BOWSTRING-ARCH BRIDGE MADE OF CFRP, GFRP AND GLULAM

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ABSTRACT

The bowstring arch bridge concept has been realized with thermoplastic CFRP tendons for six longitudinal arranged bowstrings and glulam for the finally arch shaped bridge deck. This deck is stress-laminated as a flat plate. It is constructed by placing sawn lumber laminations on edge and stressing the laminations laterally together on the wide face with thin high-strength thermoplastic CFRP tapes. It is causing the deck to act as a large orthotropic wooden plate. The bowstrings are composed of non-laminated pin loaded thermoplastic CFRP strap elements. These elements enable the individual layers to move relative to each other which allow an equalization of forces in the layers as the strap is tensioned. The approach allows excellent use of the strength of CFRP and great flexibility in terms of the geometry of the strap elements as tendons. After prefabrication of the flat glulam plate and the CFRP straps the bow has been drawn. The bridge deck, which has the arch function, was axially loaded with the CFRP straps and elastically bent with a deflection of 1/75 of the span. The described bowstring arch concept allows an extremely slender and therefore very elegant bridge design. The first bridge of this kind with a span of 12 m was built end of 2006.

KEYWORDS

Thermoplastic CFRP, pin-loaded strap elements, tapes, tensioning, arch shaped bridge deck, GFRP cover plate.

INTRODUCTION

Timber is one of the world's oldest construction materials. It was already used for timber bridges in Mesopotamia 3000 to 2000 B.C. The relatively high specific strength of timber (strength/density ratio) was often and still is an important criterion for its use. If treated correctly, timber has a long service life, as can be seen in timber bridges and multi-storey framework buildings in Asia or Europe that are over 400 years old. In cases where the dimension or load bearing capacity of wood is not sufficient, combinations of fibre reinforced polymers (FRP) and timber are used today. Post-strengthening of timber structures with FRP has been very successful since 17 years, Meier (1992). The combination of these two materials will also allow new, innovative wide span constructions in future.

CONCEPT AND CONSTRUCTION

Concept

A bowstring arch bridge is an arch bridge in which the outward-directed horizontal forces of the arch are borne as tension by the bottom chord, rather than by the ground or the bridge foundations; Gordon, J. E. (1978). Thrusts downward on such a bridge's deck as in this project are translated, as compression, by vertical struts from the deck to the polygonal bottom chord, tending to flatten it and thereby to push its tips outward into the abutments, like classical arch bridges. However in a bowstring- or tied-arch-bridge, these movements are restrained not by the abutments but by the bottom chord, which ties these tips together, taking the thrusts as tension, rather like the string of a bow that is being flattened. Therefore the design is called a bowstring-arch bridge. The elimination of horizontal forces at the abutments allows bowstring-arch bridges to be constructed with less robust foundations. In addition, since they do not depend on horizontal compression forces for their integrity, tied arch bridges can be prefabricated offsite, and subsequently lifted into place. The described bowstring-arch bridge reacts as system like a simply supported single-span beam bridge. However it is related to its dead load much stiffer.

Construction

The whole bridge was assembled in a laboratory hall of EMPA. The originally flat glulam bridge deck is stress-laminated. It is 12 m long, 3 m wide and 16 cm deep (Figure 1). It is constructed by placing 16 cm wide and 4 cm thick sawn common spruce lumber laminations on edge (Figure 2). It was delivered in two 12 m long and 1.42 m wide strips. This two glulam strips were laid out in parallel to each other. With a spacing of approximately 0.3 m in longitudinal direction, 30 mm wide and 0.12 mm thick unidirectional thermoplastic CFRP tapes were wound in lateral direction around these two glulam strips. Then these strips were pushed outwards with wedges in the central gap.

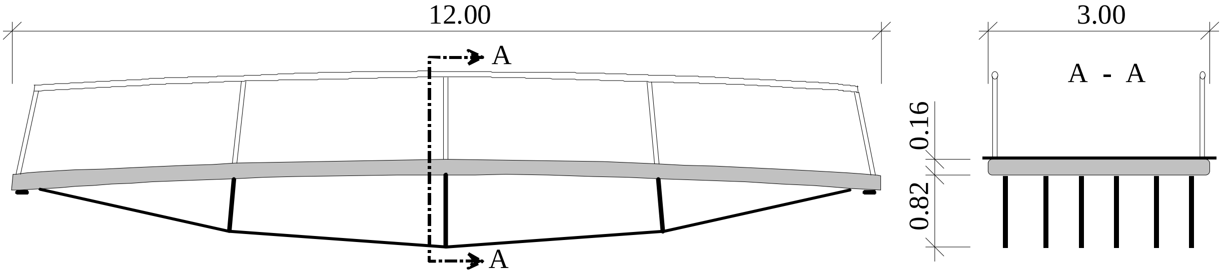


Figure 1: Geometry and main dimensions of the bowstring arch bridge. All measurements are in [m]

The stiffness (EA) of such a lateral tendon is 3 MN. The fibres used were Toray T700 and the matrix was a polyamide PA12. Finally the gap was filled with spruce lumber (Figures 3). For the outermost lumber laminations on the longitudinal edges oak was used to avoid dents of the CFRP tapes into the lumber (Figure 6 and 9) due to contact stresses. With this technique an efficient lateral post-tensioning was reached. It is causing the deck to act as a large orthotropic wooden plate. Between the lateral tendons wooden spacers were fixed to the top of the deck. Later in the construction process the glulam deck was covered with a GFRP plate of 8 mm thickness. The task of this GFRP plate is to protect the glulam against rain. The wooden spacers were arranged since nobody can ensure that the GFRP deck will be fully waterproof for the whole lifecycle of the bridge. In the case of a large leak it could be seen when the water flows out at the longitudinal edges of the bridge. In the case of a small leak the water would evaporate in the air gap. Therefore it is the task of the spacers to avoid rottenness of the wooden bridge girder.

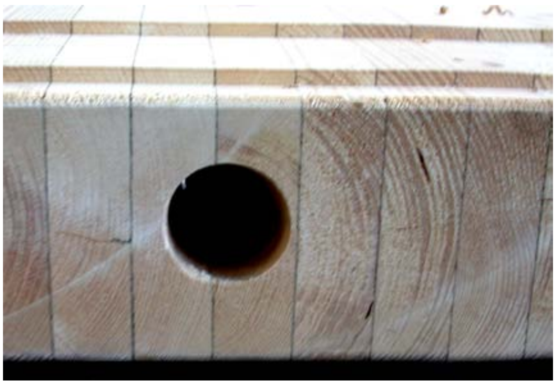


Figure 2. End of the glulam plate. Overall depth: 16 cm. The cuts on top enable to fit with the GFRP cross beam as shown in Figures 7 and 8. The hole of 60 mm diameter is leading to the termination of a bowstring

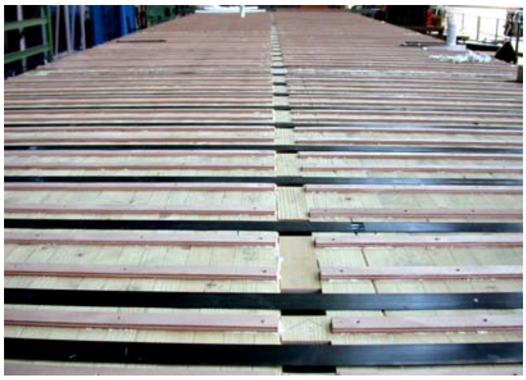
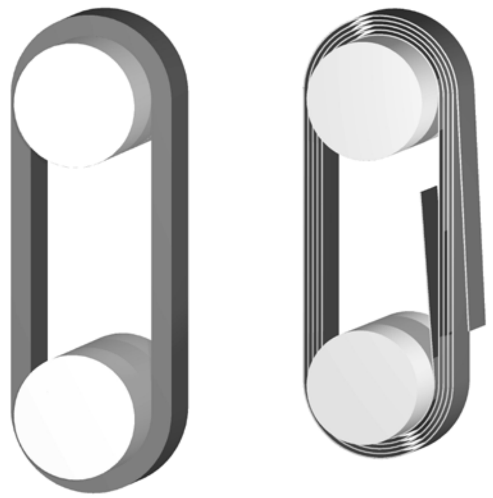


Figure 3. Bridge deck after lateral post-tensioning. The location of the original gap is in the centre of the photograph still visible. The wooden spacers should avoid rottenness of the glulam under the GFRP plate

The bowstring-arch bridge concept was realized with six longitudinal arranged CFRP bowstrings and the above described glulam plate for the finally arch shaped bridge deck (Figure 1). The bowstrings are composed of non-laminated pin loaded thermoplastic CFRP strap elements. The stiffness EA of each bowstring is 18 MN. It was the first time that such tendons were applied in a bridge construction.

Laboratory experiments and analytical modelling by Winistörfer (1999) has shown that there are severe stress concentrations in the region where the strap and the pin meet in the case of laminated pin loaded tendons (Figure 4a). The tensile resistance of the strap is therefore limited to about 60 % of the material’s expected unidirectional strength. This is attributed to stress concentrations, which lead to premature failure. Furthermore, the production process for multi-layered laminated straps is not straightforward, if fibre misalignment is to be eliminated where the stress concentrations occur. An alternative option to reduce the undesirable stress concentrations, overcome the manufacturing difficulties and to reduce cost is the use of a non-laminated strap. The concept which has been patented (Meier and Winistörfer, 2001) is shown in Figure 4b. The CFRP strap now comprises a number of unidirectional reinforced layers, formed from a single, continuous, thermoplastic tape of about 0.12 mm thickness. The tape is wound around the two pins and only the end of the outermost layer is fusion bonded to the next outermost layer to form a closed loop.



(a) (b)

Figure 4. Conceptual design of pin-loaded strap elements

The non-laminated strap element enables the individual layers to move relative to each other which allows an equalization of forces in the layers as the strap is tensioned. 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 fairly 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 less expensive because there is no consolidation process required.

An important aspect of non-laminated pin-loaded straps is the brittle nature of the carbon fibres. The stress at which brittle fibres fail usually depends on the presence of flaws, which may occur randomly along the length of a fibre. A statistical approach of this situation involves conceptually dividing a length of fibre into a number of incremental lengths. The fibre fractures when it has at least one incremental element containing a flaw sufficient to cause failure under a given stress. This analysis is known as the Weakest Link Theory (WLT) by Hull and Clyne (1996). The Weibull modulus, m, is an important parameter for characterizing the strength distribution of brittle solids. A low value of m (e. g. < 10) implies considerable uncertainty about the strength of a specimen. In practice, many ceramic materials exhibit Weibull moduli in the range from 2 to 15. Sommer et al. (1996) reported values of $m = 5.25$ for strength properties of single carbon fiber filaments type Sigrafil C. Winistörfer (1999) measured for the best suited non-laminated strap elements Weibull moduli up to $m = 49$. This is a proof for a high system reliability of non-laminated CFRP strap elements. Ongoing outdoor creep tests are being carried out at EMPA on specimens consisting of twenty-seven layers. Two specimens are loaded to 90 % of the average static load carrying capacity of equivalent straps. These specimens resist since six years these severe loading conditions without failure.

After the prefabrication of the glulam plate and the CFRP straps, “the bow has been drawn” (Figure 5). For this longitudinal pre-stressing the flat bridge deck was supported at the two outer quarter-points of its length and loaded with four concrete blocks at each beam end. This loading (approximately 32 kN per cantilever) resulted in the elastic deflection that was needed for the assembly of the struts and tendons. After putting these members into place the bowstring-arch was finally realized by the removal of the concrete blocks. The deflection is 1/75 of the span. The system is simple to install and operate, and time-consuming procedures such as bonding of post-tensioned elements and applying post-tensioning forces using hydraulic actuators are avoided. The total dead load of the bridge is 24.5 kN. The design load was set to 4 kN/m^2. All CFRP tendons were delivered by the Carbo-Link Ldt.

Figure 5. “Drawing of the bow”: Left: Flat glulam deck supported at quarter-points. Center: Bow shape of deck achieved by loading the cantilever ends. Right: Struts and cables keep the bow shape of the plate after removing the load

Figure 6. Bowstring, composed of non-laminated thermoplastic CFRP strap elements, going through the hole in the glulam deck to the termination of the pin-loaded strap. The stiffness EA of each bowstring is 18 MN. The stiffness of the lateral tendons is 3 MN

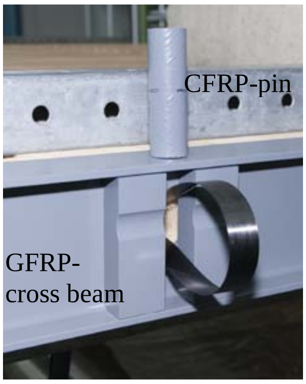


Figure 7. Termination of a pin-loaded CFRP strap before tensioning. The length of a pin is 125, and the diameter 40 mm

Figure 8. Termination of a pin-loaded CFRP strap after tensioning. The fibre lay-up of the CFRP-pin is 0/±45° (Tenax UTS/EP)

Figure 9. Top: The wooden spacers should avoid rottenness of the glulam under the GFRP plate

Figure 10. Bridge with CFRP bowstrings after installation

The bridge deck is covered, as described in preceding sections, with a plate made of GFRP and the railing is also made of GFRP components. Most of the joints are realized by gluing with an Epoxy type adhesive. After the assembly of the monitoring system components, the GFRP deck cover and parts of the railing, load tests were executed.

Installation

The bowstring-arch bridge was set in place by a light crane that lifted the bridge over a water basin in front of the EMPA head-office. Since then the bridge is monitored by photogrammetry and is structurally performing well.

Cost

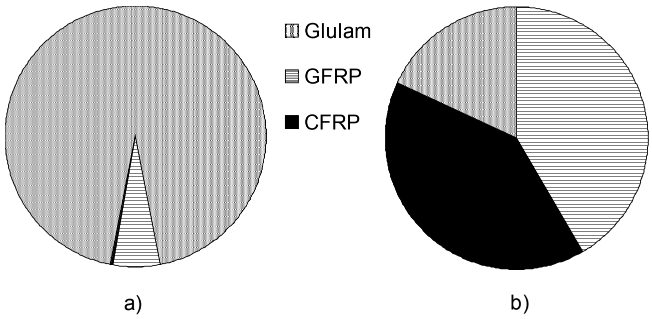


Figure 11. Materials volume fractions a) versus cost b)

It is interesting to compare the volume fractions of materials and the corresponding cost for the whole bowstring-arch bridge (Figure 11). The volume fraction (Figure 11a) of glulam amounts to 93.8%, that of GFRP to 5.9% and that of CFRP to only 0.3%. On the cost percentage basis glulam amounts to 18% (= 27’778 USD), GFRP to 42% (=26’852 USD) and CFRP to 40% (=12’037 USD). The total price for bridges of this type in regular construction will be about 3’200 USD per square meter.

Sustainability

By the increase of timber consumption the global CO_2 balance is favourable in two ways: (i) The use of timber in construction constitutes long term storage of CO_2; (ii) The use of timber in construction avoids the direct CO_2 production by steel or concrete. As shown in Figure 11, this bowstring-arch bridge made of materials by combination has a volume fraction of 94% wood. This type of bridge is therefore environmentally extremely sustainable.

MONITORING

Various advanced sensing systems have been installed to monitor the bridge. The system includes sensors for temperature, humidity, change of the width of the bridge, the tension of the CFRP bowstring tendons and a video system for distributed deformation measurements. Brönnimann and Widmann (2009) described the sensing systems in all details.

Load Tests

Prior to installation of the bridge a load test was performed in the laboratory. Simultaneously the video surveillance system was tested. The load consisted of up to three concrete blocks each with a mass of about 860 kg. They were placed perpendicularly to the longitudinal axis in the middle of the bridge. In Figure 12 the measured deflections for the quarter-points and midspan are shown.

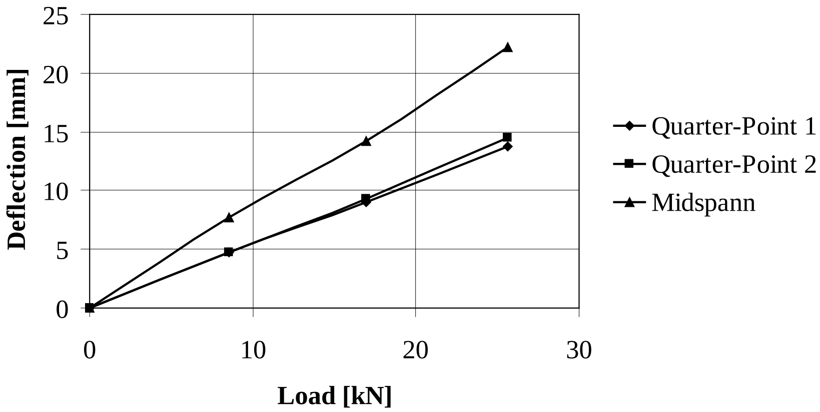


Figure 12. Results of experimental load tests

The bowstring-arch behaved during the load tests nearly perfect elastic. After unloading the deflections reached zero again. The comparison of the data of the quarter-points proves symmetrical deflections.

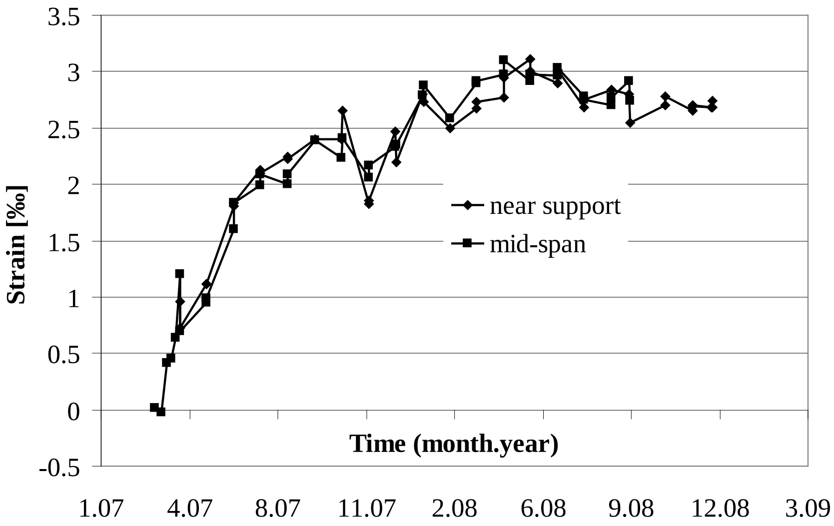


Figure 13. Results of strain measurements from 2007 until 2009 lateral to the glulam deck

Figure 13 shows the results of the strain measurements in detail described by Brönnimann and Widmann (2009) lateral to the glulam deck at midspan and near one support. These strains include all dimensional changes due to moisture and temperature fluctuations and due to creep caused by the original lateral post-tensioning forces. Due to the water take-up within the first 18 months there was a gain in swelling of $\varepsilon = 0.3\%$. Taking into account that the stiffness EA of a lateral CFRP tendon is 3 [MN], there is an additional post-tensioning force of about 9 kN for each tendon. Since the pin-loaded CFRP straps face from an engineering point of view no stress-relaxation, this additional 9 kN are a real gain.

CONCLUSIONS

Laminated wood has developed into a high-tech material due to its homogenisation. Nowadays, it can provide slender constructions and, when combined with advanced materials such as carbon fibre reinforced polymers (CFRP), constructions with a very appealing architecture. Precisely in combination with new connecting means, like pin loaded CFRP straps, it is possible to use laminated wood in highly stressed and dynamically loaded structures. Considering all the advantages of the described bowstring arch structure like lightweight, no corrosion, easy installation, good value and in the long run most important an excellent sustainability, there will be a very bright future for such structures.

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