Combination of timber, CFRP and GFRP for the design and construction of a bowstring arch bridge

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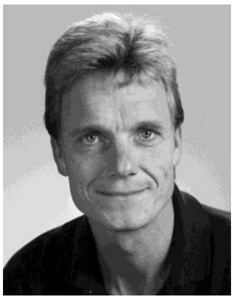

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Summary

The replacement of an existing pedestrian bridge at the Swiss Federal Laboratories for Materials Testing and Research Empa, Switzerland gave the opportunity to head for a novel and experimental bridge design. It was decided to build a bowstring arch bridge. A remarkable feature of the design is the exclusive use of non-metallic construction materials, namely structural glulam timber, CFRP and GFRP. The span of the bridge is 12.0 m and the cross section of the timber bridge deck is 3.0 m by 0.16 m. The wooden deck is prestressed laterally and longitudinally (the bow) by CFRP pin-loaded straps and CFRP loops. The lateral prestressing aims at enhancing dimensional stability of the deck while the longitudinal CFRP loops act as a bowstring of the arch and thus shape and stiffen the construction. Load tests confirmed the good performance of the bridge.

Keywords: CFRP, GFRP, glulam, pin-loaded strap elements, monitoring.

1. Introduction

A bowstring arch bridge was built and installed on the areal of Empa, Swiss Federal Laboratories for Materials Science and Technology in Switzerland (Fig. 1). The bridge represented a novel design regarding two properties, its design and the materials that were used for its construction. A remarkable feature of the design is the exclusive use of non-metallic construction materials, namely structural glulam timber, carbon-fiber-reinforced plastics CFRP and glass-fiber-reinforced plastics GFRP. The span of the bridge is 12.0 m and the cross section of the timber bridge deck is width by height = 3.0 m by 0.16 m. The timber deck is prestressed laterally and longitudinally (the bow) with CFRP loops. The lateral prestressing aims at enhancing dimensional stability of the deck while the longitudinal CFRP loops act as bowstring of the arch and thus shape and stiffen the construction. The bridge serves also as a demonstrator for the efficient use of the pin-loaded CFRP straps that formed the bowstring. Since its installation in March 2007 the bridge has been continuously monitored. Several specific sensors are used to record deformations, bowstring tension, temperature and humidity. The monitoring system of this bridge was presented at ICTB 2010 in detail [1]. This paper will mainly focus on the design and the construction of the bridge.

Fig. 1: Pedestrian bridge at EMPA Duebendorf, Switzerland

2. Design of the bridge

2.1 Structure

The design principal of the bridge can be seen in Fig. 1. Based on an idea of U. Meier the detailed design of the bridge was developed by Dr. Deuring + Oehninger AG, an engineering company in Winterthur, Switzerland that has a lot of experience with the design of structures that contain fiber reinforced plastics. The structure consists of a bow-shaped girder, a bottom chord and struts acting as spacers between the beam and the bowstring. The camber of the originally straight beam results from prestressing the chord. As the camber of the bow (or arch) is relatively shallow the struts are needed for geometrical reasons. On the other hand this creates a truss-like behavior with the beam getting bending and compression loads, the chord tension loads and the struts compression loads. Advantages of this design are the slender appearance of the structure, its high stiffness, its light weight and the possibility to prefabricate the whole bridge.

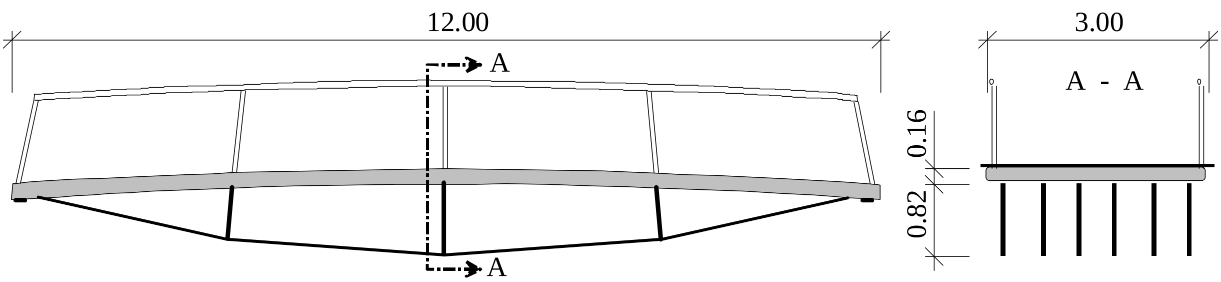

Fig. 2 Overview of the bridges design and main dimensions

3. Materials

3.1 Overview

Three kinds of materials were used for the construction of the bridge: timber, CFRP and GFRP (Table 1).

The bridge beam was made of glulam from Swiss grown Norway spruce (*Picea abies*) with the outer lamellas of the glulam elements made of oak (*Quercus robur*). The oak lamellas should prevent major indentations resulting from the lateral prestressing of the deck.

CFRP was used for the lateral and the longitudinal prestressing of the bridge deck. The bowstrings were composed of non-laminated pin loaded thermoplastic CFRP strap elements and the lateral prestressing was realized with loops from the same kind of material. It was the first time that such tendons and loops were applied in a timber bridge construction.

All other parts were made of GFRP, namely the bridge decking which consists of a plate with a thickness of 8mm, all struts, the handrails and the profiles that were used for anchoring the CFRP straps.

Table 1: Basic mechanical properties of the applied materials.

Material	E GPa	ρ kg/m^3	Strength MPa
Glulam GL24h (EN 1194 [2])	11.5	455 at u = 12% (measured)	$f_{m,g,k} = 24$ $f_{c,0,k} = 24$
CFRP	150	1500	$f_t = 2000$
GFRP	44.5	2000	$f_c = 900$

3.2 CFRP loops and pin-loaded CFRP straps

Continuous, thermoplastic CFRP tapes of about 0.12 mm thickness were the base elements for the CFRP loops and straps. Compared to CFRP lamellas they are very flexible and can be bent with radii of as small as 20 mm to 25 mm. Thus, the tapes can be wrapped around an object in one or numerous layers. The straps and loops were produced by Carbo-Link AG [3] which is a Swiss high-tech company specialized in design, development and production of structural elements with carbon fibers.

Laboratory experiments and analytical modeling [3] have 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 (Fig. 3a). As a result of the pin-loading, the tensile resistance of the strap is limited to about 50 % of the material's unidirectional strength. An alternative option to reduce the undesirable stress concentrations, overcome manufacturing difficulties and to reduce cost is the use of a non-laminated strap. The concept which has been patented [4 and 5] is shown in (Fig. 3b). The CFRP strap comprises a number of unidirectional reinforced layers, formed from a single, continuous, thermoplastic tape. The tape is wound around the two pins and only the end of the outermost layer is fusion bonded to the neighboring layer to form a closed loop.

a) b)

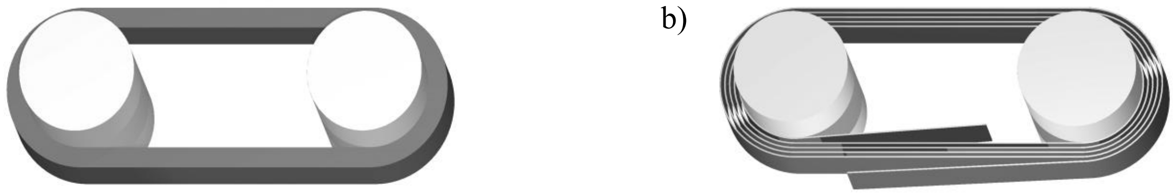

Fig. 3: Principal design of pin loaded strap elements (loops), a) laminated CFRP, b) not laminated CFRP tapes.

The non-laminated strap element enables the individual layers to move relative to each other, which allows an equalization of forces in the layers when the strap is tensioned. The stress concentrations are reduced since the new structural form is more compliant compared to a 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.

4. Assembly and installation

4.1 Overview and lateral prestressing

The bridge was assembled in a hall on the EMPA site. The main assembly steps consisted of the lateral and longitudinal prestressing of the deck, the mounting of the decks cover and hand-railing and the installation of the relevant components of the monitoring system. In order to apply the lateral prestressing, the glulam bridge deck consisted of two pieces each of which being 12.0 m long and having a width of 1.42 m which is a bit less than half the total decks target width. Both pieces were laid side by side, the CFRP loops were slipped over, arranged in a pattern with a mean spacing of about 0.30 m and the two pieces were pushed apart against the resistance of the CFRP loops with the help of inserted timber wedges (Fig. 4 Fig. 5 and Fig. 6).

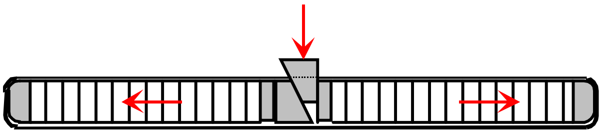

Fig. 4: Principle of the application of the lateral prestressing of the glulam slab with the help of wedges. The prestressing had to be conducted iteratively over the length of the slab and the wedges were glued-in at the final stage. The grey shaded parts ideally are made of hardwood in order to minimize the effect of possible indentations in the wood. In our case only the two outer lamellas were made of oak.

Fig. 5: Detail view of wedge, glulam and CFRP-loops (right)

*Fig. 6: Left: Sliding on and distribution of the CFRP loops on the glulam deck.
Right: Upper side of the deck before the installation of the sensors for the monitoring system and the GFRP decking. The lateral tension elements can be seen as well as wooden spacers on the plate's upper side. These spacers guarantee a minimum ventilation of the deck and protect the CFRP elements from mechanical damage. Between the spacers and the GFRP decking impact sound insulation made of plastic foam was applied. An alternative to the wooden spacers for the GFRP decking could be the application strips or mats made of rubber gravel which would also provide a protection for the CFRP straps and serve as a impact sound insulation at the same time .Along the centreline of the plate the wooden wedges and spacers that were used to apply the lateral prestressing of the plate can be seen. The method to provide the force for lateral prestressing by the insertion of wedges proved to be easy and efficient even if the desired maximum force could not be applied eventually.*

After reaching a predefined deck width the slots between the two deck parts were filled with glued-in timber blocks that serve as spacers. However, the originally predefined deck width could not be reached with this procedure as it was not possible to apply the necessary force with the insertion of the wedges. An alternative procedure for future applications could be the use of devices that apply a controlled force over the whole length of the plate, e.g. a series of a large number of hydraulic presses. However, such a procedure is more difficult to realize as the limited space between the two parts of the deck require special solutions.

4.2 Longitudinal prestressing

For the longitudinal prestressing the bridge deck was supported at the two outer quarter-points of its length (Fig. 7a). Then the GFRP struts were assembled (Fig. 7b) and the plate was loaded with concrete blocks at both cantilever ends (Fig. 7c). This loading (32.0 kN per side) resulted in a bending stress of around 15.0 MPa and a total camber of about 145 mm which was needed for the assembly of the CFRP straps. After putting these members into place and anchoring the loops at both ends of the bridge deck (Fig. 8) the prestressing was finally realized by the removal of the concrete blocks. The relaxation of the decks deflection is prevented by the truss system which results in the desired bowstring arch-shape of the deck (Fig. 7d).

a) b) c) d)

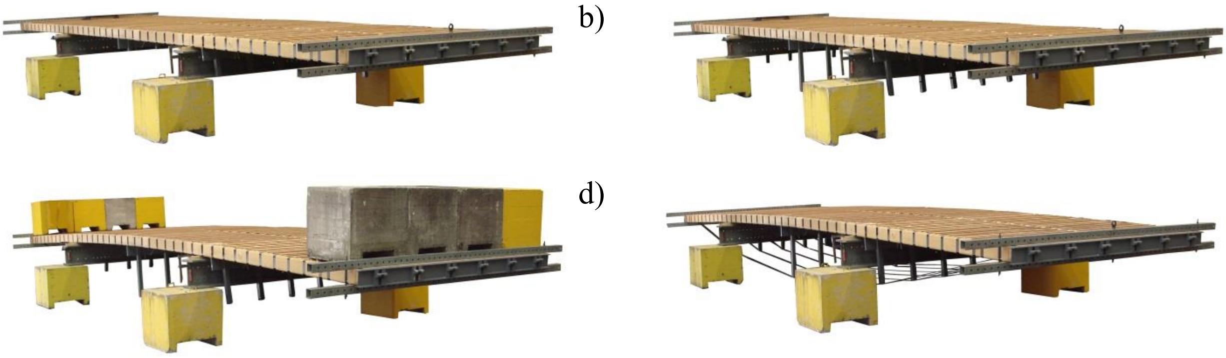

Fig. 7: Tensioning of the bow.

Fig. 8: Anchoring of the longitudinal tension loops at the plate's front end using a GFRP bolt with a diameter of 4 cm. This diameter is towards the lower end of possible bending radii for the used CFRP elements that can be realized in practice without damaging the CFRP structure. The fixation of the bolt as well as the profile that covers the front end of the plate and serves to distribute the loads originating from the loops into the slab are made of GFRP.

5. Load tests and design verification

Before the bridge was set into its final position a series of load tests was executed. The loading was realized with the same concrete cubes that served already for the tensioning of the bow as shown in Fig. 9. The aim of the tests was to gather data about the bending stiffness of the System as well as to determine the tension force within the CFRP straps. The loads were applied at midspan and consisted of one to three cubes that were arranged symmetrically and asymmetrically in reference to the longitudinal axis of the bridge slab. Two gauges were used to measure the total deflection at midspan on either side of the slab.

For the analysis shown here only symmetrical loadings of the slab are considered which results in loads between approximately 8.5 kN and 25.6 kN.

The tension force of the straps was measured "acoustically" with the determination of the first natural frequency after the strap was excited to swing with the use of a stick. The tension strength per strap could then be calculated on base of the equation for the determination of the fundamental frequency of a vibrating string like follows:

$$F_t = 4 \cdot l^2 \cdot f^2 \cdot \rho \cdot A \qquad (1)$$

with:

F_t = tension force in CFRP strap

l = length of the CFRP strap section (3000 mm)

f = first natural frequency of CFRP strap

ρ = density of the CFRP (1500 kg/m^3)

A = nominal cross section of the CFRP strap (120 mm^2)

Fig. 9: Set-up for measurement of deflections and the tension force in the straps.

Fundamental frequencies between minimum 54 Hz and maximum 70 Hz were measured depending on the loading conditions.

The so determined tension force within the CFRP straps varied due to geometrical deviations up to maximum 20% from strap to strap. This is a consequence of assembly tolerances that directly affect the tensioning of the straps. The applied method of tensioning does not permit to adjust the tension forces for each single strap individually.

Table 2: Results of load tests compared to static calculations.

Step	Load	Mean deflection	Mean tension force	Accumulated tension force	Tension from static calculation	Deflection from static calculation
	kN	mm	kN	kN	kN	mm
0	0	0	21.0	126	149	0
1	8.5	6.54	23.8	143		
2	17.2	14.1	26.6	160		
3	25.6	20.8	29.4	176	208	18.7
Design load	4/m^2				405	83.1

The results of one of several loading cycles are shown in Table 2. It can be seen that mean deflection and mean/accumulated tension force in the straps correlate well. The accumulated tension force represents the total tension force of the six straps that is needed to provide the bow shape of the slab under the different loadings. However, it can also be seen that the accumulated tension force over the 6 struts does not well fit the tension force that has been found in the static calculation. The calculation was made with the consideration of second order effects. The reason for the discrepancy could not be verified in detail. Some possible contributions to this fact can be variations in material properties as well as in the measurement of the frequency. As the strap is not made of one solid part but of several layers, this might have an influence on the fundamental frequency of the string.

For the verification of the performance of the system the bending stiffness *EI* was calculated with the data from step 2 and step 3 in Table 2. The bending stiffness was determined to be $EI_{\mathrm{bow}} = 4.54 \cdot 10^{13}$ Nmm^2. Assuming a possible bending MOE of the glulam elements of $E_{0,\mathrm{mean}} = 11.6$ GPa to 14.7 GPa (Gl24h to Gl36h according to EN 1194) the bending stiffness of the slab itself without tensioning could be estimated to range between minimal $EI_{\mathrm{slab}} = 1.19 \cdot 10^{13}$ Nmm^2 and maximal $EI_{\mathrm{slab}} = 1.51 \cdot 10^{13}$ Nmm^2. With this it can be shown that the bending stiffness of the slab increased between 3 and almost 4 times due to prestressing it into a bow shape. This confirms the initial statement regarding the expected advantages of the construction

6. Conclusions

A pedestrian bridge made exclusively of glulam structural timber, CFRP and GFRP had been designed and constructed at the Empa site in Duebendorf, Switzerland. The advanced materials glulam structural timber, pin loaded CFRP straps and GFRP elements were combined in a new bridge design, a bowstring arch bridge. It turned out and could be shown, that the required tensioning of the bow as well as the lateral prestressing of the bridge slab could be realized as planned. A potential for an improvement of some details and procedures could be identified and it is proposed to consider this for future constructions.

Load tests confirmed a superior stiffness of the system.

Considering all the advantages of the described bowstring arch bridge like lightweight structure, high stiffness, prevention of corrosion problems, easy installation, good value and an expected long service life, a good market potential for such structures can be expected.

Acknowledgement

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