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RESEARCH

Material-Oriented Engineering for Eco-Optimized Structures — A New Design Approach

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ABSTRACT

The modern industry allows producing composite materials with a broad spectrum of mechanical properties applicable in medicine, aviation, and automotive industries. However, the building industry generates a substantial part of budgets worldwide and utilizes vast material amounts. At the same time, the engineering practice has revealed that innovative technologies require new design concepts related to developing materials with mechanical properties tailored for structural purposes. It is the opposite of the current design philosophy when design solutions allow applying only the existing typical materials, the physical characteristics of which, in general, are imperfectly suiting the technical requirements, leading to an inefficient increase of the material amounts for safety's sake. Moreover, some structural solutions are barely possible using standardized approaches. This work illustrates the implementation of the proposed adaptive design concept and discusses the design perspectives.

KEYWORDS

Structural materials, physical tests, additive manufacturing, numerical modeling, parametric optimization.

INTRODUCTION

Notwithstanding the modern industry's ability to produce composite materials with a wide range of mechanical properties applicable in medicine, aviation, and automotive sectors, conservative structural design principles are predominant in the building industry. At the same time, this industrial branch generates a substantial part of the budget worldwide and utilizes vast amounts of materials. Thus, the engineering practice has revealed that innovative building technologies require new design concepts related to developing materials with mechanical properties tailored for construction purposes [**1**]. It is the opposite of the current practice where standardized engineering solutions are associated with applying existing materials, the physical characteristics of which are imperfectly suiting the structural requirements, leading to an inefficient increase of the material amounts for safety sake.

The current research trends focus on identifying fundamental relationships between the internal structure of advanced composites and the related physical properties. The article collection [**2**] reveals considerable room for improving the choice of structural materials from a scientific viewpoint. Among other promising examples, recent findings show the beneficial effect of nano-particles on the mechanical performance of advanced composites [**3**]; chemical additives can help identify the thermal impact on structural composites [**4**]; heat-resistant aluminum-based composites ensure power transmission safety [**5**]. Advanced woven fabrics reinforce soft body armor [**6**] and structural components [**7**]. Hu *et al*. [**8**] reported promising results structurally adapting the mechanical performance of cross-linked polymers.

Regarding structural applications, the Democritus University of Thrace research team achieved remarkable results in developing and analyzing fibrous reinforcement, improving cementitious composites' mechanical performance and sustainability [**9–11**]. The cyclic test results of fiber-reinforced concrete beams with bar reinforcement describe a valuable reference for further development of advanced cement-based composites [**9**].

The proper combination of advanced composite materials can also enhance impact resistance [**12**] and ensure structural integrity [**13**] and efficiency in utilizing the reinforcement components [**14**]. The latter investigation exemplifies the structural steel design alteration, extending it to the post-yielding stage when deformations but not the strength condition governs the structural solution. Unfortunately, the mechanical performance of polymeric composites is an aging and long-term deterioration subject [**15-18**] and requires further extensive investigation. In addition, the advanced composites raise the internal structure and component optimization problems, e.g., [**3,8, 13,14**], requiring innovative design solutions and concepts.

The above-identified gaps motivated this study, and the "Industrialised material-oriented engineering for eco-optimized structures" research project supported by the European Regional Development Fund inspired this article's emergence, which adapts the Award Lecture at the European Advanced Material Congress 2022 in Genoa. It summarizes the project results published in the literature [**19–26**]. The proposed design approach describes the eco-optimization criteria in a simplified and heuristic manner as reduction of the materials' amount, carbon emission, energy footprint, and life cycle costs, satisfying the required performance of the structural components. Developing a unified design methodology of reinforced polymer- and cement-based structural composites with material properties tailored for sustainable and eco-optimized construction purposes describes the target of this study. The research flow encompasses five main activities depicted in **Fig. 1:** 1) experimental characterization of composite materials and structures [**20-22**]; 2) materials engineering [**20,21,25**]; 3) tailoring structural components' material properties and production technology for construction purposes [**19**]; 4) the design methodology development employing the collected database and metaheuristic optimization algorithms [**26**]; 5) adaptive prototyping for user requirements [**23,24**]. The division into activities is formal—all tasks are interlinked (**Fig. 1**).

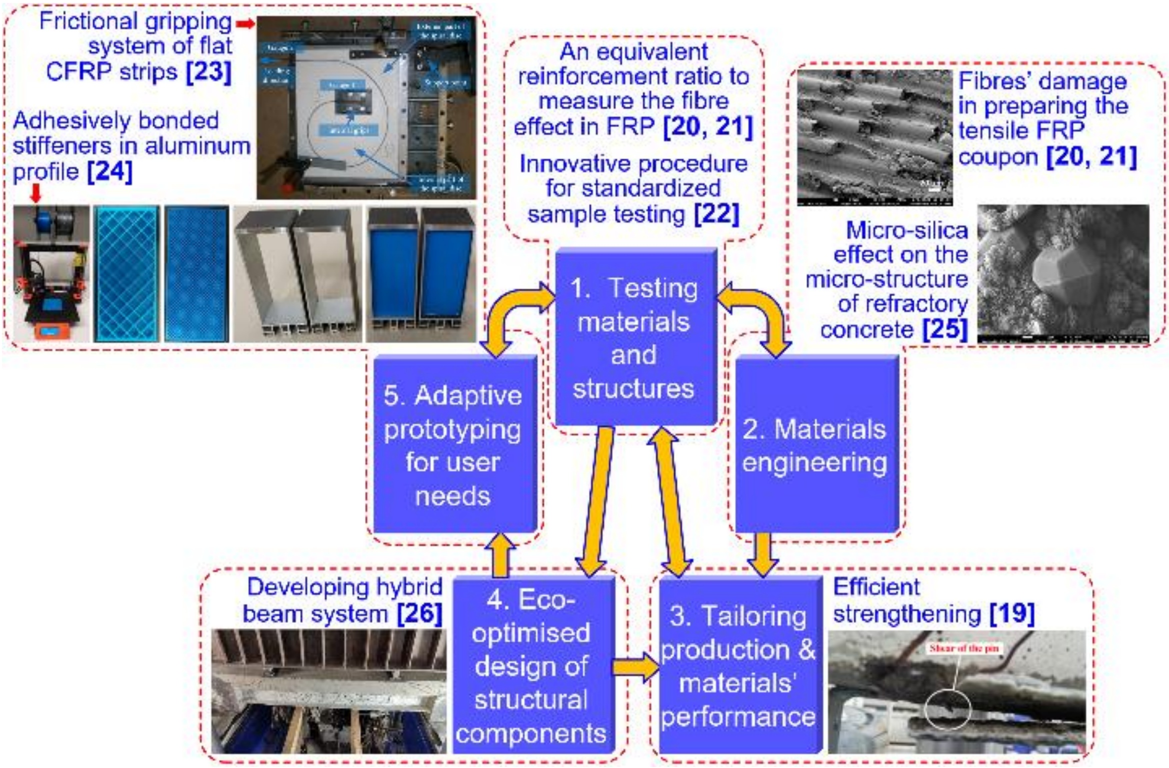

Fig. 1. The project's research flow.

The research results and discussion

The research activities in **Fig. 1** cover a variety of tests. This article summarizes the essential experimental outcomes and achieved findings, providing the reader with the minimal information necessary to follow the investigation flow and investigation trends—an expert finds all the research details in the references [**19-27**].

Developing heat-resistant composites

Within the project framework (**Fig. 1**), material engineering ensures the development of fiber-reinforced cementitious composites with outstanding mechanical performance and high-temperature resistance. The bio-fuel furnaces describe the working example for applying the developed ultra-high performance composites.

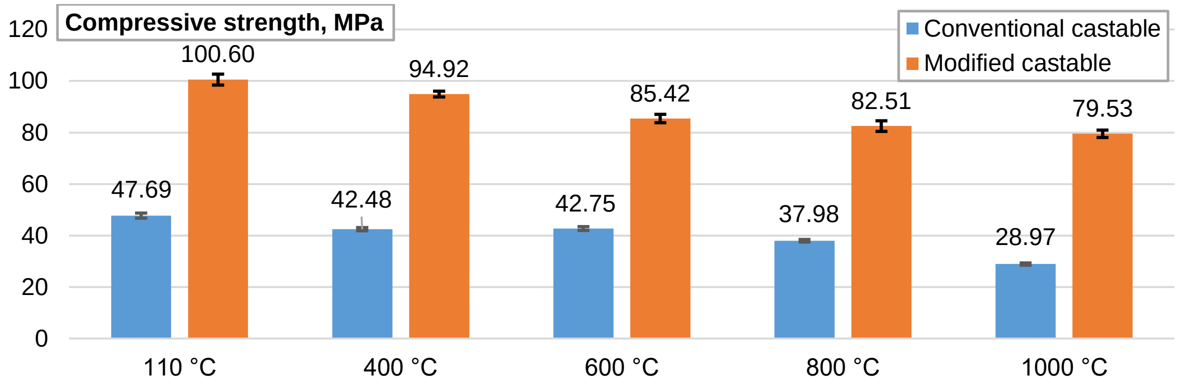

Fig.2. Compressive strength of castables after heating at different temperatures [**25**].

These heat-resistant castables, representing a mixture of a refractory aggregate, calcium aluminate cement, ultra-fine particles, and deflocculants, were designed in the mid of the ’80s for the metallurgy and petrochemical industries. The castable binder shows an excellent ability to preserve the material’s mechanical strength in the 600 °C to 1000 °C temperature range. In addition, the micro-scaled silica/alumina activation process increases the strength and sinterability temperature of the castables regarding traditional alternatives. **Fig. 2** shows the mechanical resistance tendencies of the castables subjected to elevated temperatures and expressed in terms of the compressive strength of the post-heated samples (70 mm cubes).

However, as the study [**25**] showed, the casting temperatures substantially affected the spalling resistance of such concretes—the castables poured and hardened at relatively low temperatures (10 °C) tended to spall under high temperatures, and Kudžma *et al*. [**25**] identified the test conditions for revealing this vulnerability. In addition, Plioplys *et al*. [**27**] analyzed the possibility of developing a reinforced composite employing the refractory concretes investigated in the article [**25**]. Plioplys *et al*. [**27**] also found that the stainless-steel smooth bars, typical reinforcement of the heat-resistant components, are inapplicable for structural composites — the bonding effect disappears already after heating at 400°C, and, consequently, the smooth bars lost the reinforcement essence. On the other hand, typical ribbed bars made from structural steel S500 could reinforce flexural elements even after heating to 1000 °C, allowing efficient structural components to be developed.

Fiber-reinforced polymer structure and performance

The research already identified that combining steel fibers and fiber-reinforced polymer (FRP) sheets with mechanical fastening resulted in structurally efficient and sustainable reinforcement systems for cement-based composite elements [**13,19**]. It was shown that the failure of the ordinary concrete beams was due to the splitting of the concrete cover at the level of the longitudinal reinforcement. On the other hand, the debonding of the external FRP sheet at the interfaces between concrete and adhesive caused the failure of the specimens made of fiber-reinforced concrete. Such a failure mechanism is much more predictable regarding heterogeneous concrete cracking. Jakubovskis *et al*. [**28**] discussed the illustrative example, representing the cracking behavior of ordinary concrete. Thus, the identified improvement in the mechanical resistance of composite systems, comprising fiber-reinforced cementitious and polymeric materials, e.g., considered in the studies [**19,22,26**], improves the design reliability. However, the filament content does not describe the reinforcement efficiency [**21,29,30**]. In cementitious composites for structural applications, typically reinforced with short steel fibers, the mix proportions govern the reinforcement efficiency until a certain fiber amount. In most cases, the 1.5% volumetric content describes the ultimate value, though the typical for engineering applications fiber content does not exceed 0.5% [**29,31**].

On the contrary, continuous filaments typically reinforce FRP components for structural use [**32**] under much higher reinforcement ratios than mentioned above. However, Gribniak *et al*. [**20,21**] doubted the producer datasheet adequacy regarding the adequacy specifying the fiber content. The complex internal architecture of the FIBERLINE FRP composite can explain the inconsistency between the declared (≈60%) and measured (71.0%) fiber mass contents. However, the producer did not provide any information on fiber fraction quantification. Thus, Gribniak *et al*. [**20,21**] proposed an equivalent reinforcement ratio to measure the reinforcing effect and revealed that the efficiency of glass fibers is 7% lower than expected from the manufacturer’s declared mass fraction content. The possible explanation relates the observed differences to the reduction in the mechanical performance because of the fibers’ damage observed in the test surface micro-scans (**Fig. 3**).

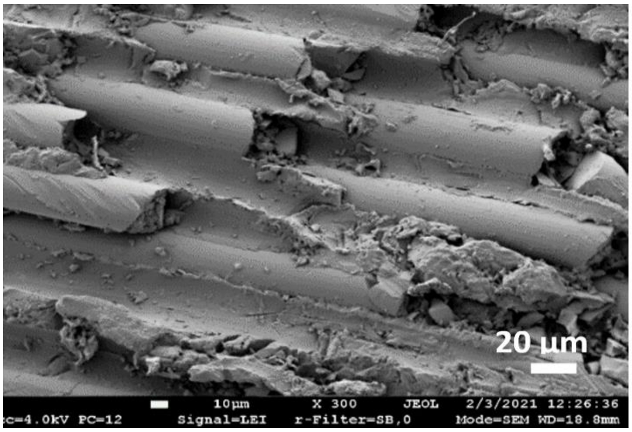

Fig. 3. The filament damage in preparing test samples [**20**].

The studies [**20,21**] demonstrated the unsuitability of the standard dumbbell-shaped coupon tensile tests to determine the equivalent reinforcement ratio for the simulation of FRP flexural elements. The experimentally verified numerical (finite element) model [**20**], employing the smeared reinforcement concept [**33**] and assuming the producer's datasheet specified fiber content, described the comparison reference. Thus, the estimation error of the fiber efficiency reached 40% by applying the standard dumbbell-shaped coupon tensile test result for modeling the flexural pultruded FRP profile. It is also expected that the material characterization error increases with the decrease of the sample size, i.e., with the coupon boundary cut-side area increase regarding the sample cross-section size.

A new testing layout and a simplified analytical model were developed in the study [**22**] to overcome the above issue and quantify the flexural stiffness of the standardized experimental samples. This proposed methodology helps to estimate the efficiency of structural reinforcement systems. The model [**22**] explicitly employs the equivalent residual stiffness approach to measure the reinforced composites' mechanical performance. The developed analytical model relates the particular moment and curvature values, requiring neither iterative calculations nor the load history. This exceptional feature, regarding the existing analogs [**29,34**], allows the explicit quantification and comparative analysis of the residual stiffness of the composite systems, varying the reinforcement type (i.e., fibers, internal bars, near-surface mounted strips, external sheets, and those various combinations) and materials.

Furthermore, the proposed analytical model [**34**] is suitable for the stiffness quantification of the elements subjected to cyclic and repeated loads, making the negative effect quantification of repeated factors, e.g., technological cycles and environmental effects. Thus, the short-term [**22**] and cyclic loading [**35**] tests, carried out within the framework of this project (Fig. 1), demonstrated the hybrid systems' efficiency in combining FRP materials and steel bars.

Adaptive design concept

Current materials engineering trends put forward the development of efficient structural solutions and new design methodologies. Hence, developing an adaptive design concept describes a central research objective of the "Industrialised material-oriented engineering for eco-optimized structures" project (Fig. 1).

Remarkably, the adaptive design combines two essential innovations—the materials tailoring for the construction purpose and developing the verified numerical models for the efficient reference of the structural behavior. The FRP efficiency analysis model [**20**] demonstrates the latter solution; the heat-resistant castables [**25**] exemplify the tailored materials. Therefore, this section combines the above principles to develop a structural prototype, illustrating the adaptive design flow, as shown in **Fig. 4**.

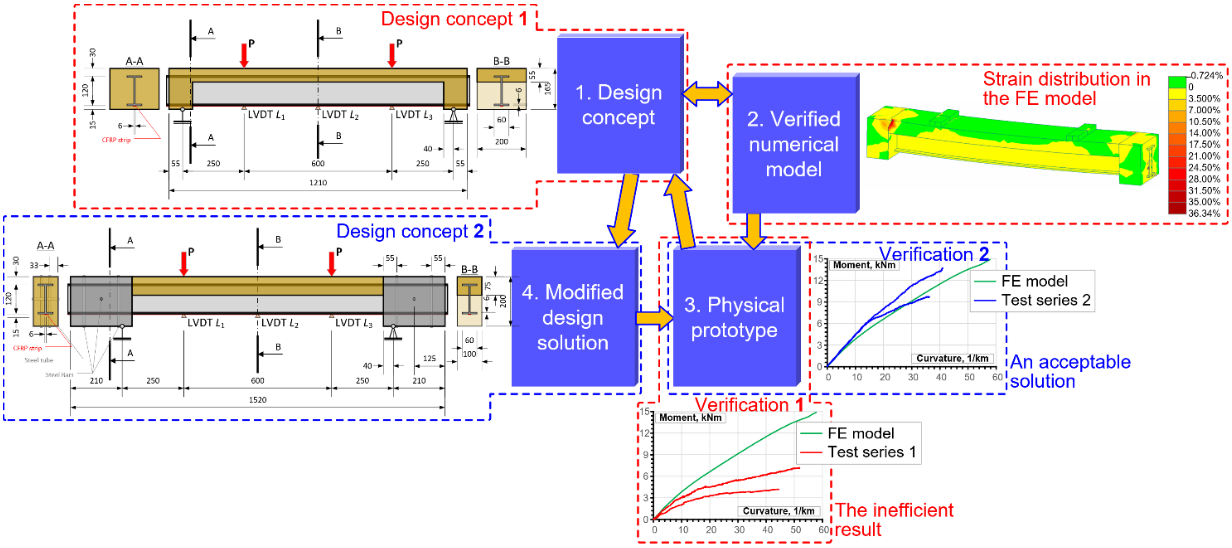

Fig. 4. The adaptive design approach (adapted from [**26**]): measurement units = mm; LVDT = linear variable displacement transducer.

As a running adaptive design example, Garnevičius & Gribniak [**26**] employed the stress-ribbon bridge concept [**36**] to create the hybrid beam system, combining the polymeric fiber-reinforced concrete slab and pultruded FRP profile. On the one hand, this innovative structural solution contradicts the traditional concept of local bond improvement, e.g., employing FRP profile perforation and mechanical anchorage systems, e.g. [**37**]. The developed prototype [**26**] demonstrated that the answer to the support problem (resulting from a low resistance of pultruded FRP profiles to transverse loads regarding the pultrusion direction) improved the structural performance of the bridge prototype. The supports' enhancement ("Design concept 2" in **Fig. 4**) doubled the beam's flexural stiffness and load-bearing capacity regarding the reference bridge with weak supports ("Design concept 1") without the additional FRP bond improvement with concrete. Comparing the red and blue moment-curvature diagrams in **Fig. 4** supports this statement. Moreover, this structural solution simplified the corresponding finite element (FE) model, assuming the perfect bond between the components.

On the other hand, the bending tests, proving the adequacy of the above FE solution, describe the design reference for developing the adaptive design concept schematically depicted in **Fig. 4**. The presented case exemplifies the hybrid structural system's design when the FE modeling describes the expected system efficiency that is the design reference. Thus, as **Fig. 4** shows, the preliminary design concept ("1") forms the numerical model ("2"), in which the predicted outcome determines the structural design target. Further physical tests ("3") verify the viability of the concept "1." If necessary, an engineer modifies the design solution (e.g., "4"). The iterative adaptation continues until the acceptable agreement between the physical and numerical outcomes is achieved (i.e., "Verification 2"). Note that **Fig. 4** exemplifies the adaptive design philosophy when the predicted outcome of the verified FE model controls the structural design. Still, the formal solution requires additional tests to ensure the result's reliability. However, the apparent difference between the alternative design outcomes (red and blue moment-curvature diagrams, i.e., "Verification 1" and "Verification 2" cases in **Fig. 4**) proves the concept in general.

Additive manufacturing of structural components

This section further develops the adaptive design idea, employing additive manufacturing (3D printing) technologies. Such fabrication ensures the tailored capacity and precise engineering of structural components [**38**]; the design for manufacturing and assembly (DfMA) principles modulate the structural units optimizing the manufacturing and assembly workflows [**39**]. Thus, the expected outcomes of the design adaptiveness are the following: efficient application of the tailored constituents used in proper combinations minimizing the material demands, and accomplishing projects impossible for the current design (e.g., ultra-durable and energy-efficient infrastructure and buildings). Gribniak *et al*. [**23, 24**] exemplified additive fabrication, producing 3D-printed polymeric components.

Carbon fiber-reinforced polymer (CFRP) parts represent a promising alternative to steel because of their lightweight, high tensile strength, and excellent corrosion and fatigue resistance. Stress-ribbon structural systems, efficient for pedestrian bridges and long-span roofs, define the potential application object of unidirectional flat CFRP strips, though anchorage difficulties make this idea problematic [**36**]. The problems result from tremendous thrust forces acting on the ribbons and the FRP materials' vulnerability to the stress concentration in the clamped region. To overcome the above anchorage problem, the study [**23**] introduces a new design methodology of the gripping system suitable for anchoring flat flexible CFRP strips. **Fig. 5** shows the gripping system proposed to anchor flexible CFRP strips of stress-ribbon structures.

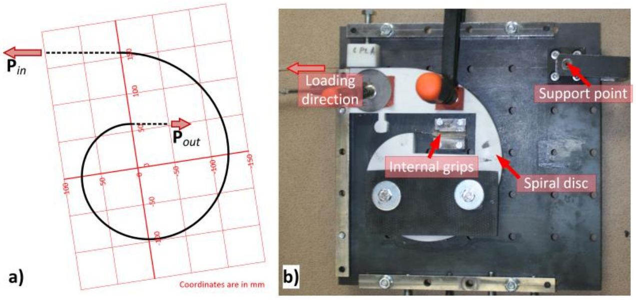

Fig. 5. The spiral FRP anchorage system [**23**]: (**a**) principle scheme; (**b**) loading setup.

The 3D printing technology was applied to produce the spiral disc prototype shown in **Fig. 5**. The physical tests [**23**] proved the efficiency of this gripping system—the CFRP strip failure (localized outside the anchorage block) resulted from the tensile stresses exceeding the material strength. Remarkably, the tension acting on the CFRP activated the internal conical grips in **Fig. 5b** only at the pre-loading stage—the friction between the CFRP strip and polymeric disk completely resisted the testing load. The tests [**23**] also proved the developed anchorage design model. Thus, the upcoming study optimizes the geometry of the grips, incorporating the frictional anchorage system into the pedestrian bridge prototype [**36,40**].

Another case of the adaptive DfMA relates to strengthening hollow-section aluminum profiles with low-modulus 3D-printed polymeric stiffeners [**24**]. Modern facades describe the object for aluminum profile usage, and the self-weight controls the structural shape progress—a decrease of the web thickness and an increase of the profile height ensure the required flexural resistance of the building components [**41,42**]. However, such an optimization process makes these structural elements vulnerable to web crippling. The literature findings [**43,44**] linked the solution to the buckling problem with applying low-modulus filler material, which stabilizes the local web's deformations and increases the load-bearing capacity and the deformation energy absorption of the thin-walled composite structures.

Therefore, the experimental program [**24**] consisted of compressive and bending fragments of aluminum profiles with various adhesively bonded polymeric stiffener configurations. The extensive tests demonstrate that even the minimum (10%) infill density doubled the bending samples' flexural resistance and quadrupled the composite fragments' compressive strength. The latter tests helped develop the component interaction model shown in **Fig. 6**. The pseudo-elastic stage (*OA* branch in **Fig. 6**) describes the structural design object. This diagram shows the substantial contribution of the adhesion component to the composite mechanical resistance.

Therefore, the adhesive contact defines the composite essence governing the structural performance of the stiffened profile. Thus, the current interests focus on developing a reliable adhesion connection and internal strengthening technology suitable for hollow-section thin-walled shapes and adaptive DfMA technologies.

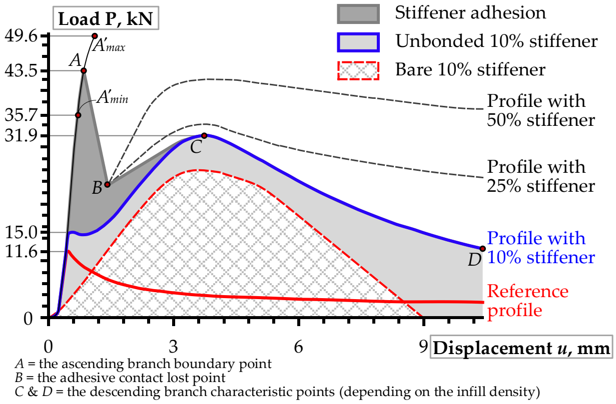

Fig. 6. The load-sharing model of the aluminum profile with low-density polymeric stiffeners (adapted from [**24**]).

Additive manufacturing (AM) technologies are flexible and efficient for prototyping, e.g., [**23,24,40**]. In addition, AM ensures waste reduction because of the continuous material addition process, distinguishing it from the conventional manufacturing methods based on material removal [**38**]. At the same time, the AM expensiveness in energy terms contradicts the low carbon footprint concept raised in this project. Therefore, production technology eco-optimization defines the upcoming research subject.

CONCLUSIONS

This article summarizes the "Industrialised material-oriented engineering for eco-optimized structures" project activities, representing the main results. Developing an adaptive design methodology of reinforced polymer- and cement-based structural composites with material properties tailored for sustainable and eco-optimized construction determines the idea of this study. The project research activities revealed the following aspects:

- The proper combination and connection of advanced structural materials ensure the synergetic effect on the mechanical performance of the composite components. However, such a solution is impossible without involving new design principles. This study exemplifies the adaptive design concept when the predicted outcome of the experimentally verified FE model controls the structural design.
- Experimentally verified numerical models describe a reliable reference for the structural efficiency analysis and developing the adaptive design concept for advanced material and structural solutions.
- The considered cases represent conceptual examples, though adequately reflecting the structural design problem and prospects.

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CONFLICTS OF INTEREST

There are no conflicts to declare.

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GRAPHICAL ABSTRACT

Developing a unified design methodology of structural composites with material properties tailored for construction purposes describes the research target. The investigation flow encompasses five main activities: 1) characterization of composite materials and structures; 2) materials engineering; 3) tailoring material properties and production technology for construction purposes; 4) the design methodology development employing the collected database and metaheuristic optimization algorithms; 5) adaptive prototyping. The activity division is formal—all tasks are interlinked.