EXTREMELY LIGHT AND SLENDER PRECAST-BRIDGE MADE OUT OF TEXTILE-REINFORCED-CONCRETE

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ABSTRACT

Textile-reinforced concrete (TRC) is an innovative composite material which uses mesh-like textile reinforcements and a fine-grained concrete as basic materials. Unlike steel, textiles are not susceptible to corrosion, thus it is possible to minimize the concrete cover to only a few millimeters. As a result, slender concrete constructions can be built, meeting the needs of modern architecture with both economical and environmental advantages.

This paper presents a precast pedestrian bridge made of TRC, which has a total length of 51 ft (15.5 m) and a width of 9.6 ft (2.94 m). Worldwide it is the first reinforced bridge, which uses no steel as reinforcement but rather carbon fibers. As a result the thickness of the construction could be minimized and let to reduction of carbon dioxide emissions in the production process, compared to ordinary steel-reinforced bridges. Further advantages are lower maintenance costs and, thus, lower life-time costs. The paper focuses on details of the design, construction and bearing behavior of the bridge.

Keywords: TRC, Slender, Light-weight, Carbon, Sustainability, Environmental

INTRODUCTION

Textile-reinforced concrete (TRC) is an innovative composite material which uses mesh-like reinforcements made of alkali-resistant glass (AR-glass) or carbon. In contrast to ordinary steel reinforcements, the textile reinforcements do not corrode and, thus, the concrete covers can be minimized, leading to extremely thin and slender concrete constructions. Due to the small openings of the textile meshes, a fine-grained concrete with maximum grain sizes of about 0.20 in (5 mm) is necessary to allow for an unproblematic casting and penetration of the concrete through the meshes.

Today, textile-reinforced concrete is often used as construction material for façade structures. By using concrete covers of about 0.4 in to 0.6 in (10 mm to 15 mm) it is possible to reduce the weight of the structure by over 50 %, compared to ordinary steel reinforced constructions. HEGGER et al. and KULAS et al. give detailed information on applications with TRC, especially ventilated façade structures, sandwich panels[1,2,3], as well as the load-bearing behavior of textile reinforcements[4]. Another field of applications are constructions, which have an impact from chlorides, e.g. due to de-icing salt. One example can be seen in a pedestrian bridge made of TRC, which described in detail within the scope of this paper.

Existing bridges made of steel-reinforced concrete often show damages induced by the corrosion of the reinforcement. The concrete covers of those constructions were designed in accordance to former standards, but are too small with regard to the required corrosion protection of steel reinforcement against carbonation and chloride ingress, leading to cracking and spalling of the concrete. These damages cause optical detractions on one hand, and on the other a reduced load-bearing capacity of the construction. The consequence is that these structures have to be improved by cost-intensive actions or replaced entirely by new structures.
To avoid such high-priced restoration work new construction concepts had to be found. One promising solution is the use of TRC for bridges. The alliance of the developing company solidian, Knippers Helbig, Max Bögl and the Institute for structural concrete of the RWTH Aachen University proved the applicability of the innovative material. In 2015 the first carbon-reinforced precast bridge was built successfully (Fig. 1).

Fig. 1: TRC pedestrian Bridge in Albstadt, Germany (picture: solidian)

Fulfilling demands on a frost-resistant construction, the construction of the bridge is made of TRC, since the textiles are resistant against the impact of chlorides, e.g. de-icing salt. Furthermore, the concrete cover can be minimized to only a few millimeters, resulting in a slender, light-weight, and sharp-edged construction with a high-quality and fair-faced concrete surface. Regarding the bridge in Albstadt, concrete covers of 0.8 in (20 mm) were realized.

Contrary to constructions made of standard concrete, the TRC Bridge can be realized without any bitumen surfacing due to the denser nature of fine-grained concrete. As a result, maintenance work can be minimized, allowing for a more economical construction, since surfaces made of bitumen typically need to be renewed several times within the lifetime of the bridge. Finally, due to high savings of concrete, TRC constructions enable significant CO_2 emission reductions compared to steel-reinforced constructions allowing for a greener construction.

This TRC bridge crosses the Schmiecha river in the city Albstadt in Germany. It is the entrance into downtown of Albstadt and the replaces the old bridge, which had to be torn down.

MATERIALS

TEXTILE REINFORCEMENT

TRC uses mesh-like non-corrosive reinforcements usually made of filaments with AR-glass or carbon as basic materials. GRIES et al. gives general information on properties and fabrication of textiles[5]. Carbon is advantageous in its high tensile strength (over 3,000 MPa). Thus, carbon filaments are used in the pedestrian bridge, where hundreds of filaments are bundled into each roving as depicted in Fig. 2a.

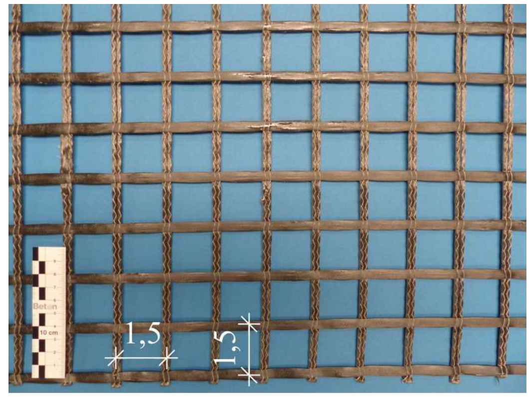
a)  b) 

Fig. 2: a) Roving made of carbon filaments; b) Laid-Scrim GRID Q95/95-CCE-38 (distance: inch)

The rovings are finished into a laid-scrim with distances of 1.5 in (38 mm) (Fig. 2b). In the next production step, the laid-scrim is impregnated with epoxy resin. RAUPACH et al. refers to the advantages of impregnated textiles in comparison to those which are not impregnated[6]. Since the filaments have diameters of only a few micrometer the concrete matrix cannot penetrate into the inner rovings due to the small space between the single filaments and, thus, the core filaments are not activated for load transfer. By impregnating the textiles with, for example, epoxy resin the resin can penetrate deep into the roving and connect the filaments with each other, creating a homogenous cross-section where nearly all filaments are activated for load transfer. As a result, the tensile strength can be more than doubled in comparison to non-impregnated rovings.

After applying the resin, the textiles have to be cured under high temperatures. Here, two different procedures can be distinguished: curing immediately after the coating process or first coating with a thermoset resin and curing sometime later. In the first procedure, the textile is driven through a tray filled with fluid epoxy resin. Immediately after this process, the wet mesh runs up into a drying tower operated at temperatures of about 320°F (160°C) where the resin is hardened, resulting in a planar reinforcement structure. The second procedure is necessary to produce spatial reinforcement structures, e.g. reinforcement for concrete webs. The resin remains in what is known as a "B-stage", where it is not hardened yet and continued processing is still possible. After laying the mesh into a mold of any shape and compressing it, the mold is placed in an oven and cured at a temperature of 356°F (180°C) for 20 min[7].

Impregnated textile structures are inherently stable and have a good handling as well as workability. This is necessary for using them for large-scale members under practical conditions in precast concrete factories. The main properties of the textile used in this project are specified in Table 1. The whole bridge was reinforced with the same textile type solidian GRID Q95/95-CCE-38.

Table 1: Main properties of the textile reinforcement GRID Q95/95-CCE-38

Property		Unit	Value
Roving	Producer	-	solidian
	Titer	tex[1)]	6,400
	Elastic modulus	MPa	240,000
Impregnation	Material	-	Epoxy resin
Roving distances	0° / 90°	in	1.5 / 1.5
		mm	38 / 38
Cross-Section	0° / 90°	in²/ft	0.045 / 0.045
		mm²/m	95 / 95
Tensile strength[2)]	0° / 90°	MPa	3,215 / 3,020

1) 1 tex = 4.3×10^{-5} lb/ft = 1000 g/km
2) Tensile strength of the textile reinforcement determined in concrete (mean values)

CONCRETE

Since the openings between the rovings are relatively small, a concrete with a small grain size has to be used to ensure a proper penetration of the textiles in the concrete. The fine-grained concrete was developed at the building company Max Bögl. In this project a concrete matrix with an enlarged maximum grain-size of 0.20 in (5.0 mm) was used. A larger grain size comes along with a smaller cement amount and, thus, the workability can be enhanced. The main properties of this high performance concrete are specified in Table 2.

Table 2: Main properties of the fine-grained concrete

Properties	Unit	Value
Maximum grain-size	in (mm)	0.20 (5)
Strength class	-	C70/85
Compressive strength	MPa	90
Flexural strength	MPa	10

As in Table 2 shown the compressive strength of the concrete reached 90 MPa during the tests and for the final bridge.

DESIGN PARAMETER

The pedestrian bridge has a total length of 51 ft (15.5 m) and is designed as a trough. The form of the walls follows the stress. Consequently the textile reinforcement doesn't need to be staggered. The highest point of the walls is 3.8 ft (1.17 m) (Fig. 3).

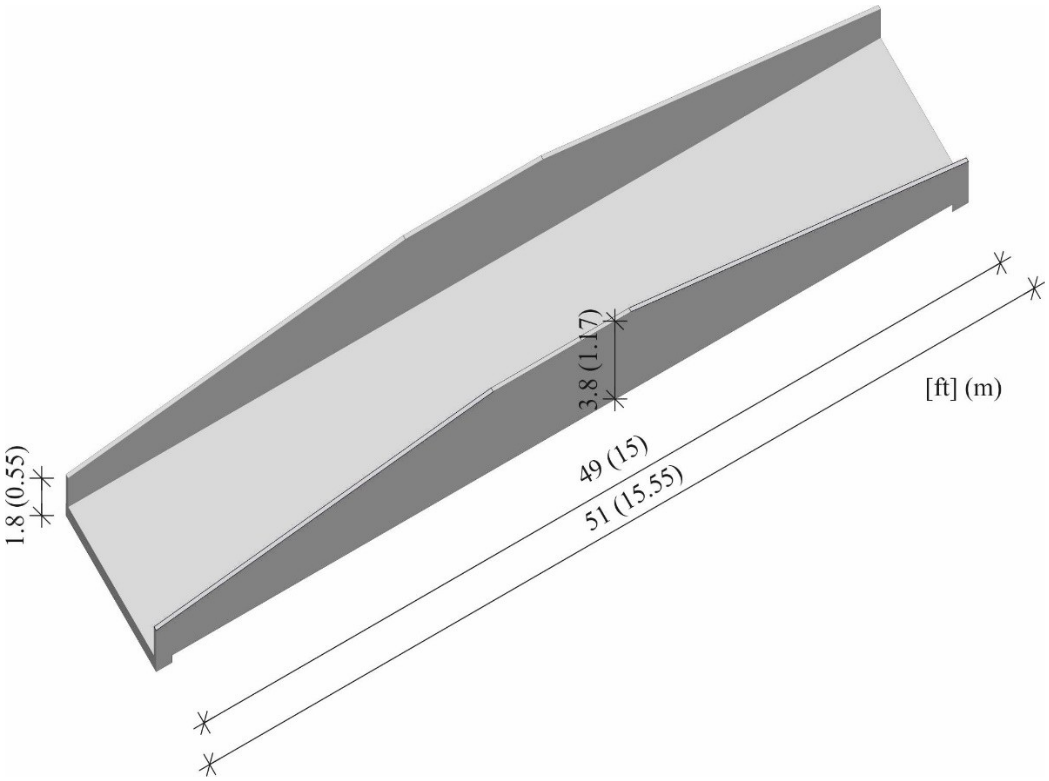


Fig. 3: View of the TRC-Bridge

The cross-section of the construction is a 115.7 in (294 cm) wide concrete U-beam, reinforced with one and two layers of the carbon grid (Fig. 4). The whole weight of the bridge is 14 ton.

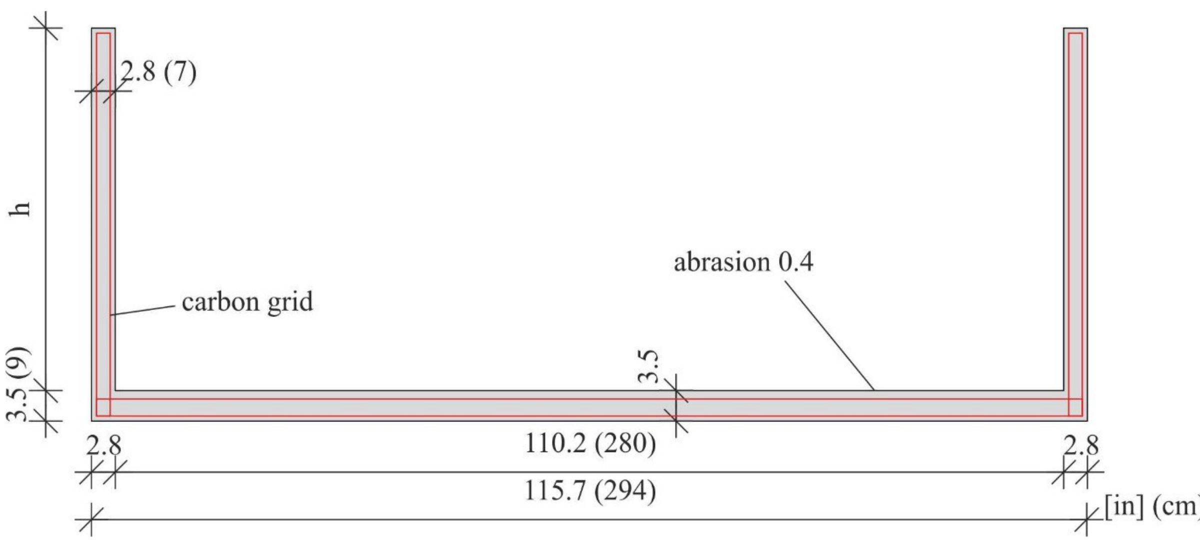


Fig. 4: Cross-section of the TRC Bridge

The textile reinforcement is made of flat and U-shaped textiles, which intersects in the corner (wall and slab) (Fig. 5). The bending moment and the shear reinforcement consists only of textiles. No steel-reinforcement was used for the realization of the bridge.

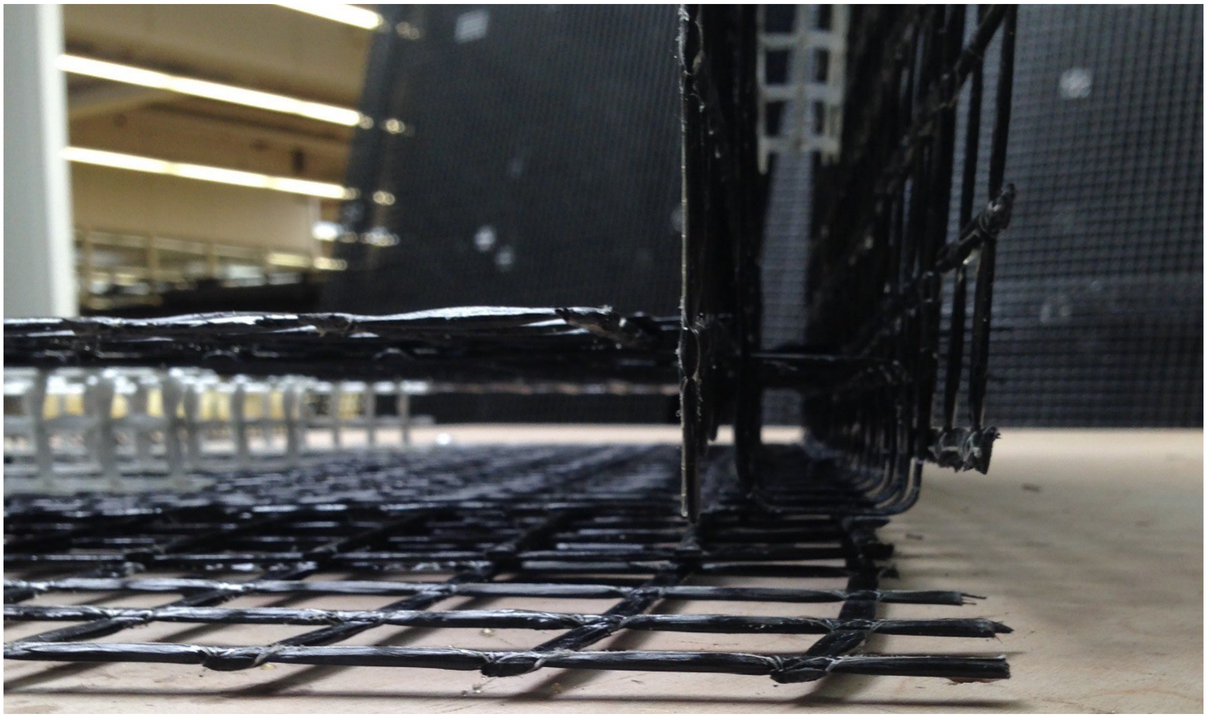


Fig. 5: Intersection of the U-shaped textiles and textile distance holder between two textile layers (white color) (picture: solidian)

The concrete cover of 0.8 in (20 mm) is determined by considering the maximum grain size and geometrical tolerances during the concreting process while ensuring a sufficient bond between the textile and concrete. The concrete cover and small bending diameter of the textiles (approximately 0.3 in (8 mm)) affords a minimum thickness of the bridge. The wall thickness is only 2.8 in (70 mm) and the slab just 3.5 in (90 mm). The upper 0.4 in (10 mm) is used as an abrasion layer to resist the mechanical action of pedestrians, bicycles, and snow ploughs during winter times. No further covering of the walkway is necessary.

PRODUCTION

The combination of the innovative textile reinforcement and the high-pressure concrete enabled an efficient production of the bridge. Due to the perfect preparation of textiles by the company solidian, the reinforcement work was completed within couple hours. Solidian provided already cut textiles pieces, which just had to be fitted together in the precast-company Max Bögl. Every piece was numbered, which avoided mistakes. The finished cage of reinforcement had to be lifted into the wooden formwork and concreted afterwards. Boards were placed on top after the reinforcement cage was inside the casing to avoid a stepping on the textiles. Consequently the workers were able to walk on the planks during the concrete process. To keep the small concrete cover of less than one inch, a special distance holder was developed. It was pressed against the formwork, which avoided the floating of the textiles (Fig. 6). Additionally, textile distance holders were used between two textile layers to keep the defined position (Fig. 5). Because of the self-impacting concrete no compaction work was necessary. Consequently the whole bridge was finished within few hours. There was no special curing needed. Just a standard cover sheet was used to cure the fresh concrete.

Fig. 6: Finished cage of reinforcement on the way into the formwork

After two days the bridge was lifted out of the framework and flipped, following by the transportation to the construction place and the setup. The bridge was placed on two foundation blocks, which were concreted few days before. Due to the light weight, just two mobile cranes were necessary for this work. After two hours the bridge was walkable. To sum up, the whole production process took just few days. Thanks to the perfect work by the companies solidian and Max Bögl a bridge was realized with no shortcomings.

STRUCTURAL ANALYSIS

The construction has to resist the following actions, specified in the structural analysis and verified within a large-scale testing program:

Ultimate limit state (ULS):	- dead loads
	- live loads due to pedestrian and wind
	- snow ploughs (max. weight 5.5 ton)
Serviceability limit state (SLS):	- decompression (“frequent combination“)

- crack width $w \leq 0.012$ in (0.3 mm) (“rare combination“)

CROSS-SECTION CAPACITY

The internal forces and the concrete stresses are determined with a three-dimensional finite-elements model, Fig. 7. Within the model the slab is generated with plate-elements and the walls with beam-elements.

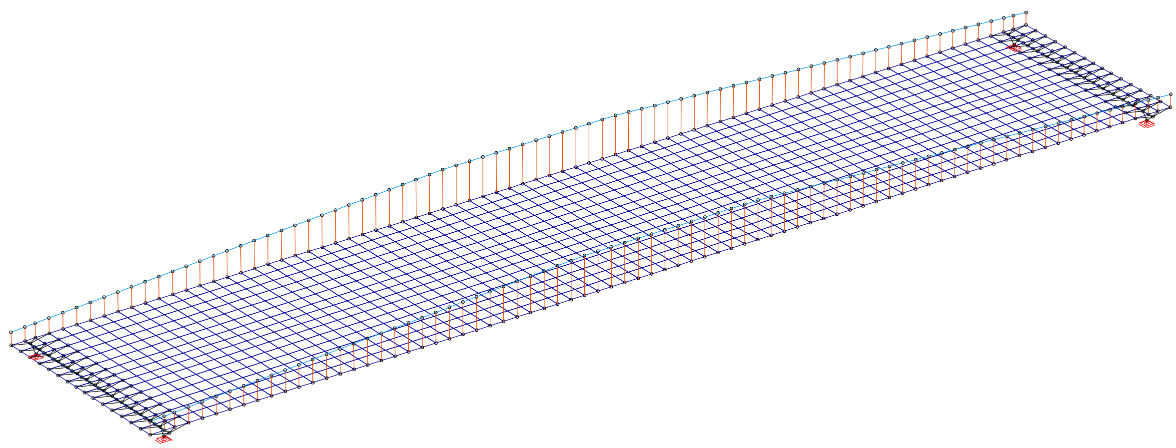


Fig. 7: Finite-elements model of the whole bridge

Considering the internal forces of the construction, the required textile reinforcement is calculated as described in Fig. 8. The internal forces (*M*, *N*, *V*) could be calculated by stress-integration, Fig. 8.

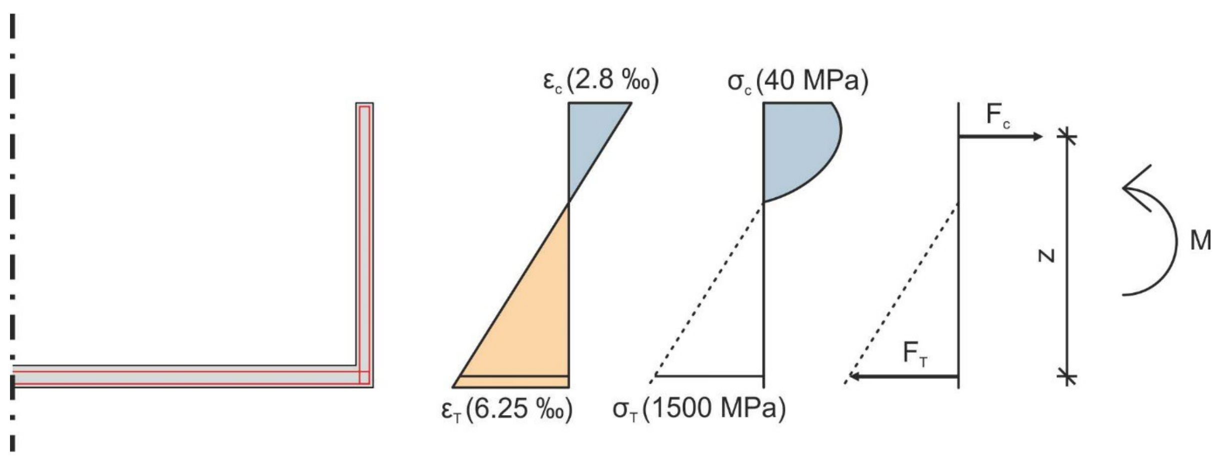


Fig. 8: Decompression and strain distribution in ULS

EXPERIMENTAL INVESTIGATION

Since textile-reinforced concrete is not regulated by any standards in Germany today, an individual approval of the construction by the building authorities is required. For this purpose, an extensive testing program was carried out at the Institute of Structural Concrete of the RWTH Aachen to assess the load-bearing capacity of the carbon concrete bridge. Based on large-scale test specimens with cross-sectional dimensions of the original scale, the load-bearing behavior, the length of the overlaps and anchoring of the textile reinforcement and also the punching bearing capacity were examined. In the following the experiments of the load-bearing behavior of the deck in transverse direction, of the suspended reinforcement of the trough walls and of the whole bridge in longitudinal direction will be presented exemplary. Detailed information regarding the load-bearing behavior of constructions made of textile-reinforced concrete are described by KULAS[8] and REMPEL[9].

CARRIAGEWAY SLAB IN TRANSVERSE DIRECTION

The bending load-bearing capacity of the deck was determined on the basis of four-point bending tests on a real plate cross-section. Though the cross-sectional height of the test specimens was reduced to 3.1 in (8 cm) to simulate the situation after a lifetime of 80 years (Fig. 9 and Fig. 10). For this purpose it was assumed that a mechanical wear of up to 0.4 in (10 mm) will occur.

The experiment showed the benefits of TRC. Due to the good bond of the textile reinforcement for concrete, a very fine crack image with distances of 1.1 – 1.9 in (2.8 – 4.8 cm) originated, shown in Fig. 10. In use, the associated maximum crack width was w_k = 0.006 in (0.15 mm) and thus fulfilled the high standards.

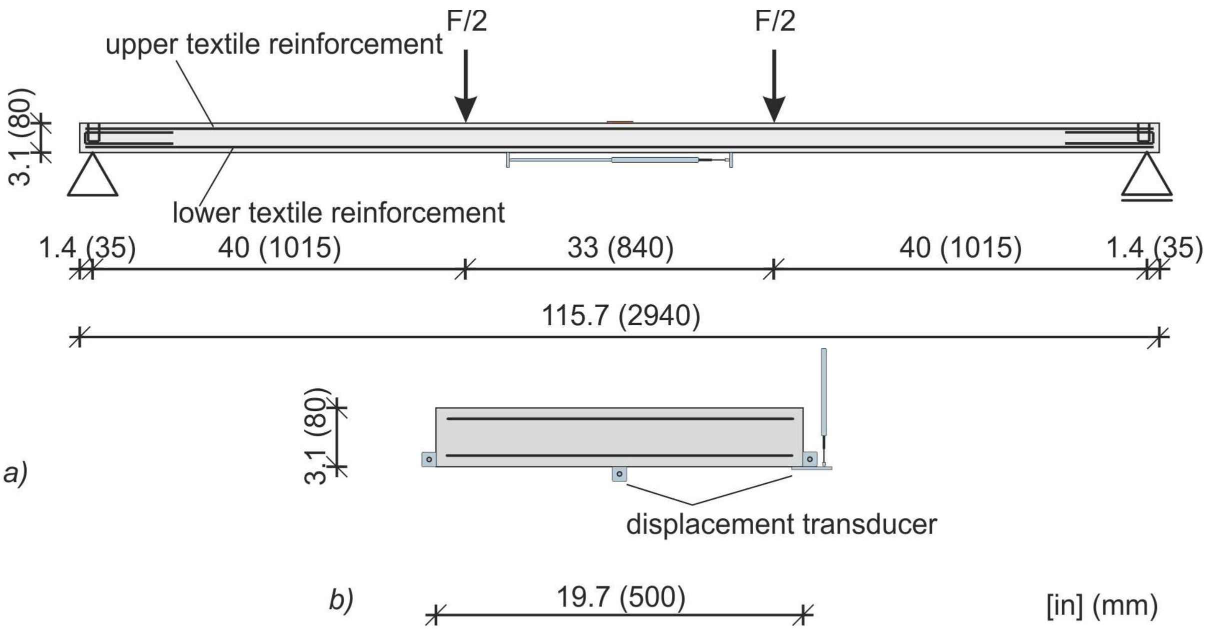


Fig. 9: Experimental setup for determining the bending load-bearing capacity of the deck: a) four-point bending test; b) cross-section

Fig. 10: Carrying out the experiment of the four-point bending test and crack image just before the break

At breaking point all requirements have been met to the load-bearing capacity. In the experiment, it was proven that the concrete strength is the decisive factor for the load-bearing capacity. Shortly before reaching the tensile strength of the roving, the concrete strength has been exceeded in the joint area of the textile reinforcement and the break was definitive. In this connection an average bending moment of m = 6.03 x 10³ lbf ft/ft (26.8 kNm/m) and a corresponding mean textile tension of $\sigma_T \approx$ 2800 MPa were reached. Thereby tensions were calculated iteratively by KULAS[8]. Fig. 11 shows that the impact moment m_{Ed} = 2.2 x 10³ lbf ft/ft (9.8 kNm/m) is lower than the designed resistance m_{Rd} = 2.59 x 10³ lbf ft/ft (11.5 kNm/m). The partial safety factor γ_c = 1.5 for concrete failure and the factor α_c = 0.85 for long-term effects were considered in the design value m_{Rd}. Overall, a global security level of η_{global} = 2.6 / 2.2 x 1.5 / 0.85 x 1.35 = 2.8 was achieved.

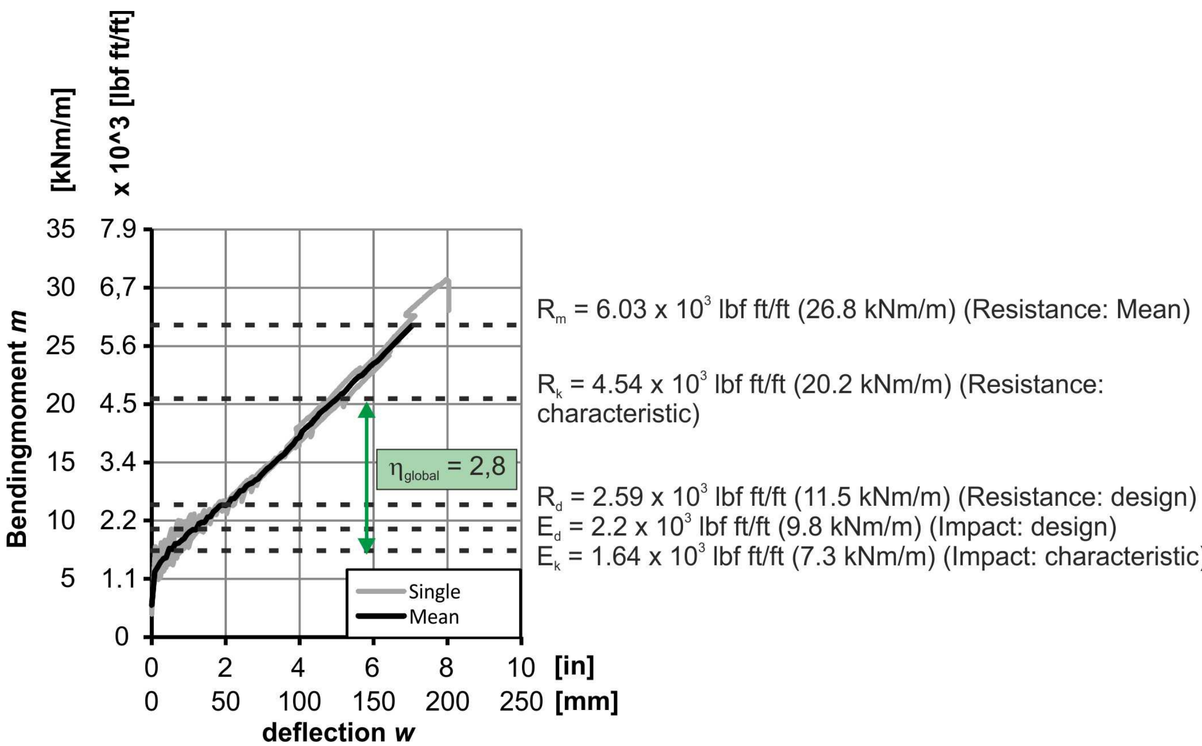


Fig. 11: Bending moment-deformation diagram - carriageway slab in transverse direction

As seen in Fig. 10 and Fig. 11, a high deformation occurred at the ultimate limit state. Although the carbon reinforcement has a linear-elastic material behavior and no plastic deformation occurs, it is possible to speak of a ductile composite at Carbon concrete. One reason for this is the modulus of elasticity (≈240,000 MPa) and the high strength of the carbon fabrics (σ_T = 3,300 MPa). Those two material properties allow an elongation of about 14 ‰ at the break point and therefore a high deformation at the ultimate limit state. This character is a positive development, since this component failure is announced well in advance.

In addition to the bending tests, the shear force resistance of the carriageway slabs in transverse direction was also determined in three-point bending tests with the same cross-sectional dimensions (see Fig. 12). The distance between support and force F was a = 9.8 in

(250 mm), which corresponds to a shear slenderness of $a/d = 9.8/2.2 = 4.5$ (Fig. 12). So the minimum shear force resistance of the cross section was determined without a direct load transfer to the support. A total of four experiments were conducted. In this process two partial tests occurred on one test specimen.

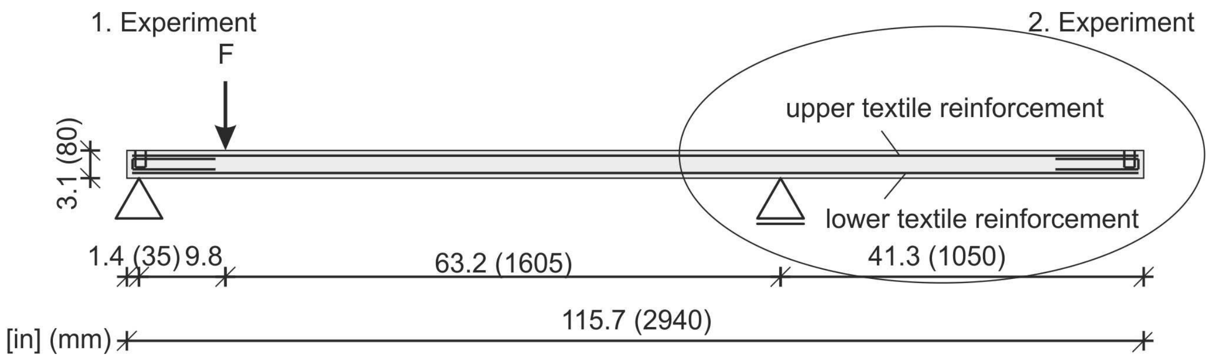


Fig. 12: Experimental setup for determining the shear force resistance of the slab

During the experiment no failure of the carbon reinforcement could be determined. The failure occurred in accordance with Fig. 13 in the joint area, as shown in the bending tests. Overall, an average lateral force $v_R = 6.9 \times 10^3$ lbf/ft (100.6 kN/m) and a fabric tension of $\sigma_T \approx 2590$ MPa were reached. In consideration of the associated partial safety factors ($\gamma c = 1.5$ and $\alpha_c = 0.85$) the design value of the lateral force is calculated to $v_{Rd} = 3.19 \times 10^3$ lbf/ft (46.6 kN/m). This resistance is much higher than the design value of the effect $v_{Ed} = 1.1 \times 10^3$ lbf/ft (16.1 kN/m). This results in a global safety level of $\eta_{global} = 6.9$.

Fig. 13: Fracture of the lateral force plate at the support

In the experiments it was observed that the results scatter very low. The decisive reason for this is the precise installation of the reinforcement, as seen in Fig. 14. Despite the two-ply reinforcement, the statically effective depth d varied by only 0.04 in (1 mm).

Fig. 14: Rupture cross-section

SUSPENDED REINFORCEMENT

The structural behavior of the suspended reinforcement, which is responsible for the load transfer of forces from the plate in the trough walls, was determined at the relevant cross-section of the trough bridge (Fig. 15 and Fig. 16). The testing force was introduced close to the support into the plate to prevent bending or shear force failure of the plate. The test specimen was stored punctually at four points, in which the supports were located at the ends of the trough wall. This should ensure that the loads of the plate flow through the suspension reinforcement into the trough wall and finally to the support. The loads were launched simultaneously on both sides. Whenever one side failed, the other half was passed on until a fraction entered.

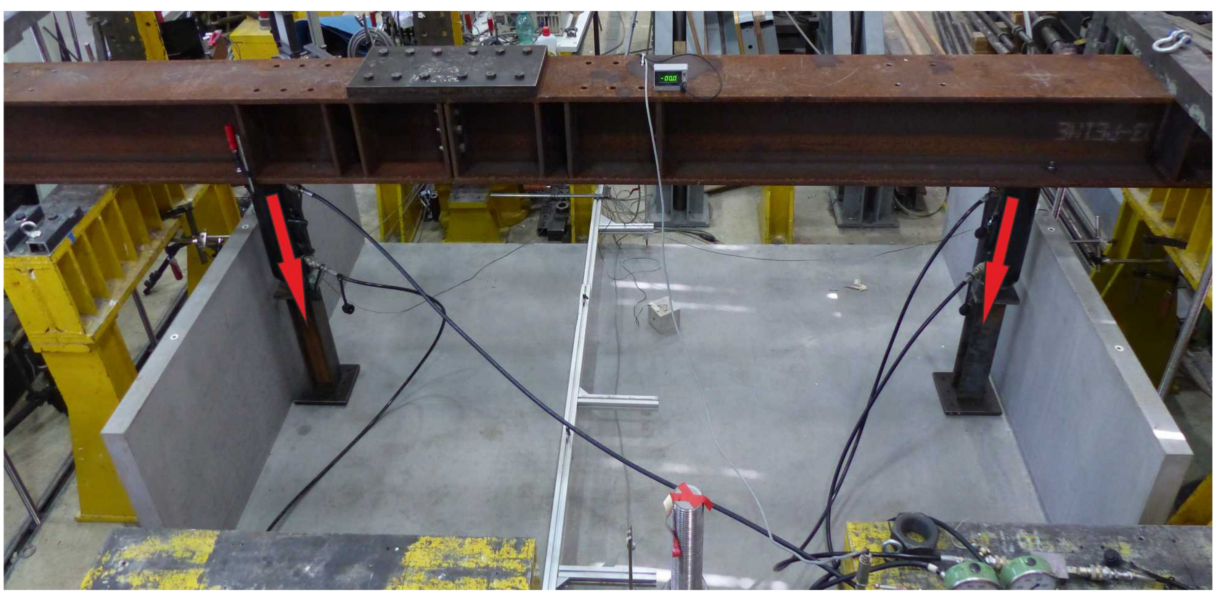


Fig. 15: Experimental setup for determining the viability of the suspension reinforcement

The breaking state was characterized by punching shear near the trough wall (Fig. 18). A punching cone with an average width of 3.3 ft (1 m) was formed (Fig. 17). Each page could apply an average testing force of $F_{punching\ shear}$ = 25.67 x 10³ lbf (114.2 kN). Taking into account the partial safety factor γc = 1.5 (concrete failure), the factor α_c = 0.85 (long-term effects) and the width of the cone, the design resistance of the suspension reinforcement per meter is calculated to v_{Rd} = 3.5 x 10³ lbf/ft (51.0 kN/m). In comparison, the effect is only v_{Ed} = 1.1 x 10³ lbf/ft (16.1 kN/m). Thus, a global security level of η_{global} = 7.5 was achieved.

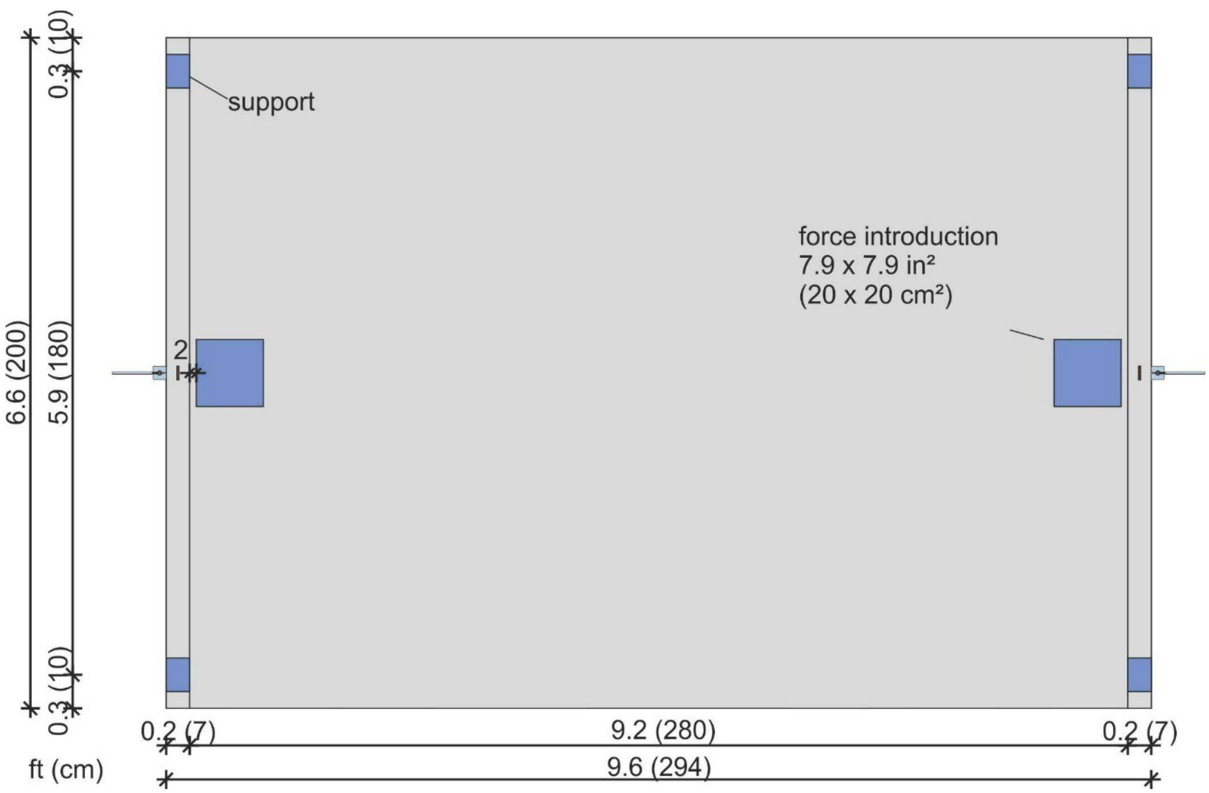


Fig. 16: View of the experimental setup for determining the viability of the suspension reinforcement

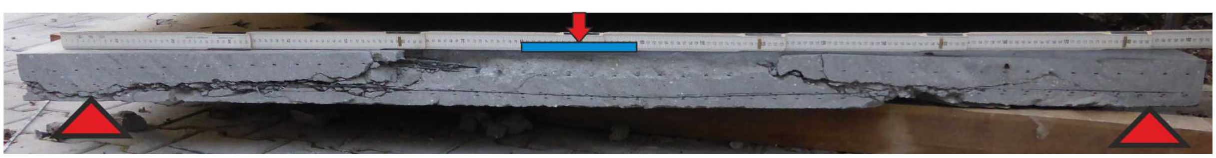


Fig. 17: View of the punching cone

Fig. 18: Plan view of the punching cone

CARRIAGEWAY SLAB IN LONGITUDINAL DIRECTION

The attempt of the bridge in longitudinal direction was of particular importance. For this, the bridge was prepared a second time and loaded in a three-point bending test until the fraction entered (Fig. 20). The testing force was introduced into the plate near the trough wall via two line loads with a length of 15.6 ft (4.75 m). As shown in the experiments in the transverse direction, a convincing load-bearing behavior could be observed in the serviceability limit state. In this state, the deformation of the 51 ft (15.55 m) long bridge was only 0.2 in (5 mm) in the middle. The reason is the stiff U-shape of the cross-section. Depending on the length of the bridge, the height in the middle of the bridge needs to be adjusted to achieve the same little deflection (Fig. 19).

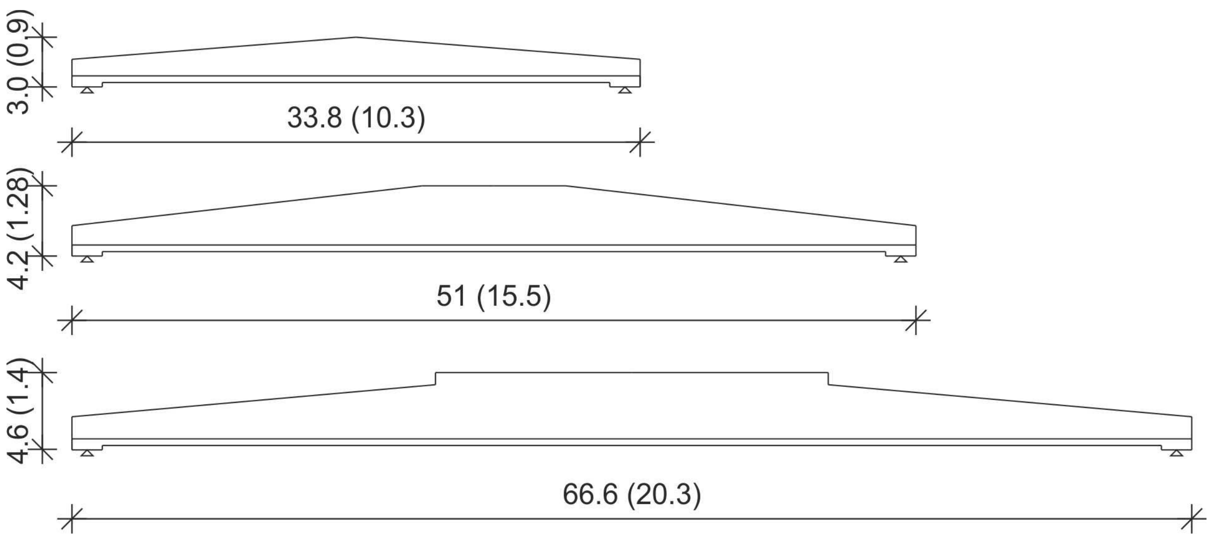


Fig. 19: Adjusted height of the bridge, depending on the length [ft] (m)

The crack widths w_k were significantly lower than 0.004 in (0.1 mm). Also at the breaking state the crack widths w_k were measured by a maximum of 0.014 in (0.35 mm), which ceased due to the positive crack distribution. A total of approximately 260 vertical cracks were counted, which were spaced 1.6 in (40 mm) apart. This corresponds to the mesh width of the fabrics.

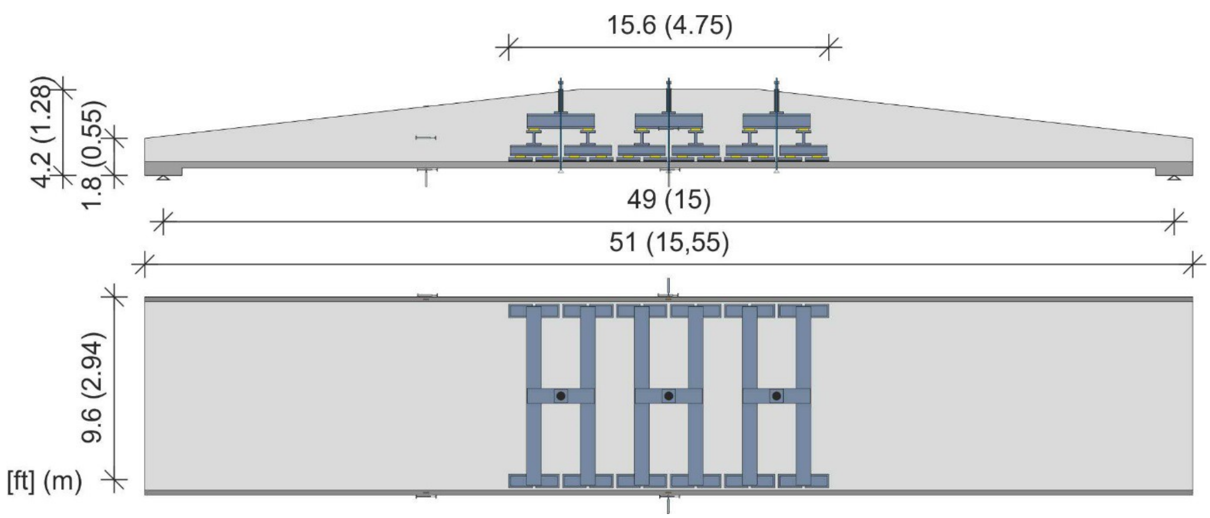


Fig. 20: Experimental setup for bending load-bearing behavior of the bridge in longitudinal direction

Due to the extremely slim 2.8 in (7 cm) webs, the concrete compression area failed at the breaking state (Fig. 21). Similar to the experiments in the transverse direction, the tensile force of the textile was not exhausted completely. Approximately 55 % of the maximum textile breaking tension $\sigma_{T,break} \approx 1700$ MPa (Table 1) were obtained in the experiment. The breaking force in the experiment was F_{max} = 144.6 x 10³ lbf (643 kN), which corresponds to a breaking moment of $M_{u,max}$ = 1722.2 x 10³ lbf ft (2335 kNm). Taking into account the partial safety factor γ_c = 1.5 (concrete failure) and the factor α_c = 0.85 (long-term effect), the rated bending moment can be calculated to M_{Rd} = 759 x 10³ lbf ft (1029 kNm). In comparison, the effect amounts to M_{Ed} = 741.3 x 10³ lbf ft 1005 kNm. Overall, a global security level of η_{global} = 759/741.3 x 1.5 / 0.85 x 1.35 = 2.4 is achieved (Fig. 22).

Fig. 21: View of the breaking point during the breaking process

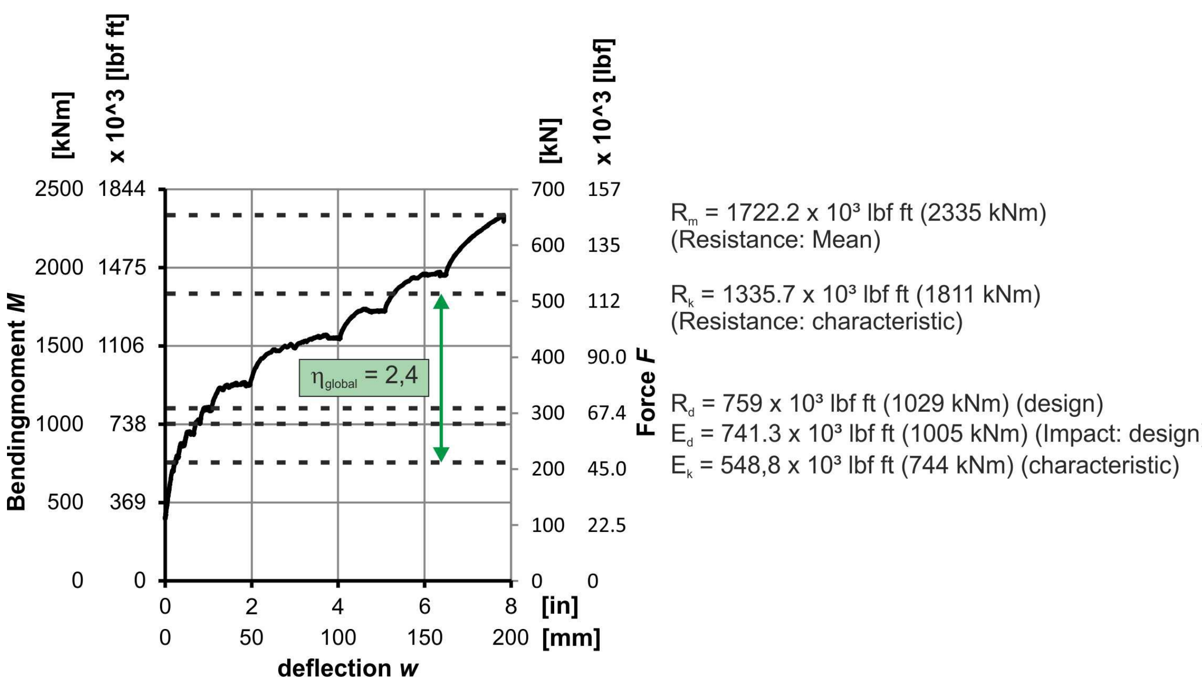


Fig. 22: Bending moment-test force-deformation diagram - longitudinal direction (middle of the bridge)

COSTS

The production costs for the TRC bridge are comparable to the costs of a standard steel-reinforced variant. The reasons are the equal prices for the concrete, the reinforcement and the manufacturing. The influence of the concrete savings on the overall costs is relatively small. While the TRC solution reduces the mass of the concrete by about 30%, the material costs are actually higher compared with typical concrete, since the fine-grained concrete consists of a large amount of cement, thereby offsetting the advantage of the lower mass. The other important cost point is the reinforcement. Right now steel is about 36 times cheaper per pound than carbon. But the carbon-strength is 6 times higher than steel. Additionally the density is also 6 times upper. That leads to a 36 times weight reduction of the needed reinforcement for the TRC bridge. Consequently the price for the needed carbon is equal to steel. The last point are the manufacturing costs. The amount of time to produce a TRC bridge is less than to produce a steel-reinforced variant. One reason is the weight of the reinforcement. The other point is the prefabricated reinforcement elements. The workers don't need to form the armor any more. They just have to put it together. That saves working time and money and equals the price for the material. After all, one can say that the costs are about the same.

In order to assess the economic aspects of the construction, it is important to look not only on the production costs, but also on the lifetime costs, of 80 years in this case. The maintenance fees of a steel-reinforced bridge construction are approximately 4.0% of the production costs per year10. Those costs cover, for example, renewing the melted asphalt layer or substituting the supportings. Since the TRC bridge does not have a separate melted asphalt layer, the maintenance fee can be set much lower and is assumed to be 0.5% of the production cost per year.

Ultimately, the lifetime costs of the TRC bridge is about 3 times cheaper in comparison with a steel reinforced construction, due to lower maintenance costs.

CONCLUSIONS AND FORECAST

In recent years, textile-reinforced concrete (TRC) has been often applied for small scale structural elements with simple load-bearing behavior and straightforward configurations of textile reinforcements. The example of the 51 ft (15.5 m) long pedestrian bridge with TRC superstructure in Albstadt, Germany, demonstrates that this innovative composite material can also be used for large-scale applications. Tests on the load-bearing behavior showed that next to the required safety-level, even further capacities are available.

These capacities will be used for highway bridges. Already at the beginning of the year 2017 the first TRC highway bridge will be installed in Margrethausen in Germany. The current tests, e.g. bending, shear and fatigue, prove the potential.

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REFERENCES

1. Hegger, J., Kulas, C., Horstmann, M., „Realization of TRC facades with impregnated AR-glass textiles", *Key Engineering Materials,* Vol. 466, 2011, pp. 121-30.
2. Kulas, C., Schneider, M., Will, N., Grebe, R., "Ventilated facade structures made of textile reinforced concrete - structural behavior and construction". *Bautechnik,* Vol. 88, Issue 5, 2011, pp. 271–280.
3. Hegger, J., Horstmann, M., Feldmann, M., Pyschny, D., Raupach, M., Büttner, T., Feger, C., "Sandwich Panels made of TRC and Discrete and Continuous Connectors", In: Brameshuber, W., *Proceedings of the 2nd International RILEM Conference on Material Science (MatSci)*, September 6-8, 2010, Aachen, Germany. RILEM Publications S.A.R.L., pp. 381-392.
4. Hegger, J., Will, N., Bruckermann, O., Voss, S., „Load-bearing behaviour and simulation of textile reinforced concrete", *Materials and Structures*, Vol. 39, Issue 8, 2004, pp. 765-776.
5. Gries, T., Roye, A., Offermann, P., Peled, A., "Textiles". In: Brameshuber, W. (Edt.), *Textile Reinforced Concrete*. RILEM Report 36. -ISBN 2-912143-99-3. 2006. pp. 11-27.
6. Raupach, M., Orlowsky, J., Büttner, T., "Epoxy-impregnated textiles in concrete – load bearing capacity and durability", In: Hegger, J., Brameshuber, W., Will, N. (Edt.), *Proceedings of the 1st International RILEM Conference*, September 6-7, 2006, Aachen, Germany. RILEM Publications S.A.R.L., pp. 77-88.
7. Hegger, J., Kulas, C., Horstmann, M., "Spatial Textile Reinforcement Structures for Ventilated and Sandwich Façade Elements", *Advances in Structural Engineering*, Vol. 15, Issue 4, 2012, pp. 665-675.
8. Kulas, C., "Dissertation on the load-bearing behavior of impregnated textile reinforcement elements for concrete components", Institute of Structural Concrete RWTH Aachen, Issue 38, Aachen, 2013.
9. Rempel, S., Kulas, C., "Bending load-bearing behavior of impregnated textile reinforcement elements for concrete components", *Civil Engineering*, Vol. 90, June 2015, pp. 248 - 251.
10. Bundesministerium der Justiz, "Ablösungsbeträge-Berechnungsverordnung vom 1. Juli 2010 (BGBl. I pp. 856)".