Experimental Test of Oblique Damper System and Its Application on Cable-Stayed Bridges

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Abstract

Long span cable-stayed bridges would experience either a significant increase associated with seismic force or larger relative pylon-girder displacement for rigid connection or longitudinal floating system. Seismic mitigation of cable-stayed bridges are mostly focused along longitudinal direction, and are usually designed to be constrained between the girder-pylon to avoid any unexpected vibration induced by vehicles or wind in the transverse direction, which would significantly increase the likelihood of seismic damage.

Researchers proposed methodology and invented devices to assess and decrease the transversal seismic demand. These transversal devices, usually together with the longitudinal dampers, have to be designed and installed in the limited space between the pylon and girder. Despite the efficiency, installing of these equipment in two orthogonal directions is quite complicated in configuration and thus costly. Moreover, the effectiveness of their collaborative work has not been fully validated considering the random direction of earthquake.

Consequently, this study introduces a new seismic mitigation strategy, namely the Oblique Damper System (ODS), trying to reduce the seismic demand of long span cable-stayed bridges along both the longitudinal and transversal directions. The design concept, overall layout, structural details of ODS are described in this study. Pressure-tight test, strength test, constitutive test (under varied velocities), collaborative behavior of two longitudinal symmetrically oblique dampers, et al., are carried out to obtain its performance under normal service and earthquake condition. Totally eight damper prototype are constructed and tested to consider the product's dispersion.

ODS was installed and applied on Wuhu second Yangtze River highway bridge, which was put into operation on Dec. 30, 2017. The main span of super long bridge is 806 meters. The bridge is a new type of bridge composed of twin separated steel box girders supported by four planes of 50 sparse harp cables each. The pylon of the bridge, designed as "column type", located between the two separated girders, is very flexible laterally. Therefore, additional damper is needed to overcome the effect of wind, vehicles, earthquake, et al.

Keywords: Oblique Damper System, Experimental test, Cables-stayed bridges, transverse seismic performance

1. Introduction

The main bridge of the second Wuhu Yangtze River Highway Bridge is a (100 + 308 + 806 + 308 + 100) m cable-stayed bridge with two towers and four cable planes, and its general layout is shown in Fig. 1. The main girder of the bridge is a steel box girder with a flat arc-shaped bottom plate and a total width of 53m (excluding air nozzle and cable inspection and repair track), and the beam height at the center of the section is 3.5m. The bridge tower adopts the split column structure, which is composed of upper tower column, middle tower column, lower tower column, tower base and lower crossbeam. The tower height is 262.48m, and the height above the bridge deck is 210.436m. The stay cable adopts steel strand clue, the standard spacing on the main beam is 16m, the whole bridge has 196 pairs, fan-shaped layout. The overall view and the characteristic of the pylon and girder are shown in Fig. 2 (a) and (b), respectively.

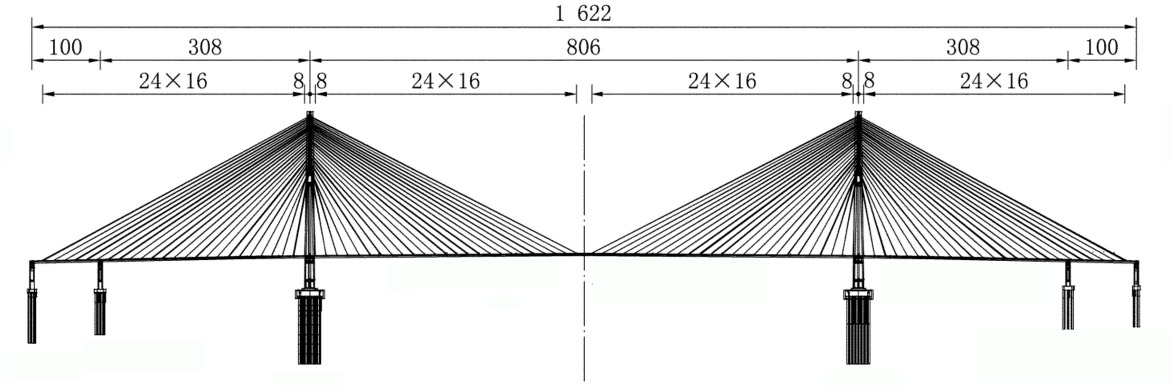


Fig. 1 Overall Arrangement of Wuhu second Yangtze River highway bridge

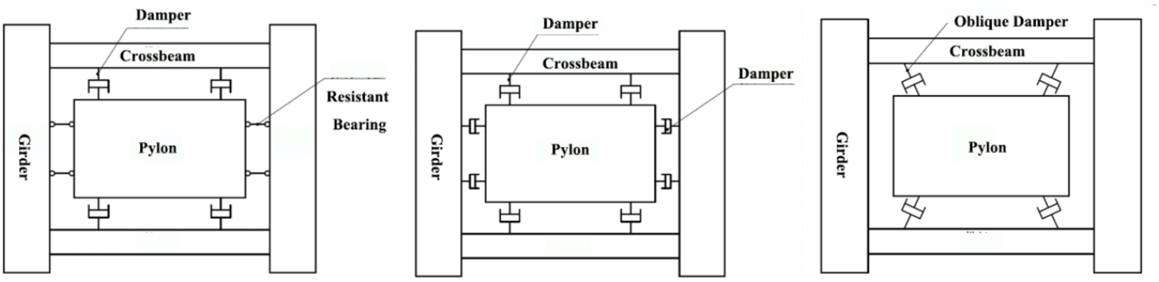
Fig.2 Photos after the completion of the bridge (a) the overall view, (b) pylon and girder

2. Conceptual design of ODS

In recent decades, cable-stayed bridges have been widely constructed around the world because of their aesthetics, efficient use of construction materials, and fast construction period. Many studies focused on the dynamic characteristics of cable-stayed bridges subjected to earthquake (Zhong, Jeon, Shao and Chen, 2019, Zhong, Jeon and Ren, 2018, Zhong, Jeon, Yuan and DesRoches, 2017, Ren and Obata, 1999, Barnawi and

Dyke, 2013, Khan, Datta and Ahmad, 2006). These studies showed that the seismic demand of towers would experience a significant increase in terms of bending moment and shear forces when restraining the bridge deck completely at tower locations. When there are no additional restraints in the longitudinal direction, larger deck displacement would occur during earthquake, resulting in pounding and unseating(Dyke, Caicedo, Turan, Bergman and Hague, 2003, Chang, Mo, Chen, Lai and Chou, 2004), which is not desirable for performance based earthquake engineering. Therefore, there is an agreement among many researchers that mitigation devices should be equipped to allow some sort of deck movement, which would lead to the balance of the force and displacement demand of the cable-stayed bridges (Sharabash and Andrawes, 2009).

Some of the protection devices are mainly to reduce the seismic demand along the longitudinal direction. The transvers direction is commonly fixed by lateral anti-wind bearing to constrain the relative movement caused by wind or vehicles, causing excessive seismic force subjected to large earthquake (Fig 3(a)). Xie and Sun(Xie and Sun, 2014, Xie and Sun, 2019), Guan et al(Guan, You and Li, 2016, Guan, You and Li, 2019), Zhou et al.(Zhou, Wang and Ye, 2019), Infanti et al. (Infanti, Papanikolas, Benzoni and Castellano, 2004) proposed lateral seismic protection system for the seismic control of long-span cable-stayed bridges (Fig 3(b)). This study introduces a new seismic mitigation strategy, namely the Oblique Damper System (ODS), trying to reduce the seismic demand of long span cable-stayed bridges along both the longitudinal and transversal directions. The design concept, overall layout, structural details of ODS are described in this study (Fig 3(c)).



(a)Longitudinal only (b) both longitudinal and transversal (c) oblique arranged

Fig. 3 Conceptual design of ODS

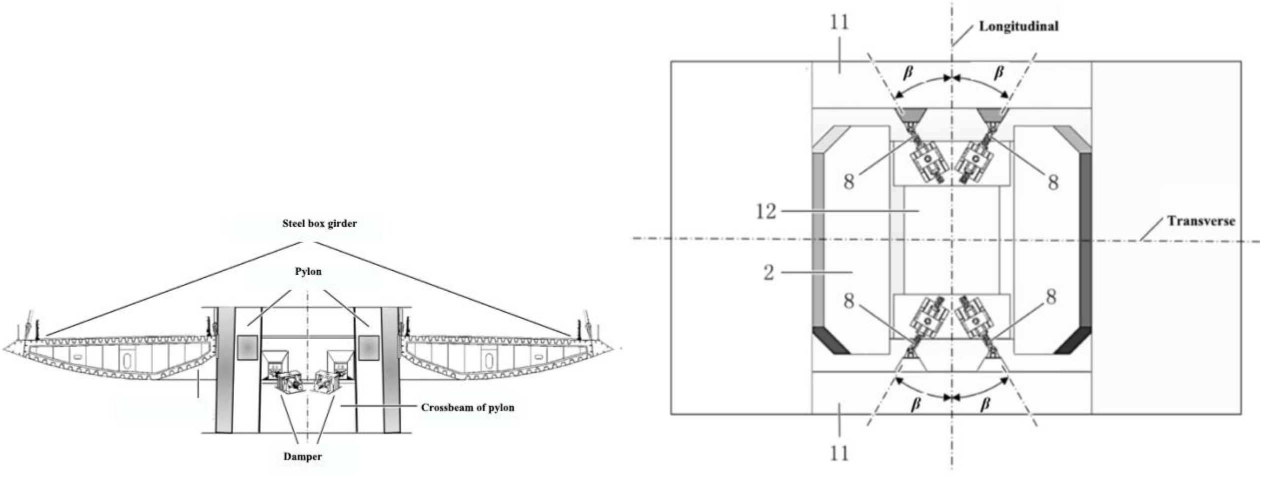


Fig.4 Arrangement of ODS on Wuhu second Yangtze River highway bridge

Four oblique fluid viscous dampers are installed at each pylon. One end of the damper is fixed on the crossbeam of the girder, the other end is installed on the crossbeam of the pylon by the special designed devices, and symmetrically arranged in longitudinal and transverse directions. (1) The oblique damper is installed on the horizontal plane, the axis of the damper is set along longitudinal axis of the main girder, with a specific angle (β) in the line, which provides both longitudinal and transversal damping constraints to the girder; (2) the oblique damping restraint system make the cable-stayed bridges as a longitudinal and transversal two-way floating structure; (3) The oblique damper has a horizontally rotating working state, and the end of the damper is provided with a horizontally large angle hinge. (4) The oblique damper is designed for both longitudinal and transverse bridge motions, and the damper deformation capacity is designed as a combination of two-way displacement. The site installation and experimental test are shown in Fig 5(a) and (b), respectively. The parameters for the single damper are documented in Table 1.

Fig. 5 Site picture of ODS.

Table 1.Parameters for single damper

Classification	Parameter	Value
Dynamic damper parameter	function	$F_d=CV^{\alpha}$
	α	0.25
	C(kN/(m/s)$^{0.25}$)	3000
	v_{max}(m/s)	0.289
	F_d(kN)	2000
Static stroke	Capacity (mm)	±500
Angel	β	25^{o}

3. Experimental Test

At present, the connection mode and structure diagram of seismic viscous damper for long-span bridges are shown in Fig. 6(a), with the following disadvantages: (1) one end is fixed on the main beam, the other end is fixed on the bridge tower (pier), and the overall installation space of the damper is large; (2) the common installation method, the seal of the viscous damper is pressed on one side, which affects the durability of the damper. Although the existing patent provides a solution to the problem, the method is complex, which increases the difficulty of construction and installation; (3) when there is vertical displacement, the force of the damper is unreasonable, which affects the normal operation of the damper. In order to solve this problem, this project developed a connection method of middle support joint viscous damper, which can reduce the installation space of damper, effectively alleviate or avoid the problem of unilateral compression of damper seal, and consider the adverse effect of vertical displacement on damper, shown in Fig. 6(b). When there is relative displacement between the main beam and the bridge tower (pier), the viscous damper starts to work, and the piston rod and the main beam are relatively static. The lifting pedestal fixed on the bridge tower (pier) drives the viscous damper cylinder to move, so as to realize the energy consumption of the damper.

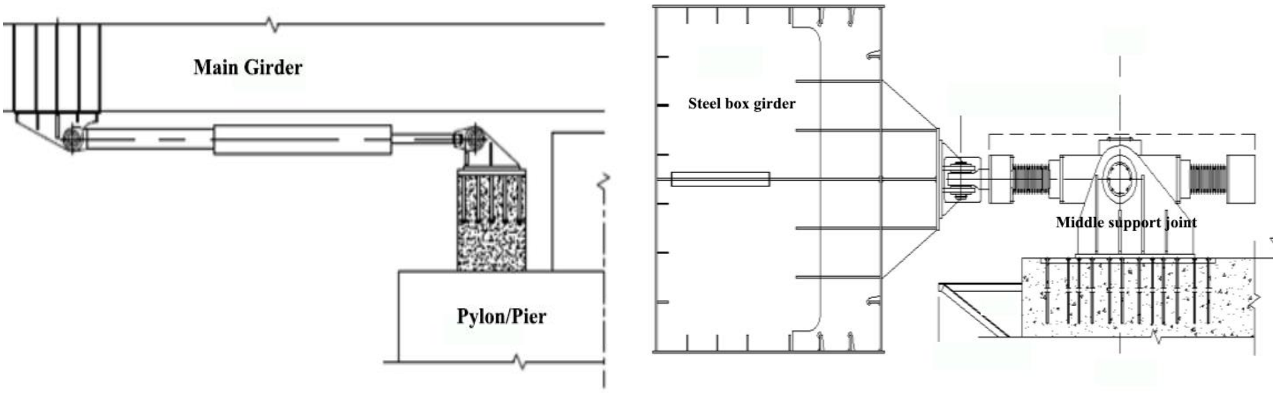


Fig.6 Detail design of middle support joint of damper

Pressure-tight test, strength test, constitutive test (under varied velocities), collaborative behavior of two longitudinal symmetrically oblique dampers, et al., are carried out to obtain its performance under normal service and earthquake condition. These experiments were tested in China Railway Bridge Research Institute Co., Ltd.

The static performance of universal joint in the middle part of tower girder damper of Wuhu Yangtze River Second Bridge is studied by combining the finite element calculation of full scale model, 1:2 scale model and 1:2 scale model test, shown in Fig. 7. The finite element analysis model and its model test results are in good agreement. Through the static load simulation analysis of the model, it can be seen that the structural strength of the damper connection of Wuhu second bridge under static load meets the requirements

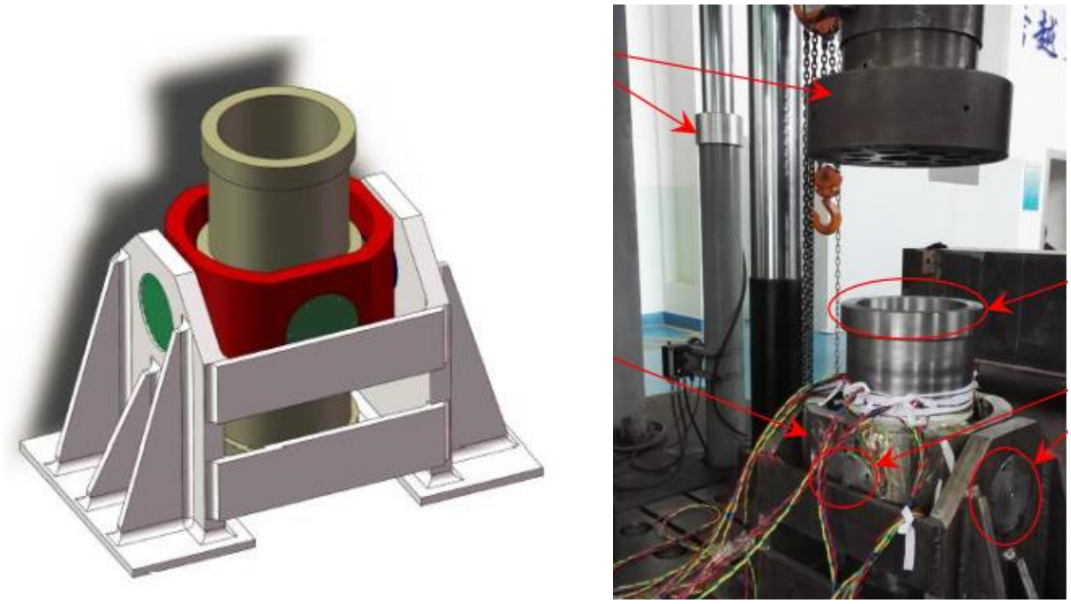


Fig. 7 Experimental test of middle supported joint of ODS

Fig.8 Experimental test of ODS for Slow and speed related performance

Totally eight damper prototype are constructed and tested to consider the product's dispersion. After the damper is installed in place as required, the slow test is carried out. The slow speed performance of the damper is tested by sine wave loading. The loading frequency is 0.001Hz, the amplitude is ±31.83mm, the maximum speed is 2×10^{-4}m/s, and the loading lasts for three complete cycles. Test parameters and results of slow test are shown in Table 2. It can be seen from the results of slow speed test that the maximum tensile force and maximum thrust value of 8 dampers during the test are less than the given allowable limit value ± 220kN, in which the maximum tensile force and thrust value is FVD17WHE01 damper.

Five working conditions were selected for the constitutive relationship test. The loading conditions were 0.1V_{max}, 0.25 V_{max}, 0.5 V_{max}, 0.75 V_{max} and 1.0 V_{max}. Sine wave loading is adopted in all five working conditions, with the maximum speed of 29mm/s, 72mm/s, 145mm/s, 217mm/s and 289mm/s, respectively. The results of the test are documented in Table 3

According to the above test results, under five different working conditions, the measured damping force of the damper is between 1 ± 15% of the theoretical damping force, which meets the specification requirements.

Table 2. Slow test results

No.	Frequency (Hz)	Cycle times	Amplitude （mm）	Tensile （KN）	Compression （KN）	Range （KN）
FVD17WHE01	0.001	3	±31.83	136.2	113.8	±220
FVD17WHE02	0.001	3	±31.83	125.8	109.4	±220
FVD17WHE03	0.001	3	±31.83	121.3	108.5	±220
FVD17WHE04	0.001	3	±31.83	127.2	110.6	±220
FVD17WHE05	0.001	3	±31.83	122.4	107.4	±220
FVD17WHE06	0.001	3	±31.83	133.5	111.5	±220
FVD17WHE07	0.001	3	±31.83	126.9	107.2	±220
FVD17WHE08	0.001	3	±31.83	118.5	106.7	±220

Table 3. Test results of speed related performance test

No.	Case		29mm/s	72mm/s	145mm/s	217mm/s	289mm/s
	Force（kN）		1238	1554	1851	2048	2200
FVD17WHE01	Pull	Test data	1119.4	1505.8	1814.1	1975.5	2147.6
		error	-9.58%	-3.10%	-2.00%	-3.52%	-2.37%
	Push	Test data	1141.2	1518.1	1861.9	2027.7	2175.8
		error	-7.82%	-2.31%	0.58%	-0.97%	-1.08%
FVD17WHE02	Pull	Test data	1127.8	1446.8	1754.9	1982.1	2144.6
		error	-8.90%	-6.90%	-5.20%	-3.20%	-2.50%
	Push	Test data	1124.1	1432.8	1766.0	1963.6	2138.0
		error	-9.20%	-7.80%	-4.60%	-4.10%	-2.80%
FVD17WHE03	Pull	Test data	1138.2	1421.5	1688.1	1878.0	2032.9
		error	-8.06%	-8.53%	-8.81%	-8.28%	-7.58%
	Push	Test data	1140.6	1433.3	1720.5	1897.4	2055.8
		error	-7.87%	-7.76%	-7.06%	-7.34%	-6.54%
FVD17WHE04	Pull	Test data	1147.9	1514.9	1825.0	2004.1	2185.1
		error	-7.28%	-2.51%	-1.42%	-2.13%	-0.66%
	Push	Test data	1126.9	1475.9	1722.7	1878.6	1986.2
		error	-8.97%	-5.03%	-6.94%	-8.25%	-9.70%
FVD17WHE05	Pull	Test data	1130.7	1408.7	1715.3	1905.4	2057.5
		error	-8.67%	-9.35%	-7.34%	-6.94%	-6.46%
	Push	Test data	1253.8	1600.8	1895.0	2119.6	2244.2
		error	1.28%	3.01%	2.36%	3.52%	2.03%
FVD17WHE06	Pull	Test data	1179.4	1459.6	1730.0	1901.0	2048.7
		error	-4.74%	-6.08%	-6.55%	-7.16%	-6.86%
	Push	Test data	1210.1	1489.7	1787.7	2007.2	2191.1
		error	-2.26%	-4.14%	-3.43%	-1.97%	-0.38%
FVD17WHE07	Pull	Test data	1270.0	1630.9	1901.5	2121.9	2269.3

No.	Case		29mm/s	72mm/s	145mm/s	217mm/s	289mm/s
	Force（kN）		1238	1554	1851	2048	2200
		error	2.58%	4.95%	2.71%	3.63%	3.17%
	Push	Test data	1205.7	1500.1	1766.9	1949.1	2115.5
		error	-2.61%	-3.47%	-4.55%	-4.81%	-3.82%
FVD17WHE08	Pull	Test data	1122.5	1447.7	1755.7	1927.1	2047.8
		error	-9.33%	-6.84%	-5.16%	-5.88%	-6.90%
	Push	Test data	1137.3	1458.1	1722.8	1882.0	2002.4
		error	-8.14%	-6.17%	-6.93%	-8.09%	-8.96%

4. Design Flowchart

When the cable-stayed bridge is subjected to longitudinal and transverse earthquake, the damping force component and equivalent damping coefficient of the inclined damper shall be converted according to the angle $\boldsymbol{\beta}$ between the damper axis and the longitudinal axis of the main girder.

When the transverse relative velocity v_t of tower and beam occurs, the transverse force F_t of damping force and the transverse equivalent damping coefficient C_t are formulated as Equation (1) and (2), respectively.

$$F_t = F\sin\beta = C(\sin\beta)^{1+\alpha} v_t^{\alpha} = C_t v_t^{\alpha} \tag{1}$$

$$C_t = C(\sin\beta)^{1+\alpha} \tag{2}$$

When the longitudinal relative velocity v_l of tower and beam occurs, the transverse force F_l of damping force and the transverse equivalent damping coefficient C_l are formulated as Equation (3) and (4), respectively.

$$F_l = F\cos\beta = C(\cos\beta)^{1+\alpha} v_l^{\alpha} = C_l v_l^{\alpha} \tag{3}$$

$$C_l = C(\cos\beta)^{1+\alpha} \tag{4}$$

According to the seismic design strength, input the ground motion along the transverse and longitudinal direction respectively, optimize the equivalent damping coefficient C_t, C_l and velocity index α of the damper; then calculate the damping coefficient C and the included angle β of the inclined damper according to the above formula; finally, check the C, α and β as the design parameters, judge whether the construction and setting conditions are met and whether the structural strength is met. The parameter design flow of oblique damper is shown in Figure 4

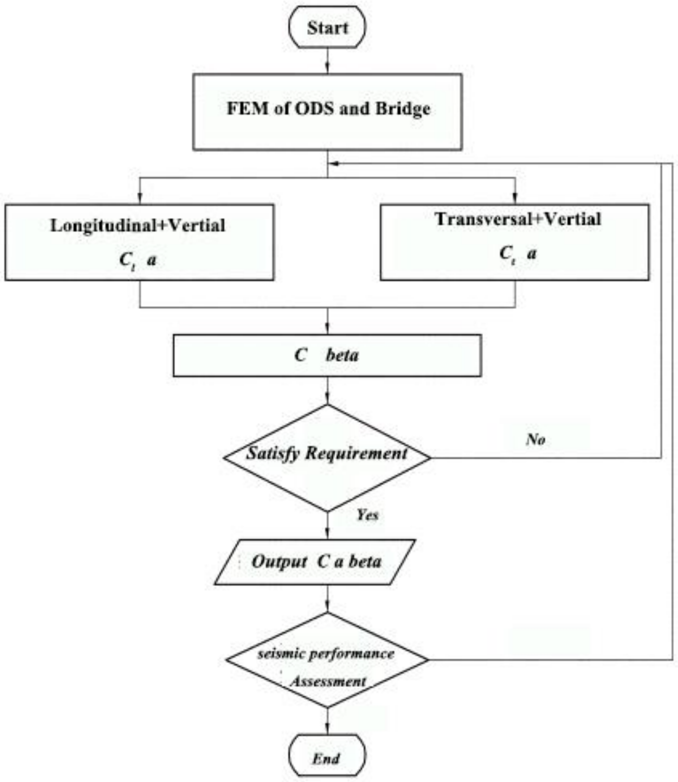


Fig.9 Design flowchart of the ODS for cable-stayed bridges.

5. Acknowledgements

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6. Copyrights

7. References

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