Product Research and Development

Technical Research on Fatigue Resistance and Durability of OVM250 Parallel Strand Cable System

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Abstract: With the development of modern long-span cable-stayed bridges, due to the parallel strand cable (PSC) being assembled on-site strand by strand, which has the advantages such as no need for large-scale equipment for cable-making, delivery, hoisting, traction, tensioning, and the corrosion protection of the cable is excellent, it is more and more favored by designers. As load-bearing components, the stay cables are known as the life cable of the cable-stayed bridge. Its reliability and durability are the key factors that determine the safety and the service life of the cable-stayed bridge. In accordance with the requirements specified in international recommendations, in-depth research has been carried out on cable fatigue, anti-corrosion, and vibration control to optimize OVM250 PSC system. All research results have been successfully applied to cable stayed bridge projects.

Keywords: high fatigue strength; corrosion protection; UV resistance; vibration control

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1. Introduction

Continuous development and breakthroughs of anti-corrosion technology of the stay cable system have provided favorable conditions for the development of modern long-span and super-long-span cable-stayed bridges. The increasing demand for cable-stayed bridge construction has promoted the development of stay cable technology and ushered in a new technological innovation in the stay cable system [1]. In order to ensure the safety and durability of long-span cable-stayed bridges, higher requirements are put forward to the reliability, durability, construction convenience, cable force monitoring and even fire and explosion protection of the stay cables [2-5]. In recent years, the PSC technology has been favored and applied in more and more super-long-span cable-stayed bridges all over the world (e.g., Russky Bridge in Russia with main span 1104m) for its multi-layer redundant anti-corrosion, strand-by-strand installation and stressing method, lightweight erection equipment, and convenience of maintenance and individual strand replacement [6,7].

In 1993, a survey on bridge stay cable systems was carried out, for the question "what are the three most important aspects/requirements for a stay cable" [8], durability and fatigue received a relatively close percentage rating of 28.3% and 26.6%, respectively, which are much higher than other aspects.

In international recommendations of Setra CIP [9], fib bulletin 30[10] and PTI [11], fatigue and subsequent static tests are specified. In these three (3) recommendations for stay cable system, the simulation of the angular deviation of the cable specimen CIP is different from PTI and fib bulletin 30. The Setra CIP recommendation adopts dynamic simulation to generate bending stress by means of transverse displacement of the middle of the cable, which can reflect the real behavior of the free length of the stay cable.

With the understanding of the influence of bending stress on the fatigue performance of stay cables [12], fib bulletin 89[13] has added provisions for bending fatigue on the basis of axial fatigue.

In the mid-1980s, Freyssinet of France developed a steel cable system with a fatigue stress range of 200 MPa. DSI of Germany also developed the DYNA Bond Achorage cable system with a fatigue stress range of 240 MPa. In 1993, the fib International Conference on Bridge Prestressing was held in Geneva, where experts, in light of developments in prestressing materials and techniques, concluded that the fatigue stress range of the new cable-stayed system should reach 250 MPa. Therefore, researching steel cable systems with high fatigue resistance has become an important task in the study of cable-stayed bridges [1,14,15].

For the PSC system, the free length consists mainly of the prestressing strands and their protection layers. If not protected adequately [16], the strand may suffer pitting corrosion and stress corrosion. There is presently no scientific model available to reliably predict these corrosion processes over time as a function of the exposure classes. Therefore, the design approach for the strands is to provide suitable permanent multi-layer corrosion protection which is adequate for the entire design lifetime of the cable [14].

In fib recommendations, a "Reference system" was defined, believed to provide a 100-year design life of prestressing steel used in stay cables with high fatigue loading and in the most aggressive environment, exposure class C5 of ISO 12944-2[17].

In addition, the internal and external barriers of the strand shall be subjected to salt spray test [18] and watertight test [19], friction test [19], and impact resistance test [20].

Similarly, different watertightness test procedures are defined in international recommendations. In the PTI recommendation, the static leak test with a cable specimen having passed the fatigue test but not subjected to the tensile test is immersed into a 3 m head of water and dye solution for 96 hours to verify the leak performance of the cable. Both CIP and fib recommendations have introduced a dynamic watertightness test to simulate the effects of mechanical and thermal aging; however, they are quite different in test set-up, water head, temperature range and test duration. The test set-up with 30° inclination defined in CIP is more in line with the actual state of cable stays.

The application environment of the stay cables is an open state, and the stay cables are exposed to periodic excitation, such as wind, rain and traffic load, under certain conditions. The stay cables can accumulate energy and oscillate with substantial amplitudes. This oscillation rarely endangers the structural integrity of the works, but it is disturbing for users and can cause fatigue damage to the cable stays if it is not controlled [21].

Since the 1990s, OVM has been working in the development and application of parallel strand stay cable system [22]. After nearly 30 years of development, in addition to occupying more than 80% of China's market share of cable-stayed bridges using strand stay cables, OVM250 (the fatigue stress range is 250 MPa) PSC has also been successfully used in South Korea, Indonesia, India, Iran, Middle East, South America, and Taiwan regions.

2. Milestones in the development of OVM250 PSC

In 1993, the OVM200 PSC was developed and first applied in the 4th bridge over cross Liujiang River.

In 1995, OVM began to develop the OVM250 PSC system. In 1997, all qualification and production acceptance tests of the cable system were accepted by the owner and designer of the Shantou Queshi Bridge (main span 518 m), which is the first cable-stayed bridge to which the OVM250 PSC was applied. During construction, the stay cable withstood the test of several typhoons above level 8.

The Queshi (Shantou, Guangdong) Cable-Stayed Bridge adopts the OVM250 PSC. There are seven types of cable with the shortest length of 61 meters and the longest length of 274 meters. The total weight of all cables is approximately 1120 tons. OVM250 PSC adopts multi-layer protection, which has better durability than prefabricated products. The OVM250 PSC system has been successfully applied in bridges, with significant economic benefits, and provides new ideas for the cable system of modern large-span cable-stayed bridges in China, which is worthy of promotion and use in the future [23].

In 2002, the individual changeability of the HDPE sheathed strand in the OVM250 PSC was verified in the erection of the main arch of the Shanghai Lupu Bridge.

In 2003, the OVM250 PSC was applied to the Sichuan Yibing Jinshajiang River Bridge, which is the first cable-stayed bridge constructed with a front fulcrum hanging basket method in China. The safety and reliability of OVM250 PSC under 10% GUTS (Guaranteed Ultimate Tensile Strength) low stress conditions have been verified.

Since 2006, fatigue and subsequent tensile tests have been carried out in the American CTL and Swiss EMPA labs in accordance with international recommendations.

In 2011, the OVM250 PSC system was applied to the Tongling Yangtze River Railway and Road Bridge (main span 630 m), which was the first railway bridge in China to use steel strand cable-stayed cables. Railway bridges have the characteristics of a high proportion of live load compared to the total load and therefore have high requirements for the fatigue performance of the cable-stayed cables. Therefore, in order to validate the overall anchoring performance and fatigue resistance of the cable-stayed system, a series of fatigue tests and material performance parameter tests are usually conducted [24]. Large-size cable with 139 strands of the 2nd generation OVM250 PSC passed the fatigue and subsequent tensile test with an upper stress of 45% GUTS and a high stress amplitude of 250 MPa for requirements specified in the Tongling Rail-cum-Road Changjiang River Bridge.

Figure 1. Tongling Rail-cum-Road Changjiang River Bridge

In 2016, the OVM250 PSC was successfully applied to the world's largest span steel truss girder cable-stayed bridge, the Guizhou Yachi River Bridge (main span 800 m), and the world's highest cable stayed bridge, the Beipanjiang Bridge on the Bidu Expressway (main span 720 m).

In 2017, an OVM250 PSC with the addition of fire protection, blast protection and an anti-vandalism system, a high-performance damping system, and a cable force monitoring system was applied in the Rod EI-Farag cable-stayed bridge. The Rod EI-Farag cable-stayed bridge, which is the world's widest cable-stayed bridge, is a key project of the Egyptian government and one of the focus projects in the Middle East. The whole bridge has 160 cable stays, which adopt the OVM250 PSC system. The cable stays are required to have fire insulation performance within a range of 8 m from the vertical surface of the bridge, i.e., the surface temperature of the steel strand should not exceed 300℃ during a 90-minute period of 1100℃ high-temperature exposure [25].

Currently, the OVM250 PSC system has been successfully applied in over 500 bridge projects both domestically and internationally, including 14 bridges with a main span greater than 500 meters, as shown in Table 1.

Table 1. The application of the OVM250 PSC system in cable-stayed bridge projects with a main span greater than 500 meters

No.	Bridge	Location	Main span (m)	Year
1	The Second Yangtze River Bridge in Wuhu	Anhui	806	2016
2	The Yachihe grand bridge	Guizhou	800	2014
3	The First Beipan River Bridge	Guizhou	720	2015
4	The Second Yangtze River Bridge in Fengdu	Chongqing	680	2013
5	Mei Yang Zhou bridge	Hunan	658	2021
6	Tongling Rail-cum-Road Changjiang River Bridge	Anhui	630	2012
7	Liuguang River Bridge	Guizhou	580	2015
8	Hongjun Bridge Over Chishui River	Sichuan	575	2021
9	Nanxi Yangtze River Bridge	Sichuan	572	2017
10	Longmen Yellow River Highway Bridge	Shanxi	565	2017
11	Xiangyang North Marshalling Yard Bridge	Hubei	520	2020
12	Shantou Queshi Bridge	Guangdong	518	1999
13	AnqingYangtze River Bridge	Anhui	510	2003
14	Honghe Bridge	Guangdong	500	2018

3. The structural composition and advantages of the OVM 250 PSC

3.1. The structure of the OVM250 PSC

Generally, the OVM250 stay cable system (as shown in figure 2) consists of anchorage caps, anchorages (fixed-end anchorage and adjustable-end anchorage), deviator (or damper), collar, waterproof cover (or anti-vandalism tube), HDPE pipe, HDPE sheathed strands and HDPE telescopic device, etc.

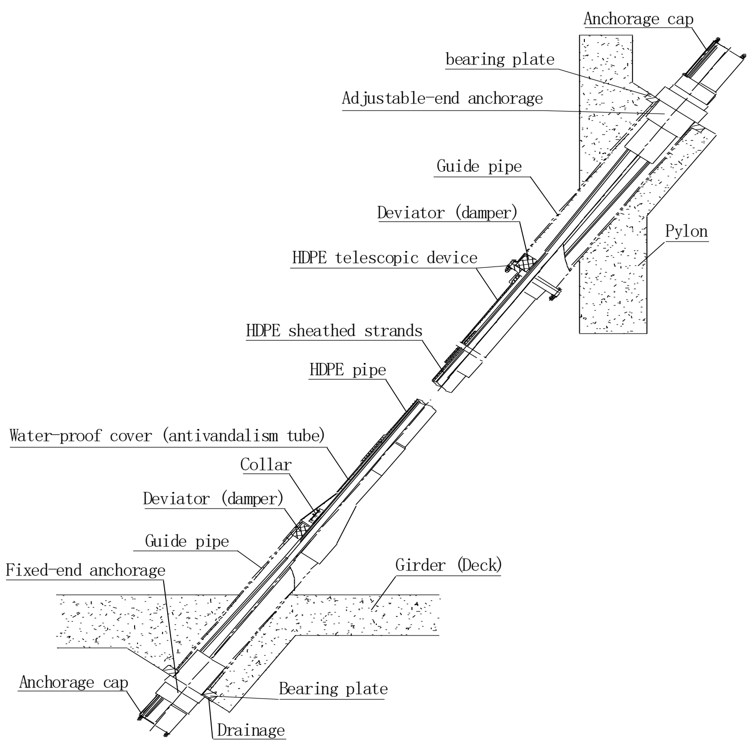


Figure 2. The structural drawing of the OVM250 PSC

3.2. The main advantages of the OVM250 PSC

3.2.1. Excellent corrosion protection of the PE sheathed strand

The main tension elements of the OVM250 PSC are a group of individually protected HDPE sheathed strands which have excellent durability and provide a degree of redundancy by means of three complementary, nested barriers. The first barrier is the galvanization applied directly on the seven-wire strand, the second barrier is the intermediate medium (wax) filled in the clearance between the wires of the stand and the HDPE sheath and strand, and the third barrier is the HDPE extruded outside the wax-coated strand.

3.2.2. Excellent fatigue and tensile performance

OVM250 anchorages are developed to provide high fatigue and subsequent tensile performance, which has been qualified in accordance with the latest PTI, CIP and fib recommendations. A large number of fatigue and subsequent tensile tests have been successfully carried out in independent laboratories. The anchorage assembly combined with 139 strands passed the fatigue test with a 250 MPa fatigue stress amplitude at 45% GUTS for 2 million load cycles and the subsequent tensile test.

3.2.3. Outstanding watertightness performance

OVM250 anchorage has a perfect elastic and compressible sealing structure, and its reliable waterproof performance has been proved by leak tightness testing under mechanical and thermal aging performed in accordance with fib bulletin 30 and Setra CIP recommendations.

3.2.4. Very easy installation, stressing, monitoring and replacing

The strands of the OVM250 PSC are individually installed and stressed on site. Strand by strand tension is applied to stress the strand individually so as to ensure the forces in the cable within a tolerance of ±2.5% of the stressing force at the end of construction. The CCT20 magnetic flux sensor, if applicable, can be equipped in the anchorage in advance to monitor the cable force during construction and in service life.

The strands in the cable are corrosion protected and anchored individually, which results in the advantages of the strand individual removal and replacement if necessary.

3.2.5. Good aerodynamic stability

The presence of the rivulets of water can modify the aerodynamics of the cable. In the OVM250 PSC, an HDPE pipe is manufactured with two helical ribs wound at 180° apart around to interrupt rivulets that may induce rain-wind vibrations of the cable.

The research on wind load performance of HDPE pipe based on wind tunnel test has been carried out at Tongji University State Key Lab of Disaster Reduction in Civil Engineering. The test results showed that the drag coefficient CD is less than 0.6 under high wind speed of 32.5~48.5 m/s, and there is no rain wind induced vibration with obvious amplitude and periodicity in the whole test range of wind speed and rainfall.

4. The main research on OVM250 PSC

4.1. Study on the mechanical performance if a single steel strand

According to the "S–N curve diagram of cables and single tensile members" suggested in the fib regulations, the fatigue resistance of a single steel strand needs to be approximately 80-100 MPa higher than that of the cable system [10]. Therefore, in order to develop the OVM250 steel strand cable system, it is necessary to first develop a steel strand that can withstand a fatigue stress amplitude of 330 MPa or higher.

To improve the fatigue resistance of individual steel strands, we improved the composition of steel wire rods and optimized manufacturing processes, with a focus on key process steps such as ingredient ratio, wire drawing, stabilization treatment, and dimensional accuracy control during steel strand production. We have developed steel strands with excellent fatigue resistance performance, with important performance parameters shown in Table 2.

Table 2. Main Performance Parameters of φ15.2 mm Steel Strands

Item	performance parameters
Nominal cross-sectional area	140 mm^2
tensile strength	≥ 1860 MPa
fatigue stress amplitude of base material（2 million cycles, stress upper limit 45% GUTS.)	≥ 330 MPa
elongation at break	≥ 5.0%
bias stretch factor	≤ 20%

4.2. The Reliability Design of the Anchoring Unit

The key anchoring component of anchorage is the wedge, which should have reliable static and low-stress anchoring performance and excellent fatigue resistance. The reliability of OVM250 anchorage is mainly achieved through the following measures:

Firstly, in the OVM250 anchorage designing, the reliability design and the finite element analysis (shown in Figure 3) are adopted, combined with a large number of tests on structural design and optimization.

Secondly, the wedge is specially designed to match the conical hole in the anchor head, which ensures uniform distribution of the occlusal stress along the entire wedge teeth and eliminates the influence of stress concentration and fretting wear on fatigue performance. The wedge can resist more than 330 MPa stress range at 45% GUTS for 2 million cycles, and in the subsequent static tensile test, the anchoring efficiency coefficient is greater than 95%. After the test, the wedge is intact.

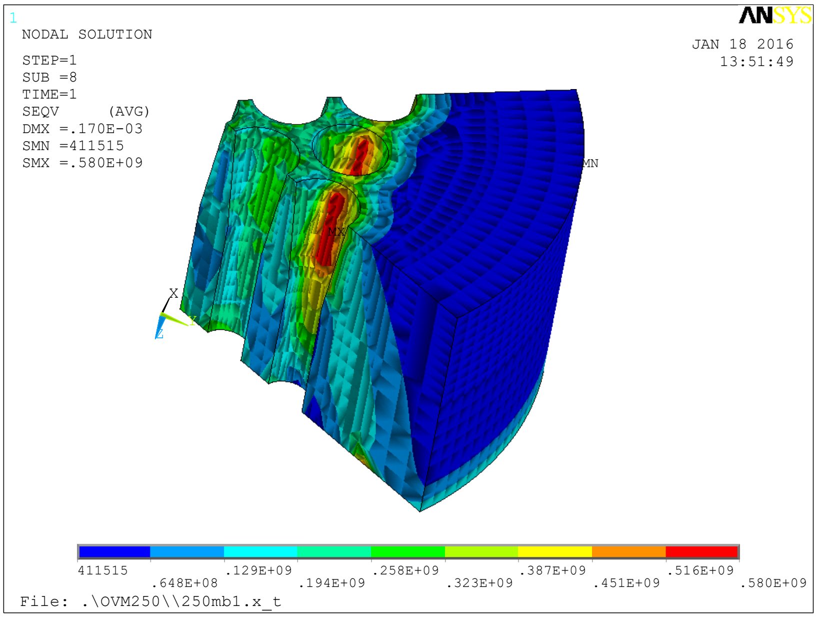


Figure 3. Finite element analysis of the anchor head of the OVM250 PSC

Thirdly, a special fully automatic controlled carbonnitriding heat treatment process is adopted to precisely control the carburized layer and surface hardness to optimize the metallographic structure of the wedge, which can ensure the toughness of the core of the wedge and the hardness of the teeth so that the teeth can bite into the base material of the strand, ensure reliable fatigue and ultimate performance.

Finally, in order to prevent fretting corrosion and fatigue, during the detailed design of the OVM250 anchorage, the protection against wear between the strands and anchorage is fully considered. In the anchorage zone, only steel-to-steel contact between the strand and the anchorage takes place at the wedge-strand anchoring points. All other contact areas are designed to be in contact with non-metallic components so that the lateral displacement of strands from the anchorage centerline can be filtered by the non-metallic material components. In order to prevent strands of the cable from generating excessive bending stress at the exit of the anchorage due to the installation error of the guide pipe, a trumpet-like shape holes are designed in the outer plate of the sealing device to guide each strand deviation curvature.

4.3. Fatigue and Subsequent Testing of the OVM250 PSC

Due to the influence of traffic loads, wind loads, etc., stay cables are always under variable loads in their service life, and excellent fatigue performance is extremely important for stay cables.

As we know, when the upper stress is the same, the magnitude of the stress variation is the key parameter of the fatigue test. In the CIP and fib recommendations, the stress range of 200 MPa is defined, and in the PTI recommendations, it is159MPa. In this point, the fatigue performance specified in CIP and fib is much stricter than that in PTI. After completion of the fatigue test, the same specimen shall develop a minimum tensile force of not less than 95%GUTS or 92%AUTS (Actual Ultimate Tensile Strength), whichever is greater.

In order to verify the fatigue performance of the OVM250 anchorage system, in the past 15 years, thirty (30) more fatigue tests with test specimens covering the representative designations with 15 to 156 strands have been carried out according to the requirements specified in the Sectra CIP, fib and PTI recommendations, most of which were performed in the USA CTL laboratory. The main fatigue test can be found in Table 3.

Table 3. List of main fatigue tests

No.	Type	Code	Fatigue stress limit	Fatigue stress amplitude (MPa)	Testing organization	Year
1	OVM250-31	PTI	0.45GUTS	200	CTL (USA)	2006
2	OVM250-55	CIP	0.45GUTS	200	CTL (USA)	2009
3	OVM250-37	fib	0.45GUTS	200	CTL (USA)	2011
4	OVM250-109	fib	0.45GUTS	200	CTL (USA)	2011
5	OVM250-27	JT/T771	0.45GUTS	200	China	2011
6	OVM250-139	CIP/fib	0.45GUTS	250	CTL (USA)	2012
7	OVM250-156	fib	0.45GUTS	200	CTL (USA)	2013
8	OVM250-73	fib	0.45GUTS	200	CTL (USA)	2017
9	OVM250-37	CIP	0.45GUTS	200	CSSRC (China)	2017
10	OVM250-55	CIP	0.45GUTS	200	CTL (USA)	2018
11	OVM250-61	CIP	0.45GUTS	200	CTL (USA)	2018
12	OVM250-15	PTI	0.45GUTS	200	CSSRC (China)	2018
13	OVM250-55	fib	0.45GUTS	200	CTL (USA)	2019
14	OVM250-61	fib	0.45GUTS	200	CTL (USA)	2019
15	OVM280-55	CIP/fib	0.45GUTS	280	CSSRC (China)	2019
16	OVM250-22	PTI	0.45GUTS	200	CSSRC (China)	2020
17	OVM250-55	PTI	0.45GUTS	200	CSSRC (China)	2020
18	OVM250-55	PTI	0.45GUTS	200	CSSRC (China)	2021

The fatigue tests cover a large range of representative stay cables, in which the cable of 139 strands has successfully passed 2 million load cycles fatigue test of upper stress 0.45GUTS with stress amplitude of 250MPa (the test setup shown in figure 4), which is much higher than the stress amplitude specified in CIP, fib, and PTI.

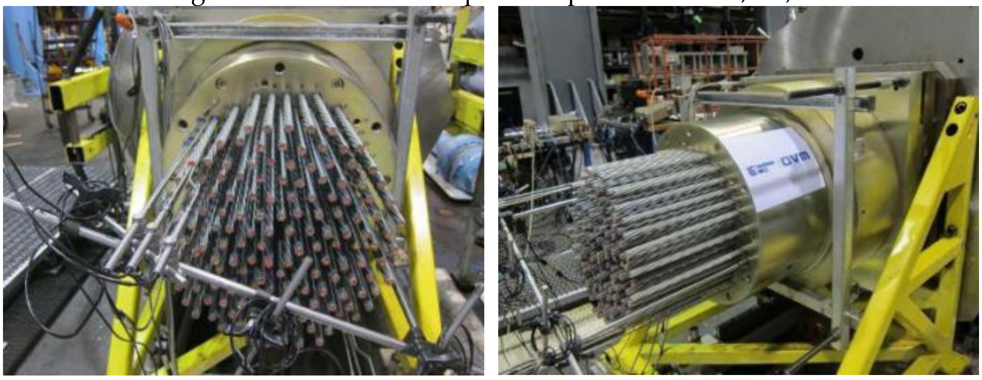


Figure 4. Fatigue test setup of the OVM250 anchorage system

4.4. Corrosion Protection Performance of the OVM250 PSC

Generally, cable-stayed bridges are built for crossing rivers, oceans, coastal harbors or mountain valleys etc. The application of stay cable system is basically in high-humidity environment, and the anti-corrosion of stay cables is particularly important. In accordance with bridge design requirements, the design life of cable-stayed bridges are usually more than 100 years. In the service life of the bridge, stay cables are allowed to be replaced once or twice, and the required design life of the stay cable system shall be more than 50 or 30 years. Based on international recommendations, high-performance corrosion protection is applied to the OVM250 PSC system.

4.4.1. Individual corrosion protection of strands

Following the “Reference system” defined in fib recommendations, in free length, the strands are protected by three complementary corrosion protection barriers: zinc (or epoxy) coated on 7 individual wires directly, HDPE sheath extruded outside the strand and the wax filled in the intermediate space among 7 wires and between strand and individual HDPE sheath.

In the anchorage zone, the HDPE sheath of the strand shall be removed for reliable wedge anchoring, the function of the HDPE sheath is replaced by the watertight anchorage, and the local casing of the anchorage is to be fully injected with the same wax used in the strand, which provides the second nested corrosion barrier to the zinc coating.

In addition, the individual HDPE sheathed strand meets the following tests specified in 3.3.9 of PTI DC45.1: chemical resistance, chloride permeability, impact, abrasion resistance and salt spray (fog) tests [11].

4.4.2. Corrosion protection of the anchorage and other components

OVM250 PSC is replaceable, in order to achieve the required design life of more than 50 years, adequate maintenance is needed, and the specific requirements depend on components according to their replaceability and accessibility.

The anti-corrosion system implemented on the anchorage and other components meets the C5M exposure class. For the exposed parts that are accessible for maintenance in situ, a corrosion protection system with a design life of 25 years is proposed, for example, and after this period. The protection system can be renewable in situ at regular intervals such as 15 years. The anchorage components that are not accessible for maintenance operation in situ after installation in the bridge are to be designed with a corrosion protection system that will remain effective during the design life without maintenance.

Traditional anchor ropes are usually treated with galvanizing for corrosion protection, with a thickness of 10 to 20 microns. However, this method has limited rust prevention capacity, and rusting may occur within 6 to 12 years [26]. To improve the anti-corrosion performance of anchor ropes, we have applied multiple layers of heavy-duty anti-corrosion technology, such as powder zinc infusion or hot spray zinc-aluminum, to anchor ropes. We have solved technical problems related to the taper fit between the anchor plate cone hole and the clamp and the thread fit between the supporting cylinder and the nut caused by the multiple layers of anti-corrosion coatings. The developed multiple layers of anti-corrosion coating anchor ropes have a coating thickness greater than or equal to 80 microns, which meets the anti-corrosion requirements of the ISO 12944 standard for marine corrosion environment C5-M [17] and has a theoretical anti-corrosion life of more than 50 years.

4.4.3. Water-tightness test of the OVM250 PSC

The purpose of the water-tightness test is to verify the adequate sealing of the stay cable system between the free length and the anchorage to avoid the ingress of water into the anchorage zone.

In order to verify the watertight performance of the OVM250 anchorage zone, 5 watertightness tests were carried out. The water tightness test of the OVM250-37 cable specimen combined the high requirements specified in the CIP and fib recommendations. The test set-up (as shown in figure 5) and procedures defined in the Setra CIP recommendations and a 3 m water head specified in fib are followed. After the test had been finished, the specimens were removed from the test rig and dissected for detection. No trace of coloring or dyed water ingress was found in the anchorage and on the strands sealed in the local casing of the anchorage.

Figure 5. OVM250-37 PSC watertightness test setup according to CIP recommendations

4.5. The durability of HDPE pipe

The HDPE pipe is designed to protect the individual PE sheathed strands from the direct action of UV radiation and to prevent rainwater from entering the cable. At the pylon side, the telescopic device is sleeved outside the HDPE pipe, which allows thermal expansion of the HDPE pipe without any tensile stress. Thus, the durability of the HDPE pipe relative to environmental stress cracking can be guaranteed, as hardly any stress arises during the service life.

The HDPE pipe is exposed to sunlight during the service life of the cable, and the photo-oxidation reaction will degrade the chemical bond between polyethylene molecules. The speed of photo-oxidation reactions depends on the UV radiation intensity, temperature and duration of exposure. Based on laboratory experiments on reaction speed, it is possible to compare accelerated aging tests to real life.

OVM and Sichuan University jointly conducted experimental research on the durability of HDPE pipes. A contrast-accelerated aging test on the HDPE samples under different constant tensile stress was designed and carried out. One set of samples was directly exposed to ultraviolet light, and the other set of samples was sleeved by a tube. In the UV accelerated aging test, the relationship between the aging cracking time and the tensile stress applied to the test samples is shown in Figure 6 and Figure 7.

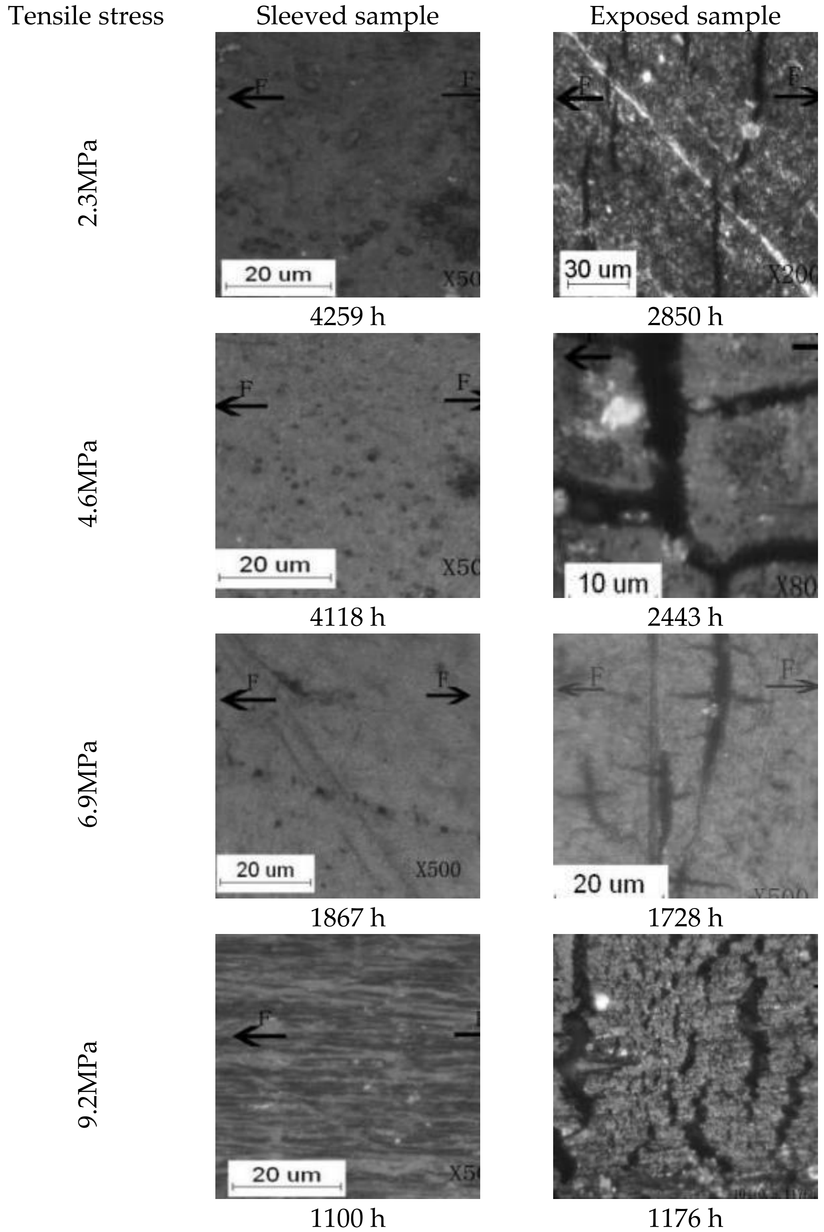


Figure 6. Microscopic Image of Aging and Cracking of HDPE Sheath

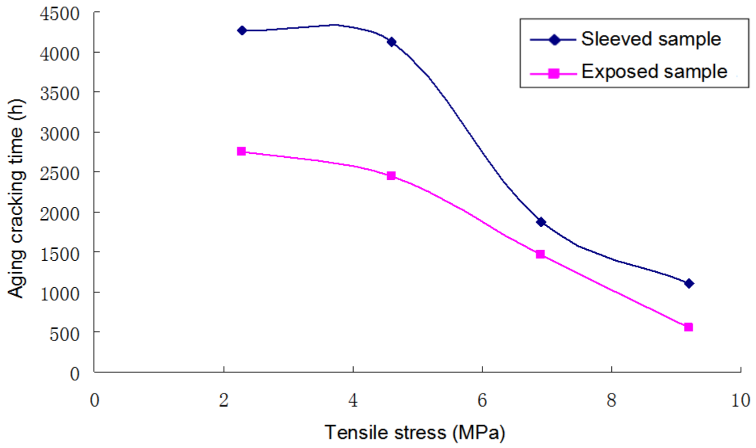


Figure 7. Aging cracking time — tensile stress curve in the UV acceleration test

From the experimental research test results, it is found that the stress in the HDPE sheath has a great impact on the service life, and the service life of the HDPE pipe can be greatly increased by ultraviolet isolation. As described above, in service life, there is no tensile stress in the HDPE. It can be speculated that the service life of HDPE pipes by adding anti-UV ingredients can be more than 50 years.

4.6. Vibration control

Generally, the causes of cable-stay vibration are of two types: one is displacement of anchorages under the effect of traffic or wind loading on the structure (deck or pylon), and the other is effects of wind acting directly on the cable stays.

4.6.1. External profile of HDPE pipe

The HDPE pipe consists of a co-extruded high-density polyethylene with a black internal layer and a colored external layer with double helix ribs. The double helix ribs can mitigate the effects of vibration on the stay cable induced by rain and wind.

Wrapping a double helix on the surface of the outer sheath of the cable will increase the wind resistance coefficient of the cable, which has a certain adverse effect on the wind load performance of the cable outer sheath. In most bridges, cable stays are in the super-critical range for extreme wind speeds, and a value of 0.7 is generally adopted for the coefficient CD to cover changes in the roughness of the sheath over time, as dust adheres to it and the materials weather [9]. In order to reduce wind-induced vibrations, in-depth experimental research was conducted on the wind load performance of the outer casing of the cable. Combining wind tunnel and wind-rain vibration tests, the aerodynamic shape of the outer casing was continuously adjusted, and the optimized design parameters of the double helix were obtained (shown in Figure 8), which not only effectively suppressed wind-rain vibrations but also had a low wind resistance coefficient, meeting the requirement of a wind resistance coefficient CD≤0.6 (shown in Figure 9).

Figure 8. The optimized double helix

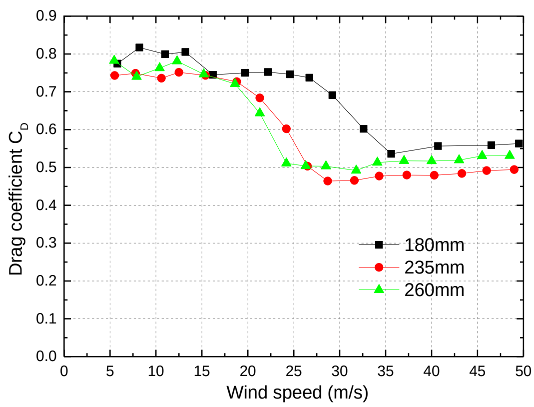
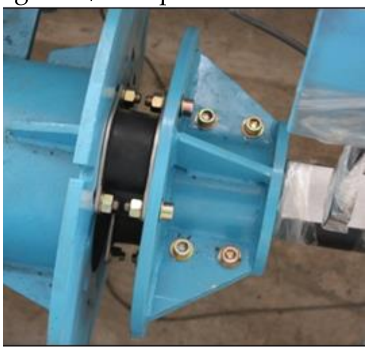


Figure 9. Variation of drag coefficient of cables of different diameters

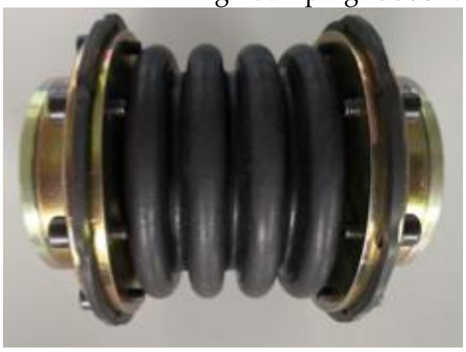
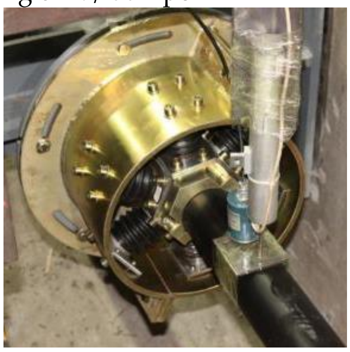
4.6.2. OVM proposed cable anti-vibration damping system

Based on the current technical and theoretical conditions, the installation of additional dampers is a more economical, simple and effective method for cable vibration control. Different forms of dampers have been widely used for stay cable vibration control. In order to meet the needs of cable vibration control in engineering projects, the proposed damping units and corresponding dampers for the OVM250 PSC stay cable system are shown in Figure 10.


Magnetorheological damping unit / damper

High damping rubber damping unit / damper

Viscous shearing damping unit / damper

Figure 10. Different damping units / dampers

For each type of damper, OVM and Tongji University jointly carried out a comparative application experimental study on the damping performance of different forms of dampers. The tests were completed in the cable over tensioning trench in the OVM cable manufacturing plant. In the test, the damper was installed at a distance of 0.04 Lstay (Lstay is 167.85 m) from the dead end anchorage after the cable was tensioned to its 0.50 GUTS (GUTS is 5460 kN). The cable was excited to vibrate by a vibrator in one single mode according to the modal frequency and then left to free decay. Sensors are installed to measure the accelerations (at 1/2, 1/4, and 3/8 of the cable length) and displacements (at the damper position and 1/2, 1/4, and 3/8 of the cable length) to evaluate the damping performance of the damper. The test results are shown in Table 3. Figure 11 takes the high damping rubber (HDR) damper as an example to show the attenuation effect for the first three-order vibration of the test cable.

Table 3. Logarithmic decrement test results for different dampers

Damper	**Logarithmic decrement (%)**		
	1st order (0.93 Hz)	**2nd order (1.86 Hz)**	**3rd order (2.79 Hz)**
No damper	0.25	0.25	0.25
HDR[1] damper	4.19	4.19	4.19

Damper	Logarithmic decrement (%)		
	1st order (0.93 Hz)	2nd order (1.86 Hz)	3rd order (2.79 Hz)
MR[2] damper	9.71	9.71	9.71
VS[3] damper	8.92	8.92	8.92

[1] HDR — High damping rubber.
[2] MR — Magnetorheological.
[3] VS — Viscous shearing.

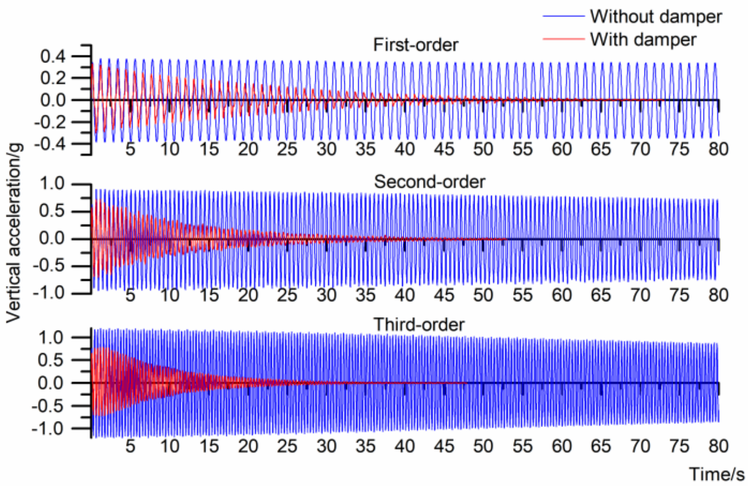


Figure 11. The decay curve of the test cable with the HDR damper applied

4.6.3. Selection principle of dampers

In accordance with the definition of Setra CIP and fib recommendations, for the cable with a length of less than 80 m, a rubber deviator is proposed to guide the cable from the transition zone to the free length.

The HDR damper with a minimum of three (3) damping units can effectively restrain the in-plane and out-of-plane vibration and axial rotation. According to the test results, the HDR damper can meet the logarithmic decrement requirement of 3%~4% for cables with lengths greater than 80 m and less than 200 m.

For the cables with a length of more than 200 m and a logarithmic decrement of more than 4% are needed, magnetorheological dampers or viscous shearing dampers are proposed.

5. Future Development and Outlook

Thanks to the application of new materials and new processes, the construction of modern super-long span bridges is ascendant. The particularity of the geographical location of super-long span bridges leads to the complexity of cable stay application environments. It is a general trend to carry out studies on stay cables with higher performance.

The rise of rail-cum-road bridges, and even the rise of bridges integrating highways and high-speed railways, will promote the study and application of the PSC system with high fatigue strength. The standard for railway cable-stayed bridges has increased the fatigue test stress amplitude to 280 MPa [30].

At the end of 2021, the China Iron and Steel Association held the final review meeting for the group standard - Ultra high strength steel strand (with nominal tensile strength not less than 2160 MPa) for prestressed concrete. The strength of the strand included in the standard is up to 2360 MPa. In the future, ultrahigh strength steel strand will definitely be introduced into the application of cable stays, which will bring about the advantages of reduction of cable weight, cable diameter and wind resistance. However, the increase in the tensile strength will increase the risk of hydrogen-induced stress corrosion cracking. Therefore, an adequate testing program shall be defined, and sufficient experimental research shall be carried out to evaluate hydrogen induced stress corrosion cracking to guarantee the safety and reliability of the application of ultra-high-strength strands in cable stayed bridges. The fatigue and subsequent tensile test research on anchorage system used for matching ultra-high-strength strands shall be carried out as well.

6. Conclusions

In practical engineering applications for 30 years, a large number of experimental studies have been carried out in combination with the actual needs of cable-stayed bridges. Through continuous improvement and optimization, the OVM250 PSC system has become a competitive product in the world that integrates durability, safety, reliability, and individual strand replaceability. Hereafter, the main achievements made in the process of experimental research and application are described:

Optimize the teeth shape of the wedge and the fit clearance of the anchoring unit to eliminate the fretting fatigue caused by stress concentration and fretting wear. The wedge can resist a fatigue range of 380 MPa under 0.45GUTS for 2 million fatigue cycles, which ensures the excellent fatigue performance of the OVM PSC system.

Optimize the sealing device of the anchorage. The sealing device is made of high elasticity and compressible material. The PE sheathed strand can be well squeezed by a compressed sealing plate to achieve the watertightness performance specified in the fib and Setra CIP recommendations, which ensures no weak point in anti-corrosion for the OVM250 PSC system.

By adding anti-UV ingredients and optimizing the formulation of HDPE raw materials, the anti-UV performance of HDPE pipes is greatly improved. Based on the cracking time of the HDPE specimen in the UV accelerated aging test, the estimated service life of the HDPE pipe will be more than 50 years.

Through comparative experimental research and analysis, the different types of dampers have different vibration control abilities. In project applications, appropriate dampers should be selected based on the cable length range to achieve a good vibration control effect.

References

1. Walton, J.M. Developments in steel cables. *J Constr Steel Res* **1996**, *39*, 3-29, doi:Doi 10.1016/0143-974x(96)00027-2.
2. Caetano, E. 23 - Cables. In *Innovative Bridge Design Handbook (Second Edition)*, Pipinato, A., Ed.; Butterworth-Heinemann: 2022; pp. 663-709.
3. Liu, Z.; Li, G.Q.; Paya-Zaforteza, I.; Cai, C.S.; Huang, Q. Fire Hazards in Bridges: State of the Art, Recent Progress, and Current Research Gaps. *Journal of Bridge Engineering* **2023**, *28*, 03123003, doi:10.1061/JBENF2.BEENG-5790.
4. Ouyang, P.; Chen, B.X.; Shen, Q.X.; Zhu, W.X. Theoretical analysis and design of fire protection and thermal insulation of parallel wire or strand cables. *Adv Mech Eng* **2022**, *14*, 1-18, doi:10.1177/16878132221127830.
5. Kotsovinos, P.; Atalioti, A.; McSwiney, N.; Lugaresi, F.; Rein, G.; Sadowski, A.J. Analysis of the Thermomechanical Response of Structural Cables Subject to Fire. *Fire Technology* **2020**, *56*, 515-543, doi:10.1007/s10694-019-00889-7.
6. Pipinato, A. *Innovative bridge design handbook : construction, rehabilitation and maintenance*; Butterworth-Heinemann is an imprint of Elsevier: Amsterdam, 2016; pp. xxxii, 844 pages.
7. Ahmed, A.R.; Ermoshin, N. Assessment of the Cable-Stayed and Cable Damping System Used in the Russky Bridge and Determination of the Force Acting on the Bridge's Cables. Cham, 2023; pp. 2719-2730.
8. Hamilton, H.R.; Breen, J.E. International survey of current opinion on bridge stay cable systems. In Proceedings of the IABSE Symposium: Extending the Lifespan of Structures, San Francisco, 1995; pp. 843-853.
9. Paris Service d'Etudes Techniques des Routes et Autoroutes. *Cable Stays: Recommendations of french interministerial commission on prestressing*; Setra, 2002.
10. fib bulletin 30 *Acceptance of stay cable systems using prestressing steels*; International Federation for Structural Concrete: 2005.
11. Post-Tensioning Institute. *Recommendations for Stay Cable Design, Testing, and Installation*, 7 ed.; Post-Tensioning Institute: 2018.

12. Winkler, J. Parallel mono-strand stay cable bending fatigue. Technical University of Denmark, 2014.
13. fib bulletin 89 *Acceptance of cable systems using prestressing steels*; International Federation for Structural Concrete: 2019.
14. Hamilton, H.R., Iii. Investigation of corrosion protection systems for bridge stay cables. The University of Texas at Austin., 1995.
15. Fang, Z.; Pang, W. OVM250 stranded steel cable system. *Highway* **2007**, 52-57, doi:10.3969/j.issn.0451-0712.2007.06.012.
16. Comité Européen de Normalisation (CEN) EN 10204 Metallic products - type of inspection documents. 2004.
17. International Organization for Standardization (ISO) ISO 12944 Paints and varnishes - Corrosion protection on steel structures by protective paint systems. 2018.
18. International, A. ASTM B117-19 Standard Practice for Operating Salt Spray (Fog) Apparatus. West Conshohocken, PA, USA, 2019.
19. (AFNOR), A.F.d.N. XP A35-037 Textiles - Tests for colour fastness - Part A37: Determination of extractable dyes. Paris, France, 1993.
20. International, A. ASTM G14-13a Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test). West Conshohocken, PA, USA, 2013.
21. Sun, L.M.; Chen, L.; Huang, H.W. Stay cable vibration mitigation: A review. *Adv Struct Eng* **2022**, *25*, 3368-3404, doi:10.1177/13694332221132316.
22. Zhang, R.W.Z.; Dong, C.; Huang, Y. Fast Algorithm and Its Application in Construction Monitoring of Parallel Strand Cables. *Journal of Bridge Engineering* **2015**, *20*, 04014100, doi:10.1061/(Asce)Be.1943-5592.0000699.
23. Ye, L. Erection of parallel strand cables on shantou queshi cable stayed bridge. *Bridge Construction* **1999**, 36-39.
24. Wan, T.; Zhang, Q. Key techniques for design of main bridge of Tongling Yangtze river rail-cum-road bridge. *Bridge Construction* **2014**, *44*, 1-5, doi:CNKI:SUN:QLJS.0.2014-01-001.
25. Pang, R.; Lei, H.; Wei, Y.; Qin, L.; Zhu, Y.; Shi, W. Experimental study and application of bridge cable fireproof insulation system. *Northern Communications* **2022**, 25-29, doi:10.15996/j.cnki.bfjt.2022.04.007.
26. International Organization for Standardization (ISO) ISO 14713-1:2017 Zinc coatings - Guidelines and recommendations for the protection against corrosion of iron and steel in structures - Part 1: General principles of design and corrosion resistance. Geneva, Switzerland, 2017.
27. Poser, M. Full-Scale Bending Fatigue Tests on Stay Cables. University of Texas at Austin, 2001.
28. Shen, G.; Macdonald, J.; Coules, H. Bending Fatigue Life Evaluation of Bridge Stay Cables. *J Eng Mech* **2022**, *148*, 159-166, doi:10.1061/(Asce)Em.1943-7889.0002064.
29. Lan, C.M.; Xu, Y.; Liu, C.P.; Li, H.; Spencer, B.F. Fatigue life prediction for parallel-wire stay cables considering corrosion effects. *Int J Fatigue* **2018**, *114*, 81-91, doi:10.1016/j.ijfatigue.2018.05.020.
30. China State Railway Group Co. Ltd. Q/CR 906.2-2022 Cable of railway cable-stayed bridge Part 2: steel strand cable. China railway publishing house: Beijing, 2022.

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