position and gaps of joints etc. The S-damper can cover this uncertainty better than H-damper and satisfied the 15% ensured error.
3) The damper socket adopted in test to support the damper

will not degrade the damping effect.

4) Compared to H-damper, the S-damper shows a more pronounced bilinear characteristic.
5) During the durability test, the degradation of H-damper is 4.5 times faster than S-damper.

In a word, the S-damper has a better behavior than H-damper during both performance test and durability test.

REFERENCES

[1] Hongwei Huang, Limin Sun and Xiaolu Jiang, Vibration mitigation of stay cable using optimally tuned MR damper. Smart Structures and Systems, 2012, 9(1):35-53.

[2] F.Weber, G.Feltrin, M.Maslanka, W.Fobo, H.Distl, Design of viscous dampers targeting multiple cable modes. Engineering Structures, 2009, 31(11): 2797-2800.

[3] Xu Z.H and Huang J.B. Considering the durability, maintaining and safety of Stonecutters Bridge. The 17th National Annual Conference on Bridge Engineering. Chongqing, China. 2006 (in Chinese).

[4] Sun L.M., Zhou H.J. and Chen A.R. Cable Vibration Control Measures of Large Span Cable Supported Bridge, Foreign Bridges, 2001. 58. 36-40 (in Chinese).

[5] TONGJI UNIVERCITY, 2006, Report of Experiments on Damper Performance for Vibration Control for Stone- cutters Bridge, Research Report, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji Univ.

[6] R.W. Clough and J. Penzien, Dynamic of Structures.McGraw-Hill Inc.1975.