MULTI-TUBE SADDLES FOR STAY CABLES

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Saddle systems for stay cables are at the moment one of the preferred solutions in the field of cable-stayed bridge design across the world, and this trend seems to increase day by day.

A stay cable saddle system allows the bundle of tensile elements to run continuously from one anchorage to the other, both at deck level, without using a terminal anchorage at pylon level. This provides a remarkable reduction in the overall dimensions of the pylon and, as a consequence, material savings as well as aesthetically pleasing architectural shapes.

The most advanced systems currently available for parallel strand stay cable systems are multi-tube friction saddles, where each single strand runs into an individual tube and the stay cable differential force is transferred by friction.

The structural behavior of a specific saddle device is a very complex topic involving many mutually dependent aspects. The development and validation of saddle systems is usually performed in design assisted by testing, a procedure which is making its way in the civil construction field.

An extended testing campaign has been performed to investigate the saddle behavior. Tests have been carried out, taking into account current developments of international recommendations, such as PTI DC45.1-12 and fib Bulletin 30. Friction, fatigue, and static behavior have been assessed through full-scale tests executed in the Structural Laboratory of Politecnico di Milano (Italy). This paper describes the results of these tests and the main design considerations that follow.

INTRODUCTION

Multi-tube saddle systems have become usual solutions in cable-stayed and extradosed bridges, mainly as a consequence of the sensible savings of material provided in the pylon erection. As a matter of fact, the absence of anchorages at pylon level allows the designer to reduce the overall dimension of the tower, making it more slender and, as a consequence, architecturally elegant and graceful.

On the other hand, a stay cable saddle is a complex structural system whose correct behavior is, in many cases, intrinsically nonlinear and strictly dependent on a proper detailing of all its components. Moreover, inspectability, maintenance, and replaceability of the stay cable system can be more complicated when saddles are present.

A careful design of the saddle and an accurate installation procedure are the two main keywords for a safe behavior of the cable-stayed bridge.

DESIGN HINTS

In general terms, a stay cable saddle is a structural device that allows continuous deviation of the tensile elements from the deck through the tower and back to the deck, as well as transferring the stay cable force into the pylon. The most advanced systems available by now are multi-tube saddles, where each single strand runs into an individual pipe and the differential stay cable force—that is, the difference between the forces acting at saddle ends—is resisted by friction.

The first key point to be considered when designing a saddle is of course its geometry, which in many cases is dictated by the configuration chosen for stay cables. It is clear that the stress level in the cable is strictly influenced by the saddle. In other words, the uniform tensile stress distribution produced by permanent and live loads over the stay cable cross section is locally disturbed by bending stresses induced by the geometrical curved configuration of the saddle. Such bending stress distribution is difficult to be properly predicted due to the intrinsically nonlinear interaction among wires. Many formulas are available in literature to compute the bending stress developing

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in a curved rope. However, different formulas often lead to completely different stress values, which are in many cases very high with respect to what is observed on actual stay cables.

The maximum bending stress in a bent rope can be computed assuming the same behavior of a beam to which a curvature is imposed. Let E, d, and D be the elastic modulus of the material, the diameter of the rope, and the diameter of the curve, respectively. Thus, the so-called Reuleaux's formula is obtained

$$\sigma_b = E\frac{d}{D} \tag{1}$$

Equation (1) provides the maximum bending stress inside a rope or a strand under the assumption of perfect interaction between wires composing the rope or the strand. However, this behavior is only valid when stresses are small. For increasing bending stress, the external wires may slip and the bending stress reduces abruptly.

In the specific case of spirally coiled wires, Timoshenko's formula provides the bending stress as a function of the strand lay angle α.

$$\sigma_b = E\frac{d}{D}\frac{2\cos\alpha}{2+\nu\cos^2\alpha} \tag{2}$$

In literature, plenty of formulas have been proposed to correct the first one, taking into account the actual working condition of a rope. For instance, Bach's formula, used for ropes, introduces an effective elastic modulus $E_0 = 3/8E$.

$$\sigma_b = \frac{3}{8}E\frac{d}{D} \tag{3}$$

Carstarphen's formula modifies the previous formula using an effective elastic modulus equal to $E_0 = 0.44E$.

$$\sigma_b = 0.44E\frac{d}{D} \tag{4}$$

Taking into consideration a standard seven-wire, 15.7 mm nominal diameter strand with 5.2 mm nominal diameter external wires helicoidally coiled around the central king wire and a saddle with a 3000 mm radius, the maximum bending stress for each of the previously introduced formulas is summed up in the following table. It can be seen that, regardless of the approach used, the bending stress is often not negligible (Table 1).

The accurate estimate of the maximum bending stress in a strand is a complex topic out of the scope of this paper. It is worth noting that bending stresses may dramatically affect the behavior of a bent stay cable and, therefore, must always be taken into account.

Secondly, interaction between strand and pipe may produce fretting fatigue phenomena, leading to significant damage of the strand and even breakage. Proper saddle detailing must be carried out to avoid any unintentional contact, which may lead to sudden and brittle failure of the strand.

The design of a multi-tube saddle must investigate all of the main aspects characterizing its response, which can be summed up as follows:

1. Mechanical performance:
   a. Transfer of differential stay cable forces (by friction in a multi-tube friction saddle);
   b. Fatigue strength; and
   c. Static efficiency.
2. Functional performance:
   a. Corrosion protection; and
   b. Replaceability.

Friction influences the force transmission from the stay cable to the pylon and may remarkably affect the saddle device's structural efficiency. As a rule of thumb, the higher the friction, the greater the horizontal load that the saddle can transfer to the pylon. Thus, the friction coefficient developing at the interface between strands and pipes becomes an important design parameter required by designers to control the maximum unbalanced load acting upon the deck.

The differential force transferred by the cable shall then go from the saddle to the pylon. To this purpose, shear connectors (studs or plates) are usually used to improve the stress transfer to concrete, which otherwise would just rely on bond.

The width of the saddle should be designed in such a way that pressure transmitted to the underlying concrete in the most severe load combination would be small enough to avoid any concrete failure.

CODE REQUIREMENTS

A base assumption of all main international recommendations is that a stay cable system with a saddle shall exhibit the same performance level of a standard stay cable system, anchored at pylon level with anchorages.

Table 1:

	Bending stress σ_b	
	MPa	%GUTS
Reuleaux	510	27
Timoshenko	507	27
Bach	191	10
Carstarphen	225	12

This refers to both the mechanical performance and the functional ones—that is, the saddle system has to ensure corrosion protection and replaceability of any individual strand of the bundle.

The analysis of the structural behavior of a specific saddle system is a very tough task and involves many independent aspects. For this reason, it cannot be approached from the theoretical point of view only. Development and validation of stay cable saddles is usually carried out in the so-called design assisted by testing. Actually, testing plays a crucial role in the evaluation of the structural and functional response of these devices.

Design, testing, and installation of saddles are generally performed according to either PTI DC45.1-12 (2012) or *fib* Bulletin 30 (2005). These are the two main international recommendations addressing stay cable systems.

fib Bulletin 30 does not have any specific requirement about friction, while PTI DC45.1-12 clearly requires that the friction coefficient is assessed through testing. However, testing details and conditions are not specified.

According to EN 1993-1-11, Section 6.3.2, the friction phenomenon in the saddle, assessed through the belt friction equation (Capstan equation or Eytelwein's formula), should prevent slippages. To this purpose, the following condition should be met

$$\max\left\{\frac{F_{Ed1}}{F_{Ed2}}\right\} \leq e^{\frac{\mu\theta}{\gamma_{M,fr}}} \quad (5)$$

where F_{Ed1} and F_{Ed2} are the design values of the maximum and minimum force, respectively, on either side of the cable; μ is the coefficient of friction; θ is the angle (in radians) of the cable passing over the saddle (deviation angle); and $\gamma_{M,fr}$ = 1.65 is the partial safety factor for friction (resistance factor).

It is reasonable to define the friction coefficient as a mean value, averaged over all the tubes for any specific saddle device. However, the recommendations do not provide any information on this topic.

In addition, current recommendations do not explain whether or how fatigue may affect the friction coefficient, even though a slight reduction in friction, due to progressive system use, seems quite reasonable.

Moreover, further and detailed information should also be provided on testing conditions, saddle deviation angles to be tested, and load levels. However, a need for recommendations improvement on the aforementioned topic is well known. More complete requirements are now under discussion and will be introduced in the next versions of the main international recommendations on cable-stayed bridges.

Both PTI and *fib* recommendations require carrying out a tensile fatigue test, which aims to validate the stay cable behavior in service conditions. The test is carried out over a specimen having at least 2 m free length, installed with a 30-degree inclination against horizontal and subjected to a 10 mrad angular deviation at saddle exits. The saddle must be moved vertically for 2 million cycles between a lower and an upper configuration corresponding to a stress in the stay cable equal to 45%GUTS-$\Delta\sigma$ and 45%GUTS, respectively. The general test procedure presented by the two standards is precisely the same, but *fib* Bulletin 30 is a little more stringent. As a matter of fact, *fib* recommendation introduces a stress range for parallel strand stay cable of 200 MPa, greater than the one reported by PTI DC45.1-12, equal to 110 MPa plus 35 MPa through vertical movement of the saddle. Acceptance criteria are the same for both standards (2% maximum wire fractures) while, for small-sized cables, PTI DC45.1-12 accepts a slightly greater number of wire fractures than *fib* Bulletin 30(three instead of two). In addition, both standards require that no cracking or fracture develop in the anchorages material.

For these reasons, a stay cable saddle fatigue test carried out achieving all *fib* requirements also satisfies the PTI requirements.

At the end of the fatigue test, the static efficiency of the stay cable system, linked up with its behavior at the ultimate limit state, must be tested. *fib* Bulletin 30 requires the performance of a tensile static test in which the stay cable is symmetrically loaded to reach the maximum attainable stress. The stay cable shall develop a minimum tensile force equal to 95% GUTS or 92% AUTS, whichever is greater.

TESTING CAMPAIGN

The TENSA multi-tube saddle system TSS-T is a steel welded box member, provided with several parallel steel pipes embedded into a high-strength cement mortar

(Fig. 1). The inner surface of each tube is covered with a special high-friction compound.

To assess the behavior of the TSS-T saddle system, a wide testing campaign was developed over a period of almost 3 years. Most of the tests were carried out at the Structural Engineering Laboratory of Politecnico di Milano, following recommendations described previously and introducing additional improvements in testing protocols.

Friction tests were performed over several TSS-T saddle systems, varying both the geometrical configuration and the loading condition. Taking into account all of the actual inclinations that a stay cable can have on a bridge, the friction coefficient was measured on saddles with deviation angles ranging between 30 and 150 degrees (Fig. 2 and 3).

Stay cables were subjected to different initial loads smaller than 50%GUTS, which is the maximum design working load of the stay cable. To properly evaluate the effect of the actual force in the cable, friction was measured on the same saddle for several load levels (20%, 25%, 30%, and 35%GUTS).

As expected, tests proved that neither the saddle deviation angle nor the stay cable initial tension significantly affect friction and provided friction coefficients ranging between 0.35 and 0.42, with an average value equal of 0.40.

To further analyze the saddle capacity, a full-scale tensile fatigue and static test was performed over a seven-strand saddle system (Fig. 4 and 5).

To this purpose, a 10-ton steel frame was designed, manufactured, and assembled in the laboratory to resist all of the loads expected for the test, with the stay cable configuration as close as possible to the one actually adopted on site. Expensive and dedicated equipment was

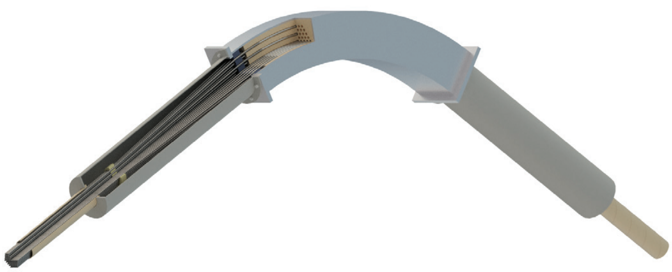

Fig. 1—TENSA multi-tube saddle system TSS-T.

Fig. 2—Setup for friction test over a multi-tube saddle with remarkable deviation angle.

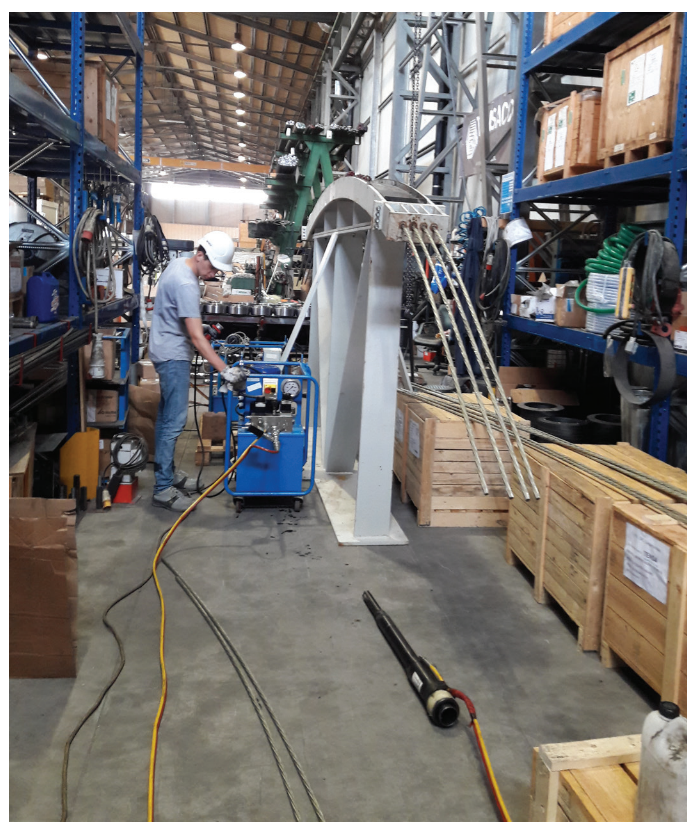

Fig. 3—Setup for friction test over a multi-tube saddle with small deviation angle.

used to stress the stay cable and to impose the vertical movement of the saddle. Moreover, all the components generally used in the free length, transition length, and anchorage zone of the stay cable—that is, deviator disks, wax boxes, and so on—were included in the test.

The real working condition on site was simulated embedding the saddle into a concrete block representing the bridge pylon. In addition, after the stressing phase, the saddle was filled with a protective material able to provide adequate corrosion protection to the strands.

Tensile fatigue test was carried out at 1.20 Hz mean frequency and lasted approximately 20 days. No wire fracture or damage in the saddle and in any component of anchor heads occurred during testing, as confirmed by a system of accelerometers that the laboratory installed on the sample to continuously monitor the cable state and, subsequently, by a visual examination carried out during dismantling. The testing fully met acceptance criteria introduced by *fib* Bulletin 30 and PTI DC45.1-12, and the system exhibited an excellent performance with respect to fatigue loading.

During the subsequent static tensile test, the seven-strand stay cable was loaded up to the maximum attainable force and a load corresponding to 97.5% of GUTS and 96.2% of AUTS was recorded. The load level reached totally satisfied the acceptance criteria of *fib* Bulletin 30. A significant stay cable elongation, equal to approximately 1.90%, was reached in the final test stages. Because it corresponded to the testing rig hydraulic jack's end of stroke, the load level was not further increased and, therefore, the test was stopped.

At the end of the static test, no evidence of damage of the saddle system and anchorages was detected. Moreover, after almost 1 month of direct exposure to atmosphere, no corrosion was noticed over any component of the tested system.

Other friction tests were performed at the end of the static test to estimate the effect of both fatigue and the strand's large strain on the friction coefficient. Values ranging from 0.25 to 0.39 were observed.

Such a decrease in friction is due to the remarkable use of the system—that is, pipe's surface and high friction compound—produced by the fatigue test and the subsequent static test. Thus, the measured friction coefficients should be considered as minimum values for ultimate limit state—that is, lower bound of the actual friction coefficient that the saddle is able to provide.

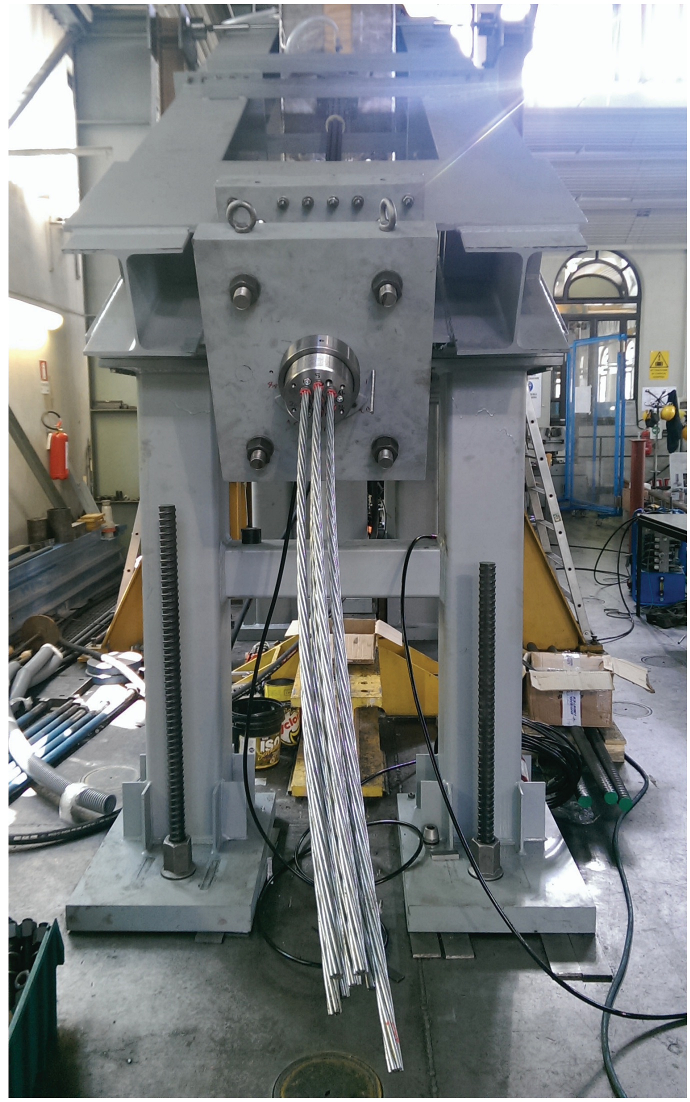

Fig. 4—Setup for tensile fatigue and static test over a seven-strand multi-saddle (front view).

Fig. 5—Setup for tensile fatigue and static test over a seven-strand multi-tube saddle (side view).

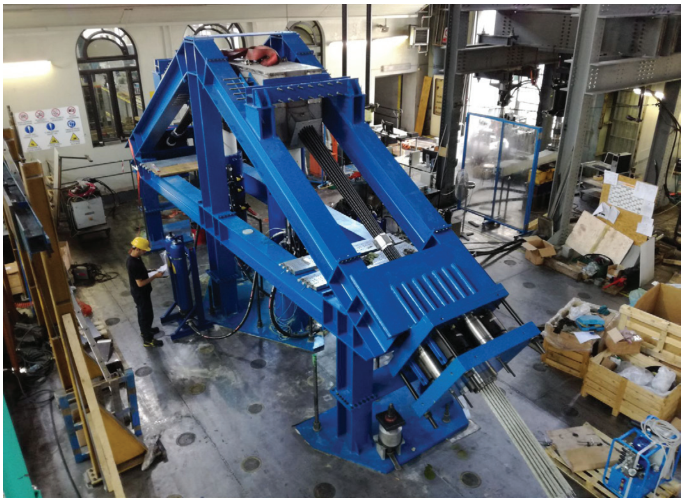

Fig. 6—Setup for tensile fatigue and static test over a 37-strand multi-tube saddle.

Fig. 7—Special dynamic jacks for fatigue testing and saddle block positioning.

The high performance of the system detected during the tensile fatigue and static tests over the seven-strand saddle system proved that saddle devices are perfectly able to carry fatigue loading—corresponding to traffic loads on the bridge—and, moreover, can be designed not to affect the stay cable performance in terms of static efficiency. However, the tested saddle was fairly small compared to what is often required and supplied on site.

The increase in dimensions may dramatically affect the actual structural behavior of a component due to an inevitable size effect. Additionally, a wider size means higher load levels as well and, in many cases, important deviation of the bundle.

For all these reasons, another tensile and static test was performed on a 37-strand saddle system, again in the Structural Engineering Laboratory of Politecnico di Milano (Fig. 6). A dedicated 25-ton steel structure was designed, produced, and assembled. The impressive load level required by testing according to *fib* Bulletin 30 required special dedicated fatigue and tensile equipment with high capacities and an accurate control system (Fig. 7). As previously mentioned, the necessity to build a testing setup as close as possible to the actual site configuration in a laboratory requires imposing important deviations to the bundle. Special attention must be paid to this point because it can dramatically affect the system performance.

A tensile fatigue test was carried out at 1.55 Hz average frequency and lasted approximately 15 days. The system of accelerometer installed to monitor the cable during fatigue cycles recorded several events during the fatigue test. However, as confirmed during dismantling, only two wires broke due to fatigue, while others were stabilizing movements from the massive steel structure. Compared to the total amount of 259 wires, the loss of stay cable cross section due to fatigue was approximately 0.77%, well below the 2% limit required by *fib* Bulletin 30. This first important result confirmed the good behavior of the stay cable system deviated by a saddle device.

During the subsequent static tensile test, the 37-strand stay cable was again loaded up to the maximum attainable force and a load corresponding to 95.9% GUTS and 93.2% AUTS was recorded. The load level reached totally satisfied the acceptance criteria of *fib* Bulletin 30. Due to the notable force imposed to the cable, the test was stopped for safety reasons to avoid any further dangerous breaks. A cable elongation equal to approximately 1.53% was reached at the end of the test.

During dismantling, two strand failures were detected. The first one was located at saddle exit, where the resisting cross section of the strand was reduced due to fatigue wire break. The other failure was recorded in the deviation length of the stay cable, close to the deviation system. No evidence of damage of the saddle system and anchorages was detected—just some negligible steel powder was observed on several strands due to an incipient fretting fatigue phenomenon.

The testing campaign provided a widespread and complete insight into the structural and functional behavior of multi-tube saddles, accounting for several working conditions. Particularly, the TSS-T saddle system matched all the existing recommendations requirements—that is, providing a structural performance equivalent to what is expected for a traditional stay-cable system, and gave up satisfactory responses for the conditions not fully described and detailed in the current recommendations.

CONCLUSIONS

A wide and expensive testing campaign was carried out during the last 3 years to develop performing multi-tube saddle systems for stay cables, able to fulfill all the requirements introduced by the main International Recommendations. Tests provided a lot of important and satisfactory results, which gave a complete and clear view of the structural behavior of these devices.

The TENSA multi-tube saddle system proved to be adequate to withstand all of the severe loading conditions required by testing, providing at the same time enough friction to avoid any strand slippage and, also, ensuring a suitable level of strand corrosion protection as required during testing by *fib* Bulletin 30 and PTI DC45.1-12. The good results obtained in all the performed tests provided good confidence in the use of multi-tube saddle systems within cable-stayed bridges.

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