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Original article

On the possibilities of using composite girders as hall covering structures

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INFORMATIONS

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ABSTRACT

The article presents the possibilities of using girders made of plastics in hall covering structures in comparison with girders made of traditional materials, such as steel and wood, commonly used in civil engineering. Profiles made of polymers reinforced with glass fibre with the pultrusion method show enormous potential in the construction business. Until today polymers have been used as construction materials only occasionally despite the numerous benefits they offer, such as improved durability in aggressive environments and smaller weight in comparison with traditional materials, to mention but a few of their flag advantages. Polymer composites have a relatively low resistance to high temperatures, especially fire has a very negative influence on them.

KEYWORDS

polymer composites, pultrusion, GFRP

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Introduction

Currently, polymer composites FRP (Fibre Reinforced Polymer) are used in numerous engineering applications. They have been present in civil engineering for over fifty years. However, so far their use in building constructions, bridges and some other civil engineering structures has been quite limited. The factor limiting this application of such materials in the construction business are the costs of FRP composites which are higher than those of traditional materials. Most often they are used to reinforce existing structures, although they could also be successfully used as independent loadbearing elements. The material has numerous advantages which would undoubtedly make it a more attractive solution for the construction business but for its rather high price. Such markets as the aviation business or military applications are more interested in the implementation of innovative materials rather than incurring the costs of materials. Some of the most desired technical properties of FRP composites encompass first of all a low weight and high strength to weight ratio. The properties of polymer composites depend mainly on the quality and type of fibres and the used resin. These are the components contributing to strength, stiffness, impact resistance and other properties resulting the requirements related to a particular construction solution and some other factors. They also influence electrical and electromagnetic properties, corrosion resistance and fire resistance. The most common types of polymer composites with reference to the used fibre type are: GFRP (Glass Fibre Reinforced Polymer), CFRP (Carbon Fibre Reinforced Polymer), AFRP (Aramid Fibre Reinforced Polymer) reinforced with glass, carbon and aramid fibres, respectively. The first of the above listed types exhibit generally good material reinforcing parameters. CFRPs significantly improve stiffness while the last type is characterised by good impact resistance. Profiles reinforced with glass fibre ensure good electrical and electromagnetic insulation, whereas carbon fibre profiles are conductors. The above listed properties predispose polymer composite for use in, e.g. aggressive environments, e.g. cellulose and paper industry plants, chemical agents manufacturing, sewage purification plants and farm buildings. High initial costs can be then compensated by reduced labour and transport costs because FRP composites are light, and first of all by savings made on the exploitation of such materials.

However, due to the lack of plasticity range under the influence of external loads, the destruction of composite materials is not signalled. It occurs suddenly when the deformation limit is exceeded.

In addition to this, due to the significant sensitivity of composites to high temperatures, special measures have to be taken to protect these materials from high temperatures (in case of fire) in the design and manufacturing process. This sensitivity is strictly connected with the issue of fibre and resin adhesion bonding. Temperature is a decisive factor in the strength properties of resins whose elastic modulus decreases with an increase in temperature. If temperature exceeds plasticization temperature T_g, the strength characteristics of composite materials are significantly decreased. Currently, additives hampering fire development and causing the self-extinguishment of materials are used, they also limit the emission of harmful substances during combustion.

In comparison with steel, a strength decrease starts much earlier. For example, in composites with a polyester binding material its only 80°C. However, due to the low heat conductivity of this material, the heating of such materials is about 200 times slower. In the case when a construction is in fire danger conditions, its fire resistance can be improved by replacing a bonding material, e.g. a polymeric one, with a bonding substance based on phenolic resins. They are the longest used substances in the manufacturing of composites and are characterised by high resistance to high temperatures. They are practically inflammable and in case of fire emit only very small amounts of toxic substances [1]. The changes in temperature in the acceptable range, i.e. not exceeding the value of T_g, do not have any negative impact on composite materials used in the construction business.

Due to the beneficial strength to weight ratio, carbon fibre reinforced composites are widely used in the reinforcement of both steel and reinforced concreted constructions [2]. Glass fibre reinforced composites, due to their higher plasticity, can make a good alternative for steel in the cases when concrete constructions need repair and reinforcement [3]. If the repaired construction has to be ‘slimmed’, it possible to use more and common composite bridging decks, used in bridges [4; 5]. The main loadbearing elements are usually made from traditional materials. A completely different example is a Polish road bridge over the Ryjak River in Blazowa near Rzeszow [6]. It is the first bridge in Poland built only using composite materials. It is also special because of the longest span in the world – 21.0 m.

In this article, the authors focus on possible uses of GFRP composite profiles of typical steel profile dimensions, already offered by manufacturers, in engineering practice. An example of a construction erected using this type of profiles is the five-storey Eyecatcher Building in Basil (Fig. 1a).

a)

b)

Fig. 1. Sample constructions using FRP profiles: Eyecatcher Building in Basil
Source: a) [7]; b) Abbott Laboratories in Puerto Rico, Source: [8].

It is the highest building with a loadbearing structure made of GFRP profiles in history. It is 15 m high and its maximum floor service load is 4.0 kN/m^2. The main loadbearing elements are three trapeze-shapes frames. Their loadbearing capacity was additionally verified in an extensive laboratory research programme. Two external frames are integrated with the elevation, however, due to low thermal conductivity, they do not make thermal bridges in it. The cross-sections were designed using standard elements, such as c-beams, double-T bars and flat bars [9]. They were connected using a glue made of two-component epoxy resin. The building was the flagship construction at The Building Trade Fair Swissbau 99, it was visited then by 20 thousand people during one week. After the exhibition, the building was disassembled and moved to its earlier planned location in Basil, 210 Münchensteinerstrasse, where its used until today as an office building [7; 9]. Figure 1b presents the view of a large span covering structure [8]. It was made using EXTREN® profiles and COMPOSOLITE building panels. The covering structure is sued to protect the building from odour in the Abbott Laboratories in Puerto Rico. It is a good example of using polymer composites in corrosion aggressive environments.

1. FRP composites

1.1. Pultrusion process

The continuous pulling or drawing process is used to make combined profiles of prismatic rods from Fibre Reinforced Polymers (FRP), which are applied to meet special user needs. The poltrusion method is used to make such construction elements as rods, pipes, profiles with a constant cross-section, and their length is limited only by the size of the production hall. The construction of machinery depends on the individual needs of produced elements, while the basic concept of the poltrusion process itself does not change and is presented schematically in Figure 2. The raw materials used in the production process encompass a liquid resin mixture (including resins, fillers and specialist additives) and continuous fibres: reinforcement and strands of mats and fabrics used as a covering material (surfacing veil). Contrary to the extrusion process, continuous pressing involves pulling raw material through dies in which a composite material is formed from fibres soaked in resin and then it is hardened in a higher temperature. The strength characteristics of a profile depend on the type and amount of used continuous fibres. After leaving a matrix and initial cooling of the material, the obtained rod is cut to the required length.

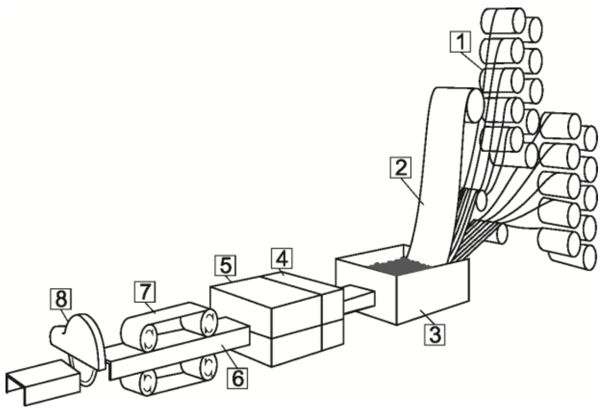

Fig. 2. Poltrusion process scheme: 1 – reinforcement fibres, 2 – surfacing fabric, 3 – resin soaked fibre, 4 – dies, 5 – formation and cutting, 6 – element, 7 – pull mechanism, 8 – cutting elements
Source: Own study.

The advantages of the poltrusion method encompass: high volume fraction of fibre in a component, high quality bonding between the components of a composite, smooth surface, repeatability of elements and their properties. The elements are also easy to process, e.g. to cut them or make openings in them. It is also possible to order custom shapes. The distribution and orientation parameters, and reinforcement types or the used resin can be changed completely [8].

1.2. FRP profile design

The design process with the use of FRP profiles is not significantly different from the approach used with traditional materials such as steel, wood or aluminium. However, there are no standards regulating the dimensioning procedures in the case of composite materials. This is why the most commonly used method in the design process is the older allowable stress method. The related detailed regulations based both on this method and experimental research are usually given by the manufacturers of composite profiles in a designer's manual.

The design process should take into account the following important issues:

- longitudinal Young's modulus of composites is more or less equal to one tenth of the same modulus for steel. This means that the decisive criterion in the design process is the deformation condition, usually of the dislocation,
- the manufacturing method of pultruded composites is characterised by direction dependence, which means that they are anisotropic materials. As a result, an important element in the design process is using the right strength characteristics along and across the fibre direction,
- low value of the shear modulus of composite elements in comparison with steel results in the necessity to take into account the additional influence of shearing stress on bending beam elements,
- as a result of high temperatures, one can observe a significant decrease in strength properties values. If the deformation of a given element is nearly critical and uncontrolled temperature fluctuations occur, the loss of stability can take place.

The basic advantage of FRP profiles is their strength – they are stronger than steel if a 1 kilo to 1 kilo ratio is adopted (along fibres). Their weight is 80% lower than that of steel and 30% lower than aluminium, which means that FRP profiles are easy to transport and assemble in their designated constructions. They can also be partly assembled and later whole structures, ready for the final assembly, are transported to a particular place.

Table 1. Maximum span of element due to dead weight

	EXTREN 625	Steel	Pine	Aluminium
	L_{max} [m]			
Drawing $\sigma_{max}/\rho g$	11405.9	3830.7	1760.7	13883.9
Bending $\left(16\ i_y\,\sigma_{max}/\rho g h\right)^{1/2}$	64.4	37.3	22.9	64.3
Deflection $\left(0.384\ i_y^2\,E/\rho g\right)^{1/3}$	11.0	16.1	13.8	15.9

Table 1 shows the comparison of a polymer composite with materials widely used in the construction business. The element selected for this comparison was a rectangular tube profile EXTREN, 625 series, made by Strongwell [10], it was 180 mm high and the radius of gyration $i_y = 0.064\ m$. It was assumed that steel and aluminium profiles are identical with the composite one, while the wooden cross-section was selected in such a way that it was equivalent to them. Aluminium alloy $AlCu_4Mg_2$ was used. Table 1 presents the limiting lengths of a rod under a load resulting only from its dead load. The analysed rod was extended and simply supported. It can be observed that in this comparison, a composite rod shows very good results in terms of its loadbearing capacity. As it was expected, sue to the low Young's modulus, the composite rod exhibited the greatest deformation. The adopted limiting value was arrow of bending $L/200$, where L is the distance between theoretical points of support.

The decisive element of the manufacturing process of composite elements are safety factors. One of the methods used to define them is the following approach [10]:

$$\text{Safety factor} = \frac{\text{limiting stress}}{\text{allowable stress}}$$

These factor compensate the allowable tolerances of elements, load related uncertainties (size, type, application method), analytical methods assumptions and tolerances of prefabricated elements (cutting shapes, process tolerances, etc.). The values of these factors are: bending – 2.5; compression – 3.0; shearing – 3.0; connections – 4.0; young's modulus – 1.0 and shear modulus 1.0, respectively. The above factor values were so selected that the first deformation of the rod, understood here as a visible structural deformation of an element under load, was prevented. These factor refer only to static loads and do not take into consideration permanent loads resulting in the creeping effect. Dynamic loads and the occurrence of the creeping effect will require adopting a higher value of the safety factor.

1.3. GFRP profiles dimensioning

In the design of compressed elements both strength and stability should be taken into account. As is well-known, compressed rods can be divided into slender and thick ones which under the influence of applied forces show characteristic types of damages. Thick elements are susceptible to local stability losses, while slender ones are characterised by the buckling of the whole cross-section. This is why calculations must take into account mathematical dependencies applicable for theoretical models. The designer's manual [10] presents simple dependencies for slender and thick rods made of GFRP composites. These dependencies allow to determine allowable stresses which depend on slenderness (Kl/r) for both cases. In the case of rods made of square profiles, limiting compression stresses F_u can be determined in the following way [10]:

– compressed thick elements:

$$F_u = \frac{\mathrm{E}}{16(\mathrm{b/t})^{0,85}} \le 206{,}8[MPa], \tag{1}$$

where:

E – longitudinal Young's modulus [MPa]

b – element width [mm]

t – element wall thickness [mm]

– compressed slender elements:

$$F_{u'} = \frac{1{,}3\mathrm{E}}{(\mathrm{K}l/\mathrm{r})^{1{,}3}}, \tag{2}$$

where:

K – buckling length factor [–]

l – element span [mm]

r – radius of gyration [mm].

Next when the limiting values of compression stresses are determined, it is possible to determine the allowable compression values for thick elements:

$$F_a = \frac{\mathrm{F_u}}{3{,}0} \tag{3}$$

and for slender elements:

$$F_{a'} = \frac{F_{u'}}{3{,}0} \le F_a \tag{4}$$

and allowable load:

$$P_a = \min \begin{cases} \mathrm{F_a} A \\ \mathrm{F_{a'}} A \end{cases}, \tag{5}$$

where A is the cross-section area of the compressed transverse element.

2. Hall building

2.1. Input data

The starting point was preparing a one-story hall building, 24.75 m wide and 47.45 m long, for service and trade activities. The first proposed solution, in which the main load-bearing structure was a spatial structure made of steel truss rafters made mainly of closed tube profiles. The next idea was the substitution of steel construction elements with glued wooden ones. An alternative solution was making the hall covering structure using truss girders made of composite profiles with a square tube cross-section, reinforced with GFRP glass fibre.

The designed building was located in the 1st wind load zone and the 4th snow load zone. A pent roof was used, 5.0% (2.9°) roof pitch. It was covered with a membrane (NRO) stretched on a layer of mineral wool which covered metal trapezoidal sheets, T55-53L-976 type, 0.7 mm thickness.

2.2. Steel roof structure

Two types of truss girders were designed: main and indirect ones. The main girder supported the indirect ones at mid-span. Figure 3 presents an indirect girder, while the main one stretches along axis B plane. The main girder is a steel truss element with parallel, horizontal flanges, whereas the indirect girders have parallel flanges, 5.0% (2.9°) slope.

The girders were made of S355JR (18G2A) steel. The top and bottom flanges and also posts are made of a tube with a square cross-section 160×160×10. The axial distance of flanges is 1100 mm. Cross braces are made of a tube with a square cross-section 90×90×5.6. The girder is fixed on the heads of reinforced concrete posts using pipe anchors.

The indirect girder was designed as an element whose top flange is a rectangular steel tube, with a cross-section of 180×100×8.8, the bottom flange is a square steel tube with a cross-section of 90×90×5.6, whereas the cross braces are made of a square steel tube with a cross-section of 70×70×5.0. The axial distance of flanges is 800 mm and the slope is 5.0% (2.9°). The girder is fixed on each hook of a reinforced concrete post and on the main girder using bolts. In the steel construction the indirect girder spacing is 7.20 m.

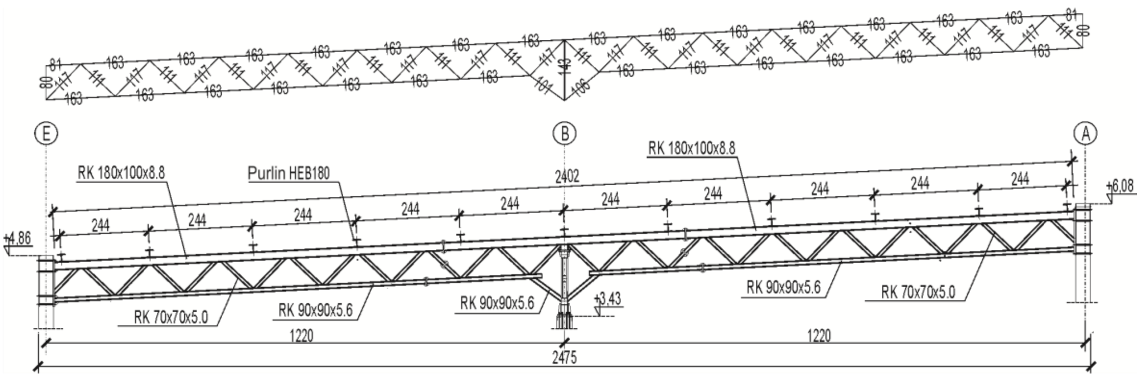

Fig. 3. Indirect girder in the construction based on steel profiles. Dimensions [cm]
Source: Own study.

Steel purlins were designed in the form of two double-T bars, HEB180 type, made of S355JR (18G2A) steel with 2.44 m spacing, they were supported on walls using steel hooks or on truss girders using welds and bolts. The covering made of trapezoidal sheets, T55-53L-976 with a thickness of 0.7 mm, was based on the steel purlins and was covered with mineral wool used as insulation.

At the plane of the indirect girder top flange located at extreme roof slopes, roof slope concentrations were designed with the use of steel rods Ø16, S355JR (18G2A) steel, with a Roman bolt, it was also possible to use steel purlins so as to limit roof concentration bending. The roof structure in its vertical plane is concentrated using the main truss girder.

2.3. Wooden roof structure

The designed roof structure used layer-glued wood, strength class GL32c. The loadbearing structure of the roof are binding joists in the central axis of the building and girders connected to them. The binding joists, with cross-section dimensions of 20×140 cm were designed as single-span, simply supported beams based on internal reinforced concrete posts with axial spacing of 14.40 m. Girders, axial spacing 7.20 m, were designed as straight beams with a cross-section of 20×82 cm. The girders are supported on reinforced concrete posts on one side and layer-glued wood binding joists on the other side (Fig. 4).

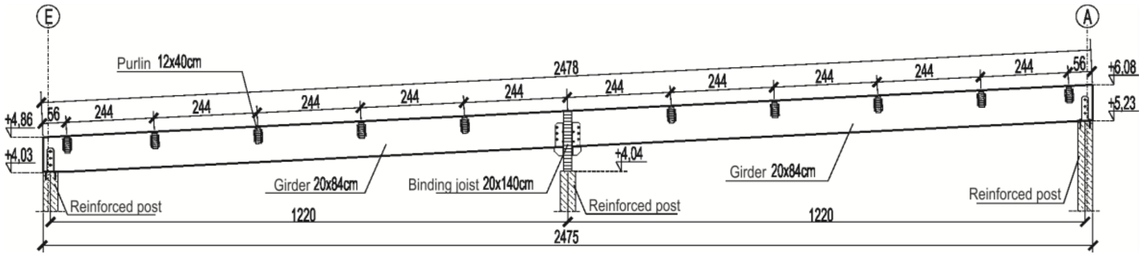

Fig. 4. Construction solution based on glued-wood girders
Source: Own study.

The structure is filled with purlins, with a cross-section of 12×24 cm and spacing every 2.44 m made of glued wood. Purlins are fixed on girders using beam support systems and, additionally, pairs of screws to take over loads during a fire. Similarly to the steel roof structure, purlins with rod concentrations improve the stiffness of the roof structure.

2.4. GFRP profiles roof structure

The calculation analysis was conducted for the indirect truss girder located transversely to the building with a slope of 5.0% (2.9°). In comparison with the indirect girder made of steel profiles (Fig. 3), mainly the spacing was changed. As it was mentioned earlier, due to the limitation of the truss displacement and stresses in its rods, the spacing of indirect girders was reduced threefold from 7.20 to 2.40 m. To eliminate the bending of the top flange, caused by the reactions of purlins, in the place where they are located additional posts were installed. The rods of the top flange and the bottom girder were made of square tubes, 160×160×10, while the posts and cross braces were made of square tubes with 100×100×6.3 dimensions. The solution used for the indirect girder is based on GFRP profiles, it is presented in Figure 5. Thanks to the elimination of rod bending in the top flange, the rectangular cross-section of the compressed top flange was changed in comparison with the steel truss to a square one, as it was considered to be more beneficial in calculations.

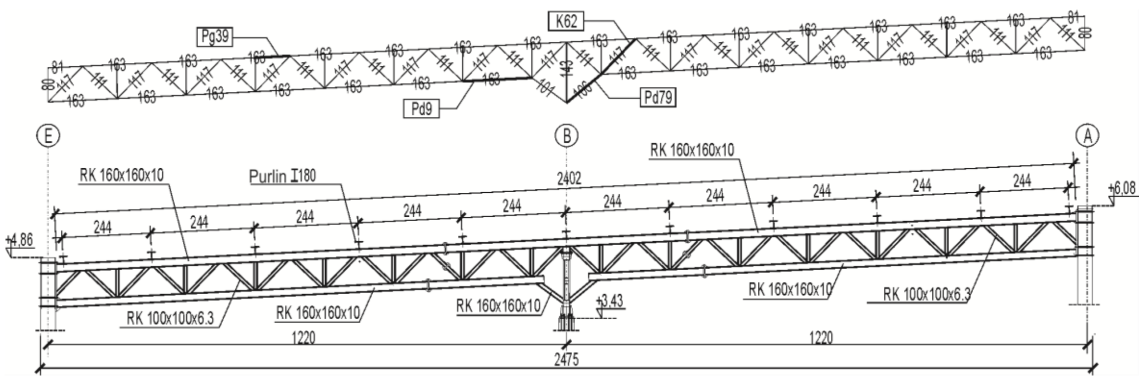

Fig. 5. Indirect girder of the construction solution based on GFRP profiles
Source: Own study.

Due to the elimination of the bending of the rods in the top truss flange by the introduction of posts, the dimensioning of rods was conducted on the basis of the formulae (1÷5)

– it was introduced for compressed elements based on the allowable stresses method. Because of the disadvantageous influence of the buckling phenomenon on the loadbearing capacity of truss rods, the calculations were made only for compressed rods and these calculations were considered reliable.

In the case of the top girder rods, the adopted buckling length was equal to the distance between purlins – 2.44 m, while for the other elements it was equal to the theoretical support points of the truss plane rods. The buckling length coefficient for all rods was assumed to be $K = 1.0$. The values of stresses and allowable loads for reliable truss rods are presented in Table 2, where $P_{s\,max}$ and $P_{l\,max}$ denote the value of the allowable compression force for the thick and slender elements, respectively, whereas P_{max} is the maximum value of the compression force determined on the basis of static calculations. The location of rods is presented in Figure 5.

Table 2. Dimensioning results for the truss and GFRP profiles

Rod	L [mm]	Thick element			Slender element			$P_{s\,max}$ [kN]	$P_{l\,max}$ [kN]	P_{max} [kN]
		F_u [N/mm^2]	$F_{u\,max}$ [N/mm^2]	F_a [N/mm^2]	Kl/r [-]	$F_{u'}$ [N/mm^2]	F_d [N/mm^2]			
Pg41	2440	105.98	206.80	35.33	40.33	190.31	63.44	202.78	364.13	114.38
Pd79	940	105.98	206.80	35.33	15.54	657.68	219.23	202.78	1258.35	168.93
Pd9	1630	105.98	206.80	35.33	26.94	321.54	107.18	202.78	615.21	94.42
K62	1170	106.70	206.80	35.57	30.71	271.24	90.41	82.87	210.66	81.43

The maximum displacement of the truss system made of GFRP composite profiles was 0.028 m and was only slightly greater than steel truss bending which was 0.019 m. Both of these values were slightly lower than the values of 0.049 m, 0.041 m, 0.035 m (for *L*/250, *L*/300, *L*/350, respectively) considered to be the limiting values.

The guidelines presented in [10] allow to make calculations for basic construction elements and to establish their limiting conditions. However, it should be emphasised that [10] is not a standard, hence the specifications presented there do not guarantee the safety of the designed constructions. Each manufacturer of composite materials has its own, separate set of requirements, as a result there are numerous unsolved issues related to calculation procedures. For instance, there are no applicable guidelines taking into consideration such phenomena as twist in bending deflection and the loss of rod local stability. In addition to this, the information related to the dimensioning of connections is not coherent or is simply ignored. Existing guidelines do not define the way of determining the fire resistance of elements, either and this issue is still the subject of research.

In the case of large scale investments, it is possible to conduct laboratory tests of materials and make a fully dimensional construction model and conduct knot tests. The information obtained in these tests can be next used in calculation models which developed with numerical models with the application of applicable limiting conditions.

Conclusions

Three different variants of a material solution for a hall covering structure. The decision to finally select a particular variant belongs to an investor and is made after cost analysis. The proposed use of pultruded GFRP profiles should be treated as a cognitive solution. It is an interesting alternative in situations when the construction is exposed to strongly corrosive factors. Hence, it should not be surprising that polymeric materials are more and more frequently used in such sectors as farming infrastructure, sewage purification plants, road infrastructure, chemical agents manufacturing plants and paper industry.

The designed girder made of GFRP composite profiles, with a span of nearly 25 m, weighs less than 500 kg, which can be compared with 1600 kg – the weight of the steel construction, and about 1700 kg in the case of wooden girders. However, the disadvantage of composites certainly is the thick distribution of girders, which is necessary due to the reduced load per a single girder. One should remember, however, that attempts were made to maintain the identical system of the steel and composite truss. Another solution could be an increase in truss height, which would improve its stiffness, or the use of a counter arrow to reduce final deflection.

Unfortunately, quite a substantial drawback of a composite material is its sensitivity to high temperatures, which is strictly related to the fibre and resin adhesion bonding. Temperature is a decisive factor in the strength properties of resins, whose Young's modulus decreases with temperature increase. If temperature exceeds the plasticization temperature, the strength characteristics of composite materials are significantly reduced. It is possible to use special additives in resins which improve their fire resistance. An important characteristic of improved resins is the lack of smoke during combustion. However, such improved elements are more expensive. The introduction of composite materials to common use is not facilitated by the lack of guidelines related to the fire protection of construction elements.

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Conflict of interests

The authors declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

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Szymon Sawczynski – Ph.D. Eng. Assistant, Field of study and specialisation: civil engineering, geotechnology, member of the Scientific Committee of the Polish Association of Construction Engineers and Technicians (PZITB), Olsztyn Office. Areas of scientific interests: construction engineering, hydrotechnical structures, geotechnics. 10 publications, contractor in two grants.

O możliwościach zastosowania dźwigarów kompozytowych jako konstrukcji przekryć hal

STRESZCZENIE

Niniejszy artykuł ma na celu zaprezentowanie możliwości przekrycia budynku hali dźwigarami wykonanymi z tworzyw sztucznych na tle dźwigarów wykonanych z tradycyjnych i powszechnie stosowanych w budownictwie materiałów, jakimi są stal i drewno. Profile wykonane z polimeru wzmocnionego włóknem szklanym metodą przeciągania (pultruzji) mają ogromny potencjał w branży budowlanej. Materiał ten do dnia dzisiejszego ma niewielkie zastosowanie jako materiał konstrukcyjny a posiada z pewnością wiele zalet, wśród których flagowymi są znacznie lepsza trwałość w środowiskach agresywnych i niższy ciężar w stosunku do tradycyjnych materiałów. Kompozyty polimerowe wykazują względnie niską odporność na działanie wysokich temperatur, chodzi tu przede wszystkim o negatywny wpływ ognia.

SŁOWA KLUCZOWE kompozyty polimerowe, pultruzja, GFRP

How to cite this paper

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