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Proposal for the application of carbon fiber reinforced polymers (CFRP) for suspenders of arch bridges in China

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ABSTRACT: Arch bridges have been a main bridge type in China since ancient times. In modern time the application of steel and composite materials to the arch bridges enriched the structural type of those, i.e. the half-through and through arch apart from the deck arch. In through and half-through arch bridges, the dead-load of the deck system and the live load are transferred to the arch rib by suspenders. Therefore, suspenders are the most critical load-carrying members. They are exposed to fatigue and corrosion. Easy installation and low cost are important factors within the application of suspenders. In the past few years, there were failures of steel suspenders due to corrosion and fatigue. Even the collapse of bridge decks happened due to suspender failures. It is definite that the corrosion and fatigue resistance of suspenders have to be enhanced.

Realizing the excellent properties of carbon fiber reinforced polymers (CFRPs), including corrosion resistance, very high specific strength and stiffness, superior equivalent moduli and outstanding fatigue behavior, a proposal for the application of CFRPs for suspenders will be introduced.

1 INTRODUCTION

The arch bridge has been a main bridge type in China since ancient times. At those times the construction materials for arch bridges were stones. Since stones have no reliable tensile strength, compression-dominant designs had been selected. Thus, the roadway was following the contour of the arch or the space between the arch crown and the skewback has been filled with stones to avoid an up and down of the roadway. It was not until the early 1800s that wrought iron and later steel began to replace stones in bridge construction.

The application of steel allowed the design of new bridge types. Especially for the arch bridge, the deck can be suspended with tendons on the arch. This leads to the appearance of half-through and through arch bridges. Apart from their pleasing appearance, less self-weight and an easy to erect design became remarkable characteristics. In addition the application of concrete and concrete filled steel tubes for the construction of arches further enriched the structure form for half-through and through arch bridges.

In through and half-through arch bridges, the dead-load of the deck system and the live load are transferred to the arch by suspenders. Therefore, the suspenders are most critical load-carrying members. They require a high fatigue and corrosion resistance and have to be easy to install at low cost. A suspender system is a combination of several individual components working efficiently as a unit. Currently, the suspenders are made of steel rods, high-strength steel wires or steel strands. The anchorages at either termination play a decisive role in achieving an optimal exploitation of the steel tendons.

There are many kind of termination assemblies, such as the classical zinc poured spelter and the wedge sockets. Since 1948 are the button head wire anchorage sockets, patented by BBRV and described by Birkenmaier, Brandestini, and Roš, (1952) in use. As called high-amplitude (HiAm) terminations have been developed in the 1960s by Andrä & Zellner (1969) in co-operation with BBRV especially for cable stayed bridges and for the roof of the Summer Olympics in Munich in 1972 as shown by Meier (1971). According to Andrä & Saul (1974) is the fatigue performance of such HiAm-terminations excellent. This might be the main reason that those are popular these days in China for the anchorage of suspenders.

2 THE SITUATION IN CHINA TODAY

It is well accepted in the global bridge engineering community that suspenders are for the long term reliability and safety a key element in the design of half-through and through arch bridges. Therefore problems with metallic suspenders will be discussed in the following sections.

2.1 Corrosion

Corrosion and fatigue are worldwide the most severe challenges for suspenders of suspension, half-through and through arch bridges and also for stay cables of cable stayed bridges. Hamilton et al. (1995), Martin & Blabac (2009), and Yanev (2009) presented numerous case studies for North America and Europe.

The construction of arch bridges with suspenders began in China about twenty years ago and it has grown dramatically over the last decade. In early stages was the corrosion protection of the suspenders in many instances not sufficient. After only 5 to 10 years of service, corrosion and fatigue problems appeared in a number of cases in the suspenders, which became a potential danger for some bridges.

For certain classes of steel high sustained stresses might also cause the dangerous stress-corrosion, which is difficult to detect.

Even when the designers realized the existing corrosion problems in suspenders and took some measures, the results are often still unsatisfactory.

2.2 Fatigue

Suspenders are subjected to high tensile forces and high stress variations, thus high fatigue resistant cables are of great importance. Designers always paid much attention to the strength requirements, but often neglected fatigue. Even if fatigue is considered, they just controlled the stress amplitude within a certain range. The vehicle-induced vibrations, impact, and subsidiary stress resulting from wind, wind-rain, vortex, and galloping oscillations, as described by DIN (2007) in the German recommendation “Design rules for suspenders of through arch bridges”, have mostly been ignored in the suspender design. Since the stress amplitudes in the static analysis of the arches are not very large, designers seldom checked for the fatigue loading of suspenders. To some extent, the durability of a half-through and through arch bridge relies on the suspender fatigue resistance.

2.3 Fretting fatigue

The ASM "Handbook on Fatigue and Fracture" defines fretting as: "A special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force." Such fretting fatigue might happen on the load side of sockets grouted with epoxy or even more critical with cement mortar. In the region, where the steel wires get first in touch with the grout, there is during the first loading a concentration of the shear stresses at the wire surface. Due to this high shear stresses there is debonding of the wires from the grout over a length of some few millimeters. Under fatigue loading there is now a relative displacement between the edges of the grout and the wires. Wear and fretting fatigue starts as shown in the example of Fig. 1.

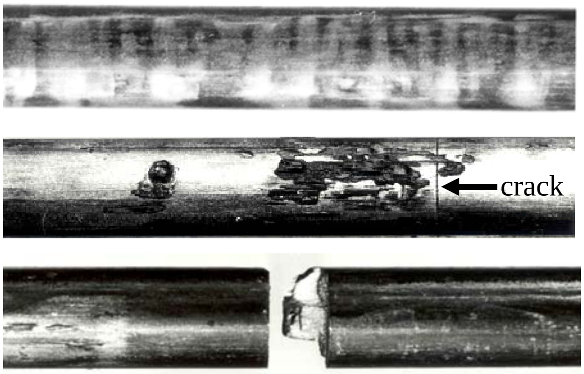


Figure 1. Fretting fatigue of high strength steel wires of 7 mm diameter due to wear between an epoxy grout and the steel wire surface. There were several crack planes; not only at the first interface on load side. *Top picture:* the bright "polished" zones show wear due to the friction of the epoxy. *Middle picture:* the wire is already having a crack due to fretting. Due to stress concentration and fatigue it will fail within few thousand additional load cycles. *Bottom picture:* broken wire due to fretting fatigue (source: Empa report 73844/1970/stay cable fatigue testing).

2.4 Superimposed bending stresses

Apart from the aforementioned problems, a special concern should be put on the shortest suspenders. They are generally located near the springing of the arch. They have a short free length, which makes their bending stiffness comparatively high. Horizontal relative displacements between the top and bottom ends of the suspenders lead to bending moments. These resulting bending stresses have to be superimposed to the normal stresses. There might be a three-dimensional stress state, especially dangerous in the case of fatigue. In addition, the temperature variation will also have great effect on the short suspenders.

2.5 Case study Xiao-nan-men Bridge

The Xiao-nan-men Bridge was built in 1984 and opened to traffic on June 30, 1990. It is a half through reinforced concrete arch bridge with a total length of 387m. The clear span of the arch is 240m and the rise is 48m, i.e., a rise-to span ratio of 1/5. Fig. 2 shows the bridge before the deck collapsed. In the early morning about 4:00a.m on Nov.7, 2001, the deck of Nan-men Bridge, about 40m in the south and 20m in the north, partly collapsed due to several pairs of broken suspenders. Fig. 3 shows the bridge after the collapse.

Figure 2. Xiao-nan-men Bridge.

Figure 3. Xiao-nan-men Bridge with collapsed bridge deck.

The bridge site has been investigated after the collapse. Figs. 4-6 show details of failed suspenders. The corrosion of the steel wires was obvious. There were totally four pairs of suspenders broken, three pairs in the south and one in the north. It was found that all failures of the broken suspenders were in the vicinity of the bottom sockets connected to the deck. The damage investigation showed that parts of the corrosion protection had been cracked.

Testing of the main arch rib showed that the arch rib was stable, and cracks on the arch rib had no effect on the entire behaviour of the rib. Therefore, the original arch ribs could be utilized. Only the deck system and the cross beams had to be consolidated. It was decided to replace all suspenders. After nearly seven months of hard work, the bridge was opened to traffic again on June 28th, 2002.

Figure 4. Load side of a socket that failed. Most steel strands broke, mainly due to corrosion, in the vicinity of the socket.

Figure 5. Socket longitudinally opened with a blow torch for investigative purposes. Strands of parallel strand cable.

Figure 6. Some wires of the strands show brittle fracture surfaces probably due to corrosion, fatigue and fretting.

2.6 Case study Kong-que-ke Bridge

Kong-que-he Bridge (Peacock River Bridge) in Xin-jiang was a half-through concrete filled steel tubular arch bridge with the main span of 150m and width of 24.5m. The deck system consisted of 5.0m and 7.5m span reinforced concrete T-shaped girders and was suspended below the truss arch rib by 23 pairs of suspenders. The bridge was opened to traffic in August, 1998. At 5:30a.m. on Apr. 12th, 2011, a part of the deck in Kong-que-ke Bridge collapsed and dropped into the river. Fig. 7 shows the bridge after the collapse. Because of the deck collapse, the Kong-que-he Bridge was closed to traffic forever. It had been in service for only 13 years, which is very far from its design lifetime. The local highway agency decided to remove the entire bridge and to rebuild a new one at the same site.

Figure 7. Kong-que-he Bridge after failure in 2011.

2.7 *Case study Gong-guan Bridge*

Gong-guan Bridge is located in Wu-yi-shan Scenic Area, Fujian, as shown in Fig. 8. It was opened to traffic Nov.20, 1999. It is a half-through reinforced concrete arch bridge with three spans, 80m+100m+80m. At 8:50a.m., July 14, 2011, when a tourist bus and an overloaded truck were passing the bridge, the deck of the first span partly collapsed as a result of broken suspenders, as shown in Fig. 8. The bus dropped into the river with 22 injured and the driver dead. However, the truck, having a self-weight of 20.6t and carrying 60t sand, was the direct reason for the collapse, because the nominal carrying capacity of the truck is only 15.65t. The overloaded truck may be the obvious reason for the collapse. But the bridge is located in a very important road and had heavy traffic. Many overloading vehicles passed the bridge everyday, which resulted in the damage of suspenders to varied degrees. Furthermore, this bridge was built in 1990', the sealing and anti-corrosion technique during that time was relatively poor. Similar like in the other case studies the failure of the suspenders was at or near the bottom sockets. This is a clear indication that corrosion played an important role. The local highway agency decided to remove the whole bridge and to build a new one.

Figure 8. Left: Gong-guan Bridge before collapse. Right: collapsed bridge deck in 2011.

2.8 *Conclusions for the situation in China today*

The main reasons for the failures of suspender cables include fatigue and corrosion related problems. Generally speaking, the failure of suspenders is especially the result of the interaction of fatigue and corrosion as described by Evans (1982) and sketched in Fig 9. There is no doubt that also overload is reducing the lifetime of suspenders.

The risk of corrosion could be reduced with the application of advanced corrosion protection methods. Corrosion could be avoided with suspenders made of stainless steel or carbon fiber reinforced polymers (CFRP). However the fatigue performance of CFRP is much better than that of stainless steel. Empa researcher demonstrated the outstanding fatigue performance even in the gigacycle range, which is instrumental for the application for suspenders. CFRP is also, in contrast to certain stainless steels, not suffering stress corrosion. The only disadvantage in comparison to stainless steel is a slightly higher price.

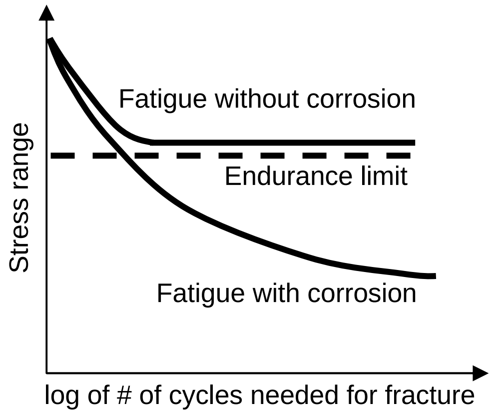


Figure 9. Effect of fatigue loading with and without corrosion.

3 CFRP FOR SUSPENDERS OF ARCH BRIDGES

Empa researchers were developing several anchorage systems for unidirectional CFRP tendons. Meier (2012) described the development of a gradient anchorage system for parallel CFRP wire/strand bundles and its application for stays and for post-tensioning cables. The load capacity of this system ranges from 60 kN to 25 MN. It has successfully been applied for stay and post-tensioning cables since seventeen years. Such tendons have been loaded with sustained loads corresponding to stresses higher than 1600 MPa. There is a comprehensive monitoring on such tendons and other load carrying CFRP applications in bridge engineering since 1991 described by Meier, Brönnimann, Anderegg, and Terrasi (2013). All results are very satisfactory.

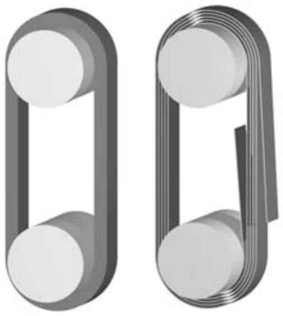
The gradient anchorage system for parallel CFRP wire/strand bundles is having one disadvantage: it is relatively expensive. Therefore a “pin-loaded CFRP strap system” has been developed at Empa by Winistörfer (1999) for load capacities up to 3 MN. This system is very efficient and easy to handle. Originally it was intended for active shear strengthening applications as described by Lees, Winistörfer, and Meier (2002). Since ten years it is commercially successful produced by the Carbo-Link Company, e.g. for the strengthening of historical structures, and most important, for corrosion free, lightweight and fatigue resistant tendons for duty cycle crawlers of the Liebherr Company, one of the world's largest heavy machinery makers. This application is, considering the fatigue load spectra, very similar to that of bridge suspenders.

3.1 Concept of pin-loaded CFRP strap system

A carbon fiber reinforced laminated pin-loaded strap, as shown in Figure 10 a), might provide a practical tendon for suspenders. Such an element consists of a unidirectional fiber reinforced polymer, having a fiber volume fraction of about 60%, wound around two cylindrical steel pins in a racetrack shape. No machining of holes is required to make a pin-loaded strap. The two pins could transfer the tensile load from the bridge deck through the strap to the arch rib. However laboratory experiments and analytical modeling by Winistörfer (1999) have shown that there are severe stress concentrations in the region where the strap and the pin meet. The tensile resistance of the strap is therefore limited to less than 60 % of the material’s expected unidirectional strength. This is attributed to stress concentrations, which lead to premature failure.

An option to reduce the undesirable stress concentrations and cost is the use of a non-laminated strap. The concept which has been patented by Meier and Winistörfer (1998) is shown in Figure 10 b). The CFRP strap now comprises a number of unidirectional reinforced layers, formed from a single, continuous; tape of about 0.12 mm thickness. The tape is wound around the two pins and only the end of the outermost layer is bonded to the next outermost layer to form a closed loop.

The non-laminated strap element enables during loading the individual layers to move relative to each other, which allows an equalization of forces in the layers as the strap is tensioned; Winistörfer (1998). The stress concentrations are reduced since the new structural form is more compliant than the laminated equivalent. Control of the initial tensioning process reduces interlaminar shear stresses so that a more uniform strain distribution in all layers can be achieved. The approach allows greater flexibility in terms of the geometry of the tendon, and it can be manufactured on site. Moreover, the concept is going to be more effective since more than 90% of the high strength of the CFRP will be applied.



a) b)

Figure 10. Conceptual design of pin-loaded strap elements.

Figure 11. Seismic retrofitting of a masonry wall post-tensioned with a pin-loaded CFRP strap system. *Left picture:* termination for pin-loading. *Middle picture*: Attachment of the CFRP strap to the concrete foundation with pin-loading. *Right picture*: Post-tensioned CFRP tendon of 1 MN load capacity.

3.2 Fabrication and installation of pin-loaded CFRP strap system

Suspenders made of pin-loaded CFRP straps can be fabricated with an automatic tape-laying machine in the factory of the Carbo-Link Company or on site. Thermoplastic polymers like polyamide 12 or thermoset polymers like epoxy are used as matrix materials. The best solution for suspenders would be: to fabricate the strap elements with epoxy prepregs on an automatic tape-laying machine in the factory, to load it up to service load, to wrap fibers around the straps to get a circular or even better an oval-shaped (better aerodynamics!) cross section, to roll and ship it. As a flexible element it could easily be connected with a pin to the deck and another pin to the arch rib. Then the epoxy resin will be cured on the bridge site using the load carrying carbon fibers as an electrical resistance heating element. Results of such a process are shown in Figure 11.

4 CONCLUSIONS

CFRPs are, due to the excellent properties of the carbon fibers, one of the most advanced materials in technique today. Aircraft industry is relying since decades on CFRPs. The wing box of the Superjumbo Airbus A380 e.g., which is connecting the wings with the fuselage, is 100% made of CFRPs. Most critical in many CFRP applications, including aircraft industry, are the adhesively bonded joints. The great advantage of the above proposed pin-loaded CFRP strap system for bridge suspenders is that there are no such joints. As described are the carbon fibers wound in a racetrack manner around the pins. That means we have only to rely on the carbon fibers, the pins and not on grouts, polymers or adhesives. It is very difficult to make long-term life cycle predictions. However based on the best knowledge available today we can assume that CFRP suspenders will outlast steel suspenders at least three times. This justifies a higher price.

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