INFLUENCES OF ADVANCED COMPOSITE MATERIALS ON STRUCTURAL CONCEPTS FOR BRIDGES AND BUILDINGS

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Introduction

The consideration of different properties of new materials leads to new structural concepts. In bridge construction, the low rigidity of glass fibre reinforced polymer (GFRP) composites is a particularly important factor that influences the structural form. Low material rigidity can be compensated for by using material-adapted structural forms with adequate system rigidity.

In building construction, the low thermal conductivity of GFRP materials and therefore the absence of thermal bridges is an advantageous factor that can positively influence structural concepts of buildings. The possibility of integrating different functions into individual building components can allow the load carrying structure to be merged with the facade into a single-layered building envelope.

The bridge and building projects described herein and carried out at the Composite Construction Laboratory CCLab of the Swiss Federal Institute of Technology in Lausanne represent first approaches to so-called material-adapted structural concepts in bridge and building construction.

Bridges

Pontresina Bridge

The pedestrian bridge in Pontresina, Switzerland, constructed in 1997, has two 12.50 m spans and an inner width of 1.50 m (Fig. 1 and 2). The live load for the bridge is a maximum of 5 kN/m^2. Every year, the bridge is used only during the winter and removed in the spring. Composite fibre material was chosen mainly for its low self-weight, high strength, and good resistance to corrosion.

Two truss girders composed of GFRP pultruded shapes form the two main load-carrying elements of the bridge. Due to the required rigidity, the truss girders have a relatively low slenderness ratio (cross-section depth / span length) of 1/8.5. The comparatively deep girders were therefore positioned laterally on the upper side of the deck, at the same time the top chords act as the hand rails.

The connections in one of the bridge spans were bolted as in conventional steel construction. The connections in the other span, however, were bonded with a two-component epoxy resin based adhesive. For anisotropic composite materials, bonding is a more material-adapted connection technique than bolting. Joint forces, which must be introduced into the weak matrix before being transferred to the strong glass fibres, are well distributed and do not cause local stress concentrations.

In order to reduce joint forces, the trusses were constructed in five layers and with crossed diagonals (the chords comprising two layers, the tension diagonals comprising two layers, and the compression diagonals comprising one layer, Fig. 2).

As a safety precaution, since the bridge is a public structure and there had been little prior experience with bonded load-carrying joints, the bonded joints were also bolted on a lower structural safety level. The bolts are effective only if the bonded part of the connection fails. The bolts were also usefull to provide the necessary fixation and contact pressure during hardening of the adhesive. Furthermore, the safety of the system is increased through the structural redundancy provided by the crossed diagonals, which allow for the failure of individual connections without causing failure of the entire bridge.

Figure 1. Pontresina Bridge

Figure 3. Load tests

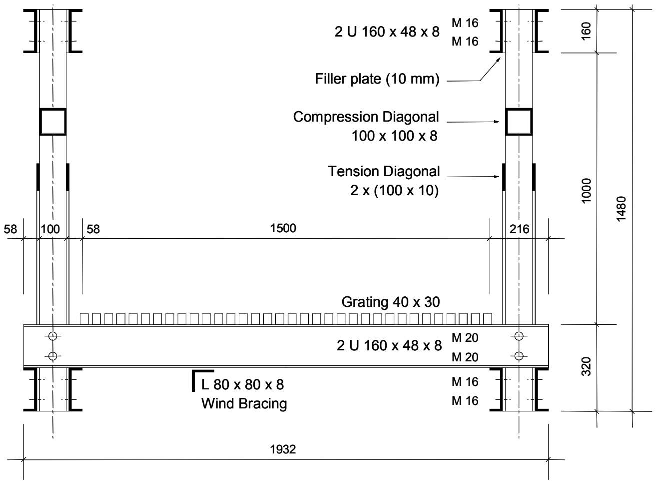

Figure 2. Section (bolted span)

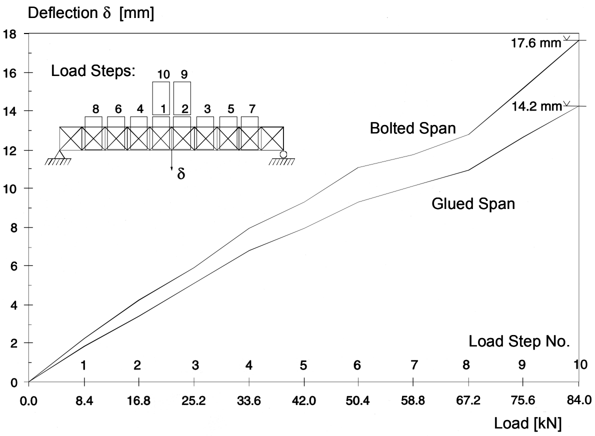

Figure 4. Results from load tests

A simple load test was performed on each of the two spans by applying a uniform load of about 5 kN/m^2 (Fig. 3 and 4). As expected, the deflection of the bonded span (14.2 mm) was smaller than the deflection of the bolted span (17.6 mm). A study of the load-carrying capacity of the bonded connections consisted of performing simple tension tests on doubly-spliced plate connections.

Modular Bridge System MBS

The construction of the Pontresina bridge showed clearly the non-favourable aspects of the truss concept using only pultruded GFRP shapes. The determining factor for the choice of the members is always the joint capacity and not the section capacity.

Successive steps to move from bolted pultruded shape construction towards material-adapted construction are made at the CCLab. These steps include the introduction of adhesive bonding as a connection technique, the use of sandwich elements, the use of carbon fibre cables and the development of material-adapted load-carrying structural forms. An adaptation of the structural form is necessary in particular due to the relatively low rigidity of the GFRP. The low material rigidity can be compensated for by an adequate structural system rigidity [1].

In the MBS-Project, the diagonal bar system from the truss concept was replaced by GFRP sandwich element webs (Fig. 5). In this way, the web-chord connections are continuous and can be bonded easily, the shear forces are no more transferred at concentrated locations as in the truss joints. The translucent GFRP sandwich panels consist of two outer layers separated by a composite fibre sheet

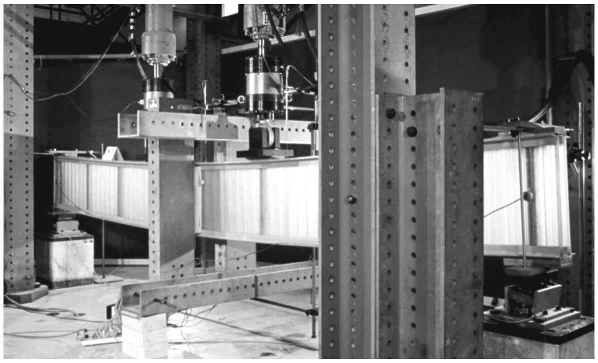

Figure 5. Translucent sandwich girder

Figure 6. Modular bridge system - MBS

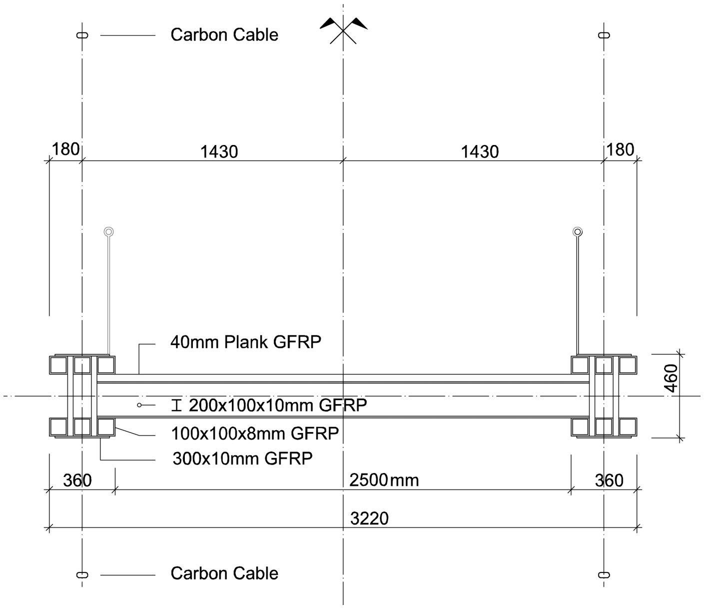

Figure 7. MBS, section for 30 m span

Figure 8. Translucent sandwiche panels

with trapezoidal corrugations (Fig. 8). Two 6m-span test girders were constructed and tested successfully at the CCLab (Fig. 5 and [2]).

The MBS was developed for pedestrian bridges with span lengths between 20 and 50 m and a widths from 2.50 to 4.00 m (Fig. 6). The live load for these bridges is a maximum of 5 kN/m^2. The bridge superstructure is composed of two exterior translucent GFRP sandwich girders (Fig. 7). The deck consists of a GFRP plank supported by transverse girders. The system rigidity of the structure is achieved with two prestressed carbon fibre cables that run above and below each sandwich girder, which force the girders to act as large compression struts. The two cables are deviated at the one-third span points by vertical sandwich struts and anchored at the ends of the sandwich girders. The bottom cables are prestressed so that the upper cables remain stressed under ultimate load. In the event of failure of the upper cables the entire bridge will not fail. Depending on the span length and width, the vertical struts are braced with sandwich girders. All connections in the bridge are bonded. Depending on the bridge size, it can be fabricated and transported in one, two or five pieces to its erection location. The translucent sandwich elements can be designed in various colours and with integrated lighting.

Buildings

Eyecatcher Building Basel

Fibre reinforced polymer composites are used in building construction today primarily for the strengthening of girders, columns and masonry walls. There is also, however, some interest in the use of these materials for load-carrying structures of buildings. FRP composites are characterised by a high specific strength and GFRP have the added benefit of a low thermal conductivity.

The high specific strength results in smaller structural elements and therefore a lower mass of inertia, which can be favourable in high-risk earthquake zones.

Due to their low thermal conductivity, GFRP load carrying components can act as insulating elements, in addition to their structural functions. The possibility of integrating different functions into individual building components can allow the load-carrying structure to be merged with the facade into a single-layer building envelope. This re-opens for architects the lost conceptual and structural possibilities of the “bauhaus” or modern architectural style. Furthermore, GFRP elements can be translucent or transparent and come in a large range of colours.

The five-storey 15 m tall Eyecatcher building was constructed in 1999 for the Swiss Building Fair, Swissbau 1999 (Fig. 9). It was visited by 20'000 visitors in one week. The maximum live load of the building is 4 kN/m^2 per storey. After its first use at the exhibition the building was disassembled and reconstructed at another location in Basel, where it will remain permanently. It represents the tallest GFRP building in the world today.

The primary load-carrying structure of the Eyecatcher consists of three parallel trapezoidal GFRP frames that are connected by wooden decks (Fig. 10). The two outer frames are integrated into the façade without creating thermal bridges. Due to a selection of cross-section shapes and sizes that is still limited today, members were assembled from individual standard elements (Fig. 11). Connection of these built-up members was done with a two component epoxy resin based adhesive. The load-carry behaviour of the built-up members was tested in large-scale laboratory tests [2].

Figure 9. GFRP Eyecatcher Building Basel

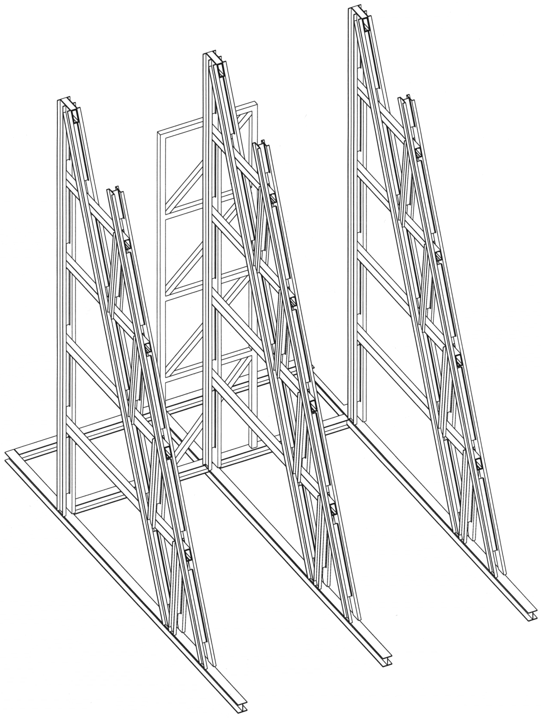

Figure 10. Primary load-carrying structure

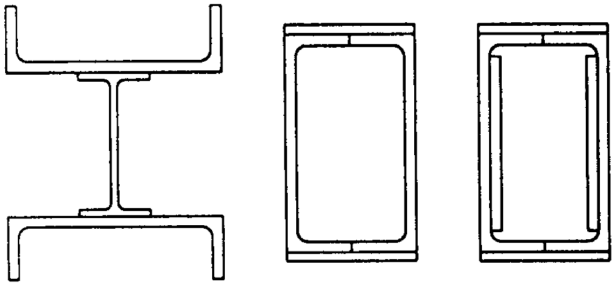

Figure 11. Built-up GFRP members

Figure 12. Multiple-layered frame

The structural joints in the frames are bolted in order to facilitate dismantling of the structure after its first use at the fair. In order to minimise the number of bolted connections, the frames are built in multiple layers with spliced joints (Fig. 12). The horizontal floor girders made of bonded-together box sections are placed in the middle layer of the frames and extend the entire length of the structure. The columns made from channel sections pass through the entire height of the building on both sides of the floor girders. Buckling of the columns between floors is prevented with I-shapes, inserted and bonded between the channels. Admissible deformations and required frame rigidity were determinant in the design of members for the Eyecatcher.

The frames were built by a steel fabricator. This provided two notable advantages. First, hardening of the bonded connections was achieved in only two hours at 80°C in the available paint drying oven. At ambient temperature, hardening of the adhesives would have taken several days. Second, it was possible to check the bonded connections partially with the non-destructive ultrasonic method – like that used for welded steel joints – thus providing a substantial level of quality assurance.

For the side-facades, the same translucent sandwich panels as for the MBS were used (Fig. 8). The main function of these facade elements is thermal insulation. For this reason, the sandwich panels are filled with translucent aerogels. With a panel thickness of only 50 mm it is possible to obtain a k-value of 0.4 W/m^{2}K. The aerogels also possess good sound absorbing characteristics.

The facade components of the Eyecatcher could not yet be implemented with primary load-carrying functions. Since the construction of the Eyecatcher, however, tests on the MBS girders have shown that they could have been used as bracing for the building. With the facade acting as bracing, sizes of the pultruded shapes used in the frames could have been substantially reduced. The Dock Tower, presented below, was designed accordingly.

Dock Tower Basel

The Dock Tower has 36 storeys and an overall height of 108 m (Fig. 13). The structure was designed for the Swiss Building Fair, Swissbau 2002, with the goal of demonstrating further the potentials of FRP materials in building construction.

The structure of the Dock Towers is based on the concept of the function-integrated building envelope. This concept can also be seen in stem plants in nature, which are also composed of fibre reinforced materials (Fig. 14). The ground-plan of the Dock Tower has been derived from the circular cross-sections of these naturally optimized load-carrying structures. Five elevator shafts form the main vertical load-carrying elements, which lie on the exterior of the 27.0 m diameter floor cross-section and merge with the circular façade (Fig. 16). In addition to the building physics functions, the façade serves as horizontal bracing for the shafts, so that these act together statically as one cross-section. Internally, five smaller vertical load-carrying service shafts are found. The floor slabs are supported by all ten shafts, the facades are not loaded. A final vertical element, a spiral stair case, is located in the centre of the building. Based on this arrangement of vertical elements, the ground-plan can be divided into five sections. The dead load of the tower is only about 40% of a comparable building with primary steel construction and glass facade.

The configuration of the main structure on the outside obstructs the path of natural light into the building. In order to increase the amount of natural light entering the building, two-storey Sky Gardens with transparent facades were included in the design. The placement of the Sky Gardens – always located between two elevator shafts – alternates: facing south, south-west, south, south-east, south, and so on. By alternating the location of the Sky Gardens as well as with the use of circular window shapes, the bracing function of the facade is maintained. Furthermore, through the integration of the Sky Gardens, an inner facade enclosing the central staircase is formed.

The Tower will be used as living and office space. The three south-facing sectors include apartments with access to the Sky Gardens. On floors where the Sky Gardens are facing directly south, one-storey 3.5 room apartments and two-storey 6.5 room duplex apartments are foreseen. Whereas on floors where the Sky Garden face south-east or south-west, the floor arrangement allows for one-storey 6.5 room apartments. The offices in the two north facing sectors are of variable size. Access to the apartments and offices is primarily by means of the four elevators, but also through the central and northern staircases.

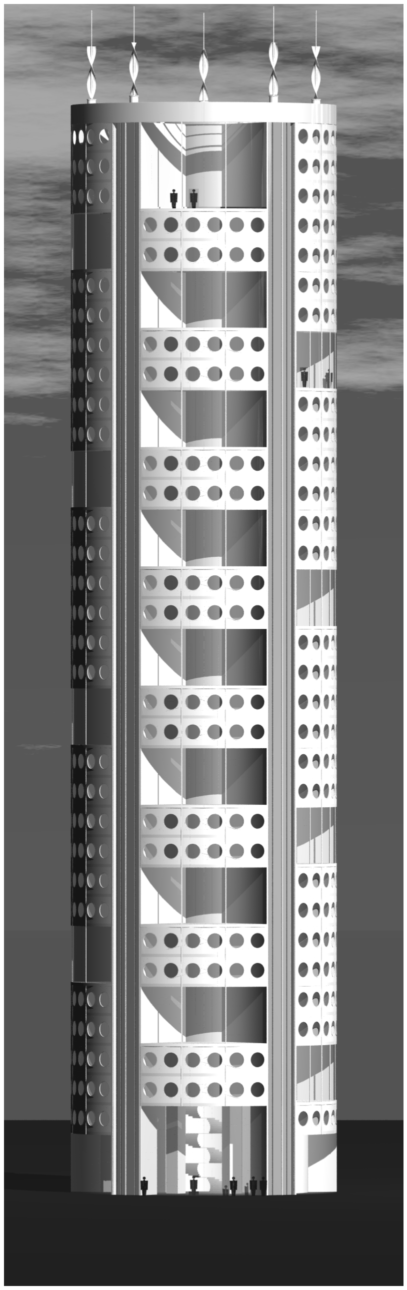

Fig. 13: FRP Dock Tower

The facades can be opaque, translucent or transparent. The degree of transparency is determined by the content of glass fibres. Due to the 70% fibre content, the exterior walls of the elevator shafts, which have main load-carrying functions, are opaque-white. The façade in the living and working areas, which has the bracing function, appears translucent-white due to the approximately 30% fibre content. The material used for the Sky Gardens and the round windows is without fibres and therefore transparent. The facade has the appearance of a smooth, jointless cylinder.

The Tower is provided with a mechanical ventilation system. In the summer the system - which cools the south side of the building - is powered by photovoltaic cells integrated into the external walls

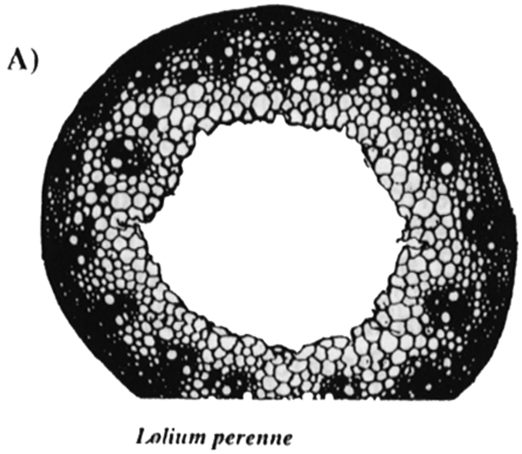

Figure 14. Plant cross-section

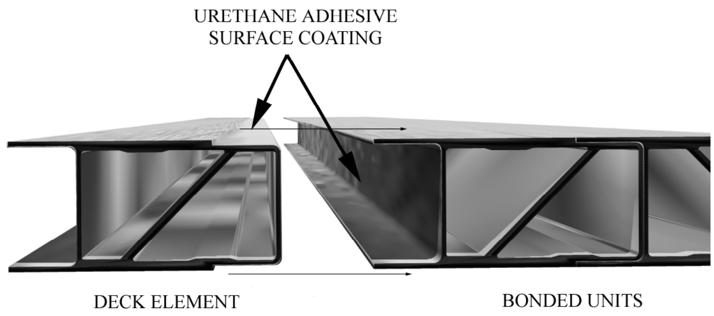

Figure 15. DuraSpan wall elements

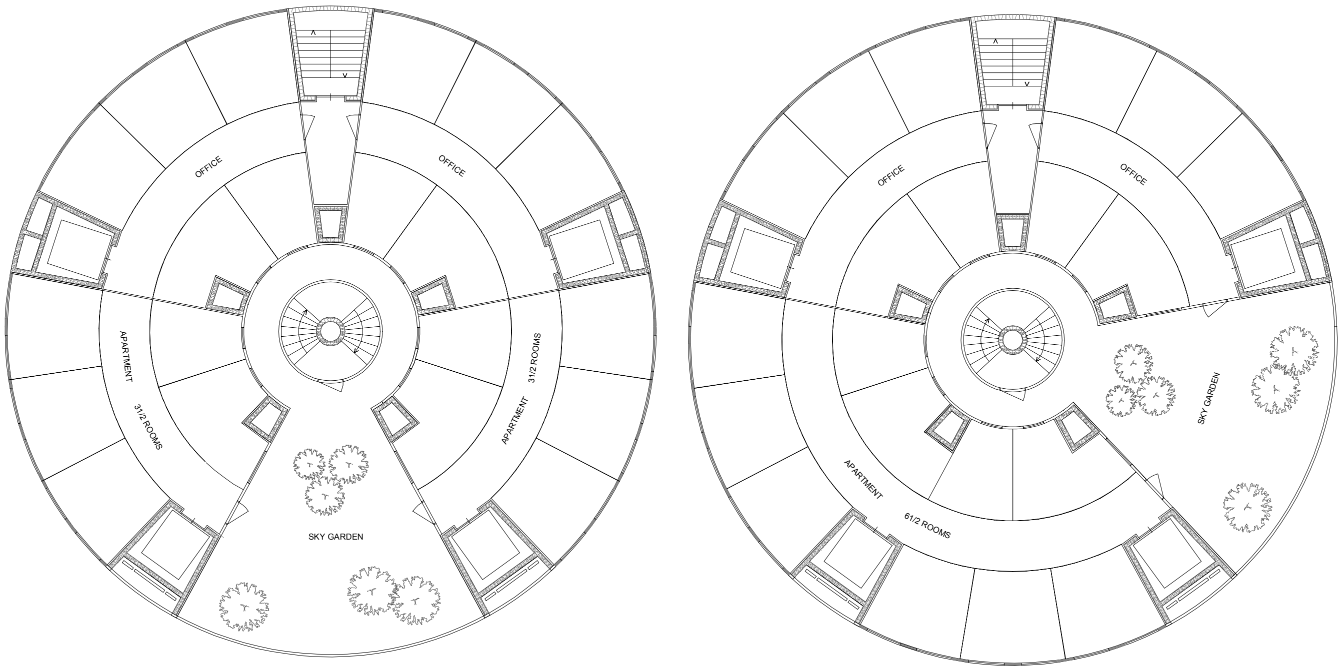

Figure 16. Ground-plans of Dock Tower (diameter 27 m)

of the two south shafts. Energy is also supplied by five vertical wind turbines located on the roof of the Tower.

The northern office and southern housing areas each form fire sections. The central and north stairs act as fire escapes. The walls of the main load-carrying elements consist of cellular cross-sections, therefore minimising the amount material exposed to the fire (Fig. 15). All main vertical load-carrying elements and the central stairs are fireproofed. The floor slabs and facades are equipped with sprinkler systems. In the case of fire, the load-carrying capacity of the facade is not required.

At Swissbau 2002 a two-storey, 6 m high segment of the southern elevator shaft with one facade section of the Sky Gardens and living quarters were constructed (Fig. 17). The walls of the shaft consist of vertically oriented, pultruded DuraSpan members (Fig. 15 and 18). The 15 cm thick sandwich facade

Figure 17. Facade section

Figure 18. Walls of the elevator shaft

consists of three layers in the living areas. The three layers are composed of translucent glass-fibre reinforced polyester laminates, which are held together by glued transverse stiffeners. The space between the outside and middle layers is filled with transparent aerogels, which act as insulation. The circular and curved windows composed of polycarbonate are glued into the translucent facade.

Conclusions

Composite fibre materials are new building materials with the potential to lead to substantial innovations in bridge and building construction. In order for these materials to be fully exploited, material-adapted structural forms and construction methods must be developed. The concepts presented herein - the use of standard structural elements, sandwich panels, carbon cables, adhesives and material-adapted structural forms - are first steps towards this development. At the CCLab of the Swiss Federal Institute of Technology Lausanne research is underway in order to further develop the use of these promising materials in bridge and building construction.

References

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