Bio-based composite pedestrian bridge.Part 1: design and optimization

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Bio-Based Composite Pedestrian Bridge–Part 1: Design and Optimization

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Abstract

The Bio-based composite bridge is a 3TU project which aims to design and realize a 14m span pedestrian bridge made from fibre-reinforced polymers (FRP) that have a high percentage of bio-based content. The bridge will be installed over the river Domel, at the campus of the Eindhoven University of Technology (TU/e) in the Netherlands. The present paper investigates the design potentials and challenges of bio-based fibre-reinforced polymers, which is a relatively new material in architectural and structural bridge design. Along with the design possibilities of the material, the paper presents the entire design process followed from conceptual stage to detailing, focusing on the evaluation of different structural typologies and the optimization of selected geometry.

Keywords: structural design, bridge design, naural fibres, bio-based FRP, fibre-reinforced polymers, bio-composites, monocoque structures, structural optimization.

1. Introduction

Fibre-reinforced polymers are composite materials that consist of a polymer matrix reinforced with fibres. Fibres widely used for their high mechanical performance are glass, carbon, or aramid, while the polymer is usually an epoxy, vinylester or polyester thermosetting plastic. Both fibres and the matrix exhibit different physical and chemical properties which combined together create a strong and rigid composite material. Besides the exceptional strength, their high stiffness to density ratio embodies the potential of creating lightweight structures. Consequently, costs in transportation, hoisting, assembly, supporting structure and foundations are significantly reduced. In terms of durability there are advantages as well, as FRP composites show high resistance to corrosion leading to low maintenance requirements.

Concerning the environmental impact of FRPs, several studies prove that they perform better in terms of CO_2 footprint in comparison to traditional building materials such as steel and concrete. However, the majority of these composites is based on non-renewable sources. Therefore, under the recent environmental awareness, materials based on renewable raw resources entered the composite industry and found application in various sectors, such as the automotive industry, industrial design and packaging. Naturally occurring fibres, such as flax, hemp and jute replaced successfully artificial fibres while new types of resins based on natural substances have been introduced, aiming to reduce the environmental impact of composite plastics.

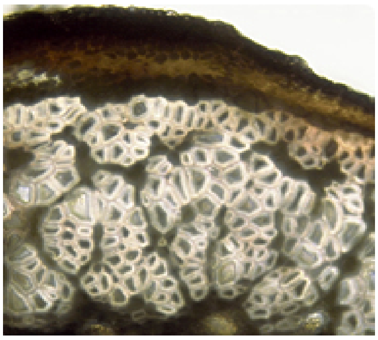

Fig. 1: Cross-section of hemp fibres under the microscope
Fig. 2: Non-woven flax mat
Fig. 3: Flax fibres stitched together into a unidirectional textile

Nevertheless natural fibres are characterized by poor durability. Studies[5] conclude that excessive moisture absorption due to the hydrophilic behaviour of cellulosic fibres causes accelerated reduction of their mechanical performance. Poor compatibility between natural fibres and hydrophobic resins is another reason responsible for the degradation and loss of strength. Natural fibres are also susceptible to UV radiation. Photochemical degradation by UV light results in changes in the molecular structure of the composite, promoting surface embrittlement, cracking, discolouring and loss of tensile and impact strength.

Due to the reasons mentioned, the building industry is yet cautious with integrating natural fibres in FRP elements. Considering load-bearing applications, the use of organic ingredients is at even lower and research level. Thus, the Bio-based composite bridge consists an experimental step towards the employment of bio-based materials in FRP structures. The bridge will be monitored for a period of one year after its installation on site, in order to preserve safety and observe the behavior of the structure.

2. Design potentials of FRP molding processes

Apart from the exceptional mechanical performance and durability, low maintenance and environmental benefits, FRPs unlock potentials in terms of design and shaping as well. In the field of architectural design, the qualities of composite plastics in three-dimensional forming, have been under research and use for decades.. On the contrary, in regards to bridge design, none of the early FRP designs expressed concern for the aesthetical potentials of the material.

Opposite to architectural applications, in the field of infrastructure and specifically bridge design, FRPs design potentials are rarely considered. The majority of bridges constructed out of FRP, comprise out of structural components which are produced as standard pultruded beam profiles or decks and are assembled into trusses, arches, pylons or U-beams. As a result, these bridges resemble to typical steel structures without expressing visually the fact that their structures were not a result of welding but molding.

Nevertheless, as previously mentioned, FRPs through their different molding techniques allows for building structures with complex geometries and achieving a high degree of plasticity. These types of structures are often influenced by the efficiency of load-bearing geometries existing in nature, such as monocoques, shells or folded plates.

Producing a bridge geometry with more than one degree of freedom can be a challenging procedure. First, in order to obtain a smooth and maintenance friendly surface, the use of a mold is essential. Mold-making can become quite expensive part of the total manufacturing cost, in case of complex shapes that require a special mold. In the contrary, mold cost can be effectively reduced by employing simple flat molds.

Considering surface quality, the production method chosen is critical for the final result. With vacuum injection, the texture of the vacuum foil and surface imperfections are visible at the exposed underside of the bridge, similar to an old-fashioned canoe hull that has a bumpy surface on the inside. Alternatively, manual hand lamination allows for more design freedom but it is not optimal due to low fibre-volume fraction that leads excess resin requirement and finally to a heavier structure with increased shell thickness. In both vacuum injection and hand lamination, a highly smooth surface is possible only through extensive post-grinding, coating and polishing.

2.1 Monocoque structures

Monocoques are structures with a loadbearing exterior shell, comparable to that of a shellfish. These structures have efficiently concentrated the material on the outer region of the cross-section, while the rest of the cross-section is normally filled with a lightweight material. These elegant structures not only offer design potentials with the various slender forms they can take, but show advantages in terms of maintenance as well. The fact that the undersides of monocoque bridge decks are smooth and closed offers actual advantages. For instance, as no flanges or complex structural components are exposed dirt does not accumulate on the skin while even the case of bird nest creation under the structure is avoided.

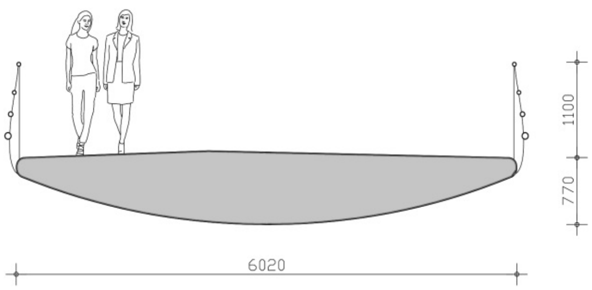

Fig. 4: Design of a monocoque FRP drawbridge for pedestrians and bicycles (left)
Fig. 5: Cross section of the beak of a hornbill (right)

2.2 Folded and shell structures

Load-bearing structures out of FRP can also be designed as shell structures or three dimensional folded shapes and benefit structurally by the intrinsic stiffness that these structures offer. Folding relatively flat elements, such as FRP sandwich panels, into three dimensional shapes increases the stiffness of the structure significantly. U-shaped beam geometries are the simplest variant of folded structures, but more intricate folded designs inspired by origami paper folds become also possible.

However, an expected downside of folded structures is caused by the folds themselves and the fact that forces within the material cannot be transmitted by axial forces only. Thus, bending momentum is introduced due to the folds, which leads in extra material and preferably rounded edges in the corners.

Shell structures, opposite to folded solutions, are more efficient regarding material use, especially in case the form of the shell stays close to the catenary plane induced by the loads. In these cases the deck itself can be quite thin as the structure derives its stiffness from three dimensional curvatures. An example of such a shell structure is the design for a modular FRP pedestrian bridge (Fig. 8), developed by Royal Haskoning DHV in cooperation with composites company FiberCore. The cross section of the deck curves upwards, forming part of the bridges' parapet. As the bending momentum increases towards the middle, so does the height of the shell.


Fig. 6: Pringles: fried potato snack with optimized stiffness (left)
Fig. 7: The Delft Design Composite Bridge for pedestrians and bicycles (right)

3. Design evolution

3.1 Design variations development

The design approach towards achieving an optimal structure in terms of structural efficiency and aesthetical quality is based on the generation of various alternative designs which are evaluated according to specific factors. Concerning the structural efficiency of the structure, one of the notions that influenced the design evolution is the assumed predominant strength and stiffness of bio-based materials in tension rather than compression. As a result, the design variations are characterized by enlarged compression zones and thinner tension zones. Apart from structural sensibility and design aesthetics, criteria that influences the design evolution, are the functionality in terms of use, safety, as well as the realistic and cost-effective producibility.

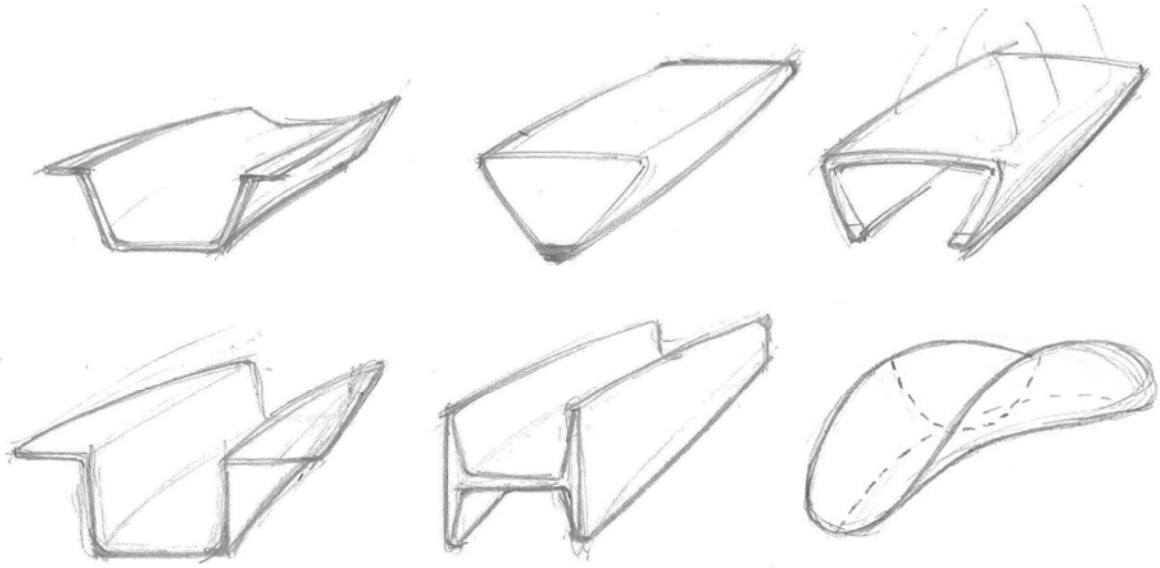

Fig. 8: Variable bridge cross-sections

The outcome of the first design approach consists of multiple cross-sections of either beam or monocoque structural solutions. U-shaped and I-shaped beam variations achieve an effective structural use of their solid composite parapets, while certain alternatives introduce horizontal top flanges that increase towards the middle of the span in order to enhance compressive strength of the structure. Inverted U-shaped beam solutions maximize strength under compression, though are weaker in tension and require additional railing.

One of the geometries researched has a triangular middle cross-section that gradually becomes rectangular towards the edges, offering high compression strength at the walking surface and providing space at the bottom of the cross-section for additional tensile reinforcement. Nevertheless, this structure requires a massive core material which is enclosed within the FRP facing. A structurally optimized solution is also offered by a smooth shell, double curved in two different directions.

All various cross-sections generated through the design phase, were modeled using parametric design digital tools, such as Grasshopper and Caramba. Through these software, a precise structural comparison of the different sections was achieved.

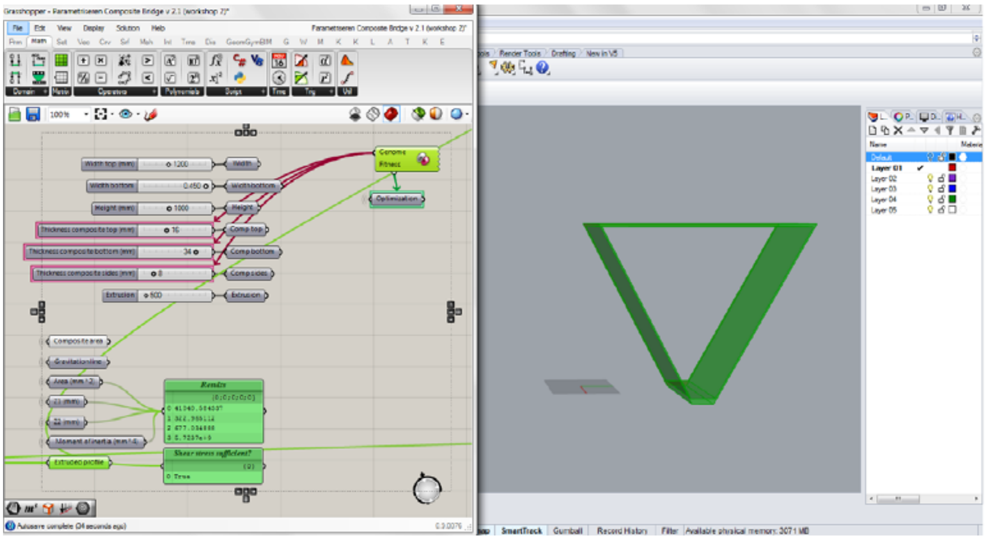

Fig. 9: Structural evaluation of the triangular cross-section in Grasshopper.

Besides the structural characteristics of each design, aesthetical aspects were equally critical for the design evaluation. Maximization of transparency and slenderness of the structure are major parameters. Illustrating the alternative designs proved that the solid parapets that the U-shaped and I-shaped beams embody, result in massive geometries, considering a minimum height of 1m for the railing according to the safety rules. Additional horizontal flanges on top extend the problem of the lack of transparency while the addition of perforations on the composite parapets increases production complexity.

Therefore, a non-structural railing which is attached on the deck justifies as a more elegant solution compared to the solid U-shaped beam alternatives, while complexity of deck fabrication is lower. Considering the criteria mentioned, the typology that complies with all the parameters is the monocoque deck with a triangular middle cross-section that becomes a slim rectangle at the edges.

3.2 Structural optimization of selected design

Many different sections (u–shaped and triangular shaped) have been evaluated on strength and section properties (second moment of inertia mostly). The different generated ideas where subsequently discussed and narrowed down to a limited number of most promising preliminary designs. For these designs the structural dimensions where estimated based on preliminary calculations and estimated material properties. The structural dimensioning of the structure is departing from a required uniform live load of 5,0 kN/m. Using Grasshopper and Rhino parametric design rules were implemented in a digital model, in order to create and evaluate many different shape configurations, curvatures and material thicknesses in terms of maximum stresses and deflection. Finally a shape that develops from a rectangular cross section at the abutments towards a near triangular shape in the middle has been selected. Selection criteria were sufficient stiffness, architectural appearance as well as criteria for easy production. The structural, material and production aspects of the design process are described in more detail in the second paper: Bio-Based Composite Pedestrian Bridge–Part 2: Materials and Production Process.

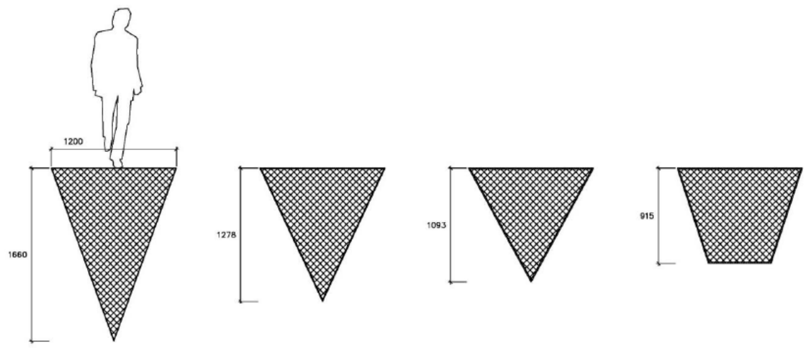

Fig. 10: Different sizes and shapes of filled sections evaluated

Composite thickness		Height		Filler material		Composite material		Stresses	
4	mm	1580	mm	0,667	m^2	0,028	m^2	$-21,2 < \sigma < 40,7$	N/mm^2
8	mm	1225	mm	0,530	m^2	0,046	m^2	$-16,2 < \sigma < 32,1$	N/mm^2
12	mm	1060	mm	0,457	m^2	0,062	m^2	$-13,9 < \sigma < 27,7$	N/mm^2
Trapezoid									
12	mm	855	mm	0,487	m^2	0,066	m^2	$-14,6 < \sigma < 18,9$	N/mm^2

Table 1: Resulting thickness of shapes based on minimum required strength and maximum bending stresses.

The selected deck geometry develops from a thin rectangular cross-section at the edges into a triangular section of approximately 1m height in the middle of the span. However, in order to enhance mechanical performance under tensile forces at the area where the maximum structural height is, without further increase of the height of the structure, the triangular cross-section slightly grows into a trapezoid with a bottom edge of 240mm. The bottom area of the structure increases gradually in width while at the same time the structural height drops as the structure reaches the abutments. At the position of the support, the width of the bottom surface is equal to the size of the walking area and the cross-sectional height reaches its minimum.

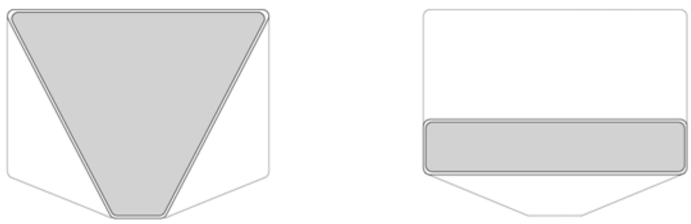

Fig. 11: Cross-sections of the structure at the middle (left) and the end of the span (right)

An additional geometry adjustment concerning an optimized structure with low deflection values is the considerable increase of the structural height at the ends of the bridge. During the concept design phase, in order to achieve a slender structure, the geometry was designed more than 8 times thinner at the ends than in the middle of the span, which created the impression of a remarkably curved structure. Nevertheless, calculating the geometry resulted in a minimum height of 350mm at the ends of the deck span and a maximum of 1m cross-sectional height in the middle. The width of the top surface of the structure is constantly at 1.2m

Apart from structural optimization through adjusting the geometry of the structure, FRPs offer maximization of the mechanical performance through optimal use of different fibre orientations. Thus, the bridge geometry was calculated using a stepped 2D frame program and afterwards it was modeled and calculated using a 3D FE program: Abacus. Using Abacus, different material properties representing the resulting material stiffness of various combinations of fibre orientations and configurations, were applied on different areas of the bridge sections. Configurations with Unidirectional, Woven (two-directional) and Non-Woven fibers were compared aiming to optimize the deck in terms of fibre cost and structural performance. The optimum solution achieves a maximization of the low-cost Non-Woven fibre plies and reduces the amount of the expensive, though stronger, Woven or Unidirectional fibres to the minimum required.

As a result, the top and bottom areas that proved to be structurally more critical than the side surfaces, they enclose a better quality laminate that has a high percentage of woven and unidirectional (UD) flax textiles oriented towards the critical direction. On the contrary, the side surfaces of the structure have a laminate structure that is built primarily out of non-woven mats. Non-woven mats consist of randomly arranged short fibres that show consistent properties along the plane, without any dominant direction. Opposite to woven and UD flax fibres, for the mats, hemp fibre is chosen as compared to flax they have a lower mechanical performance and consist a more cost-effective solution for the areas of the structure with lower structural capacity required.

Considering the core material of the structure, PLA foam was chosen as a bio-based solution. PLA also known as polylactide, is an aliphatic thermoplastic polyester produced from renewable resources while normally it is compostable when exposed in the environment.

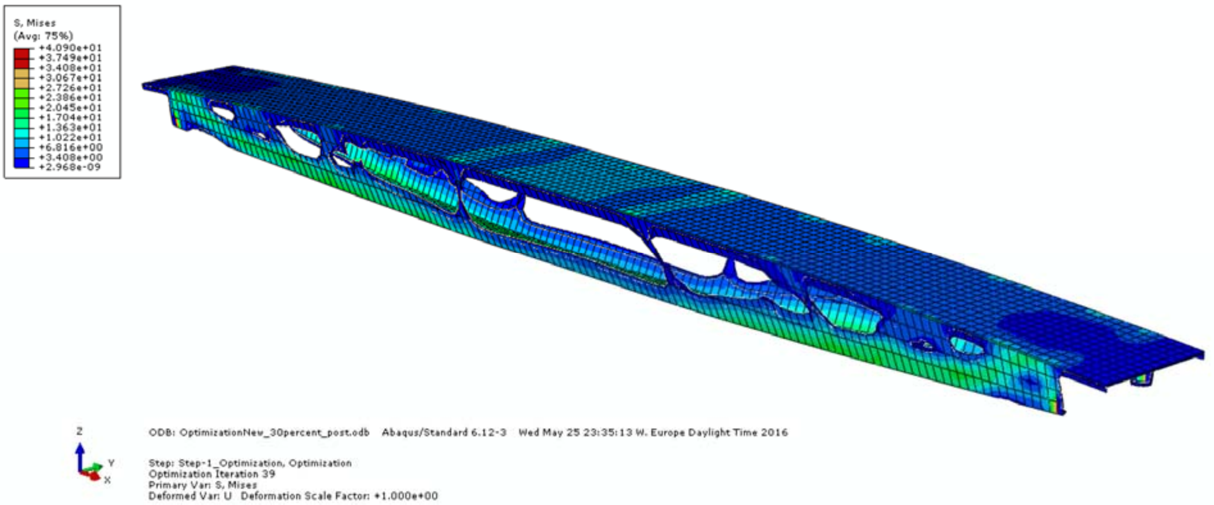

Fig. 12: Result of topological optimization in FE program Abacus

4. Final design

4.1 Deck structure

The walking surface of the structure is a low arc with a radius of approximately 50m with a maximum 6^o slope angle. An important element of the deck is also the filleted edges of the geometry that add into smoothening the sharp edges especially at the areas where the cross-section becomes into a pointy trapezoid. This rounded edge effect is a result of high pressure force applied evenly on a thick laminate of dry fibre plies that are wrapped around the geometry. During resin injection the plies are pressed under a flexible vacuum bag and at the same time are getting impregnated with the resin.

4.2 Railing

As the geometry chosen during the first design phase, involved no railing solution, additional parapets had to be designed. In the direction of maximizing the renewable content of the structure and having an innovative solution in terms of materialization, the railing is decided to consist out of FRP reinforced with natural fibres as well. In order to express the bio-based content of the structure on the overall design, the shape of the railing was chosen to resemble to an organic form or grass blades. The design consists of vertical taper-shape elements that end on a continuous 260mm-wide bottom flange which connects them. The railing panels are manufactured as flat elements and are attached on the side of the deck.

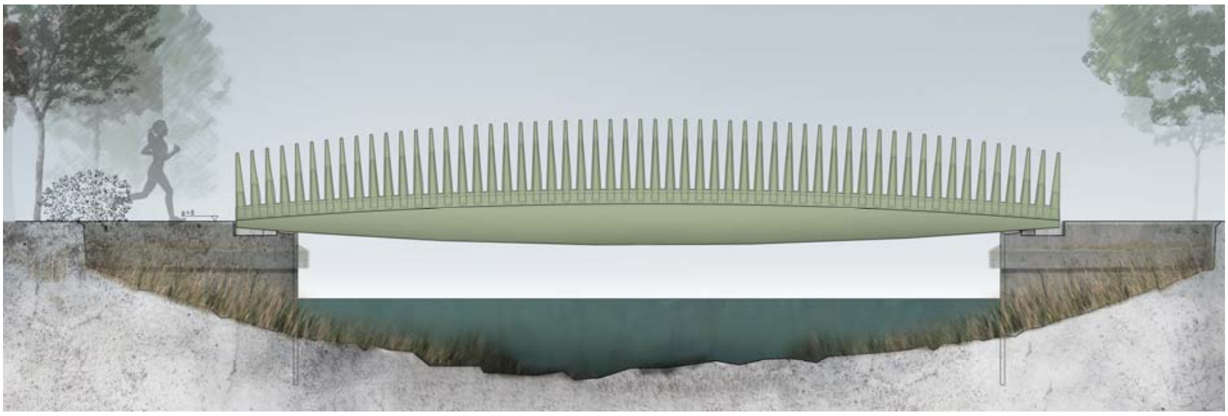

Fig. 13: Side elevation of the bridge

Fig. 14: Cross-section at the middle of the span

A main characteristic of the design is the gradual outer inclination of the posts from their vertical position which is at the ends of the bridge, while it reaches the maximum inclination at the middle of the span. However, as the railing panels are produced as flat elements, the shifting from the vertical is only created as a result of fixing the bottom flange on the non-uniformly angled side of the deck. Being flexible due to its material and comb shape, the railing absorbs slight torsional force resulting in various inclinations that create an ellipse shape in top view. As a result, it brings the feeling of an open and comfortable space for the users towards the center and gives a dynamic character to the design.

Concerning an accentuation of the arched shape of the bridge, the railing is designed with a non-constant height with the top outline following an arced path. Therefore, in the middle of the span the projected height of the railing reaches 1,2m while at the edges where the lowest height is, the railing is 0,9m. Regarding the color of the bridge, a double color solution is suggested, with the outer surfaces of the bridge being painted light green and the inner light beige.

4.2 Detailing

In the direction of enhancing the stiffness of each individual element, the thickness of the laminate is increased at the areas of high stress concentration by adding long cork pieces. Following the stiffness requirement of each railing element, the length of the cork reinforcement is not constant either. In the middle of the span where the posts are inclined and longer, the cork stripes reach their maximum length, which drops smoothly towards the edges. To create sufficient leverage area between the railing and the deck, the thickening of each post extends approx. 200mm below the walking surface.



Fig. 15: Cork pieces used to reinforce the each railing element
Fig. 16: Final railing element coated with paint
Fig. 17: Mock-up of the deck structure

Concerning the connection and alignment of the railing with the deck, the first is attached at such a height so that the openings at the lowest part of the railing, are 5cm higher than the decks walking surface. In that way, a gutter is created at the two sides of the deck, which will direct the rain water towards the abutments. Although these areas normally susceptible to dirt accumulation, dark stains from rainwater will be prevented at the sides of the deck. Finally, the attachment between the railing and the deck is achieved by gluing the two elements.

5. Conclusion

From material research to mock-up model production, throughout all stages of the Bio-based composite bridge project it is proved that using bio-based materials in FRP raises different parameters and require special approach than traditional fossil-based constituents. Not only the special structural behavior of natural fibres leads to certain design possibilities, but also during production these materias demand for certain treatment. For instance, bio-based resins tend to increase excessive temperatures during injection, making the use of insulating layers of cork necessary in order to protect the PLA core. At the same time, natural fibres demand full and assured enclosure within a coated matrix for avoiding their direct exposure to weathering conditions and UV radiation.

Next to the environmental character of the project, the bio-composite bridge addresses issues of the aesthetics of FRP as well. Since composite polymers were introduced in the field of architecture and infrastructure decades ago, the perception over the aesthetics of buildings and structures, have been gradually changed. Complex designs became feasible, pushing the architectural design limits forward, while advantages concerning the structural efficiency, maintenance and durability attracted the field of construction as well. Therefore, throughout these decades, after having seen structures that either consider the aesthetical value of composite plastics or they simply follow standard traditional building systems, the question of how fibre-reinforced plastics should be expressed on the shape of a structure remains valid.

Thus, a major goal of the present project was to develop a geometry that shows high structural efficiency through optimization, while through its plasticity and uniformity it reveals the fact that it is molded as one whole element. As a result, both the railing system and the deck structure are produced by the same material and technique, while they follow the same aesthetical language giving the impression of a uniform structure.

One other factor, critical for the design of the bio-composite bridge, was the restriction within a given low budget. Consequently, cost driven decisions had to be done in order to avoid a complex molding processes, in which the use of special and labor intensive mold would be required. Additionally, the material use is optimized with the stronger but expensive fibres applied only were needed and the overall material use minimized as a result of the effective deck geometry. In the same direction, the bended railing is produced by resin injection as a flat element that is bended when attached on the deck structure.

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