Benefits and risks of application of non-metallic composites as an alternative to steel reinforcement in concrete elements

Maciej Dutkiewicz[1*] and *Paweł* Majkowski[2]

[1]Faculty of Civil and Environmental Engineering and Architecture, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland
[2]Doctoral school, Bydgoszcz University of Science and Technology, Al. Prof. S. Kaliskiego 7, 85-796, Bydgoszcz, Poland

Abstract. The paper presents an overview of possible alternative reinforcement solutions to the most popular steel reinforcement currently used for concrete elements. Particular emphasis was placed on the use of composite reinforcement, taking into account the types of components concerned, possible applications and presenting an analysis of the risks and opportunities facing the construction industry related to the use of this type of reinforcement. In addition, an analysis of the material parameters taking into account the division of composite reinforcement due to the different types of fibers used in their production is presented. The paper also presents a comparative analysis of the parameters of steel and composite reinforcement, among others: tensile strength, susceptibility to corrosion, compressive and bending strength, fire resistance. It also analysed the needs of the construction market in the search for alternative concrete reinforcement in reinforced concrete structures, particularly in the context of recent events such as the Covid-19 pandemic and armed conflicts, which disrupt the supply chain and force the search for alternative materials that can replace reinforced steel. The availability of standards and instructions for the design of concrete elements and the related responsibilities of structural designers were analysed, identifying the research directions necessary to popularize and ensure the safety of the design of concrete elements with the use of alternative material solutions – in particular composite reinforcement in concrete slabs.

1 Introduction

Concrete elements (reinforced and non-reinforced) are the most popular construction material in today's construction alongside steel and wood. Due to the increasing year-on-year construction production, the demand for materials in construction resulting from the use of several main ranges of materials in each facility, sourced from natural resources, is increasing every year. In view of the above, it is necessary to consider and search for alternative material solutions that could replace the world's dwindling natural resources in the future. The

* Corresponding author: macdut@pbs.edu.pl

phenomenon of reduced availability of construction materials has recently been exacerbated by phenomena such as the COVID-19 epidemic, the armed conflict in Ukraine, disrupted supply chains (e. g. due to the blockade of the Suez Canal) – these events, which have taken place in the short period of the last few years, have raised the industry's awareness of the need to undertake research activities towards the development of alternatives to traditional construction materials. The basic problems to be considered is not only the search for alternative material solutions in general, but above all conducting research with the use of new construction materials, in order to develop standards / instructions enabling design structures with their application. The process of not only conducting studies, drawing conclusions from studies and finally developing appropriate standards on the basis of completed studies is a long-term process, so the effect of currently observed worldwide trend of searching for alternative material solutions for the construction industry, in the form of responsible and safe use of this type of materials on squares, can be expected only in a few or several decades. An extremely important aspect in the context of the search for alternative solutions for the construction materials used so far is the care and responsibility of the industry for the environment. The long-standing exploitation of iron ore for the production of steel materials, the cutting of trees to obtain elements of wooden structures that require the cutting of healthy, large-diameter trees undoubtedly has a negative impact on the environment and in the long term may lead to the complete exploitation of natural resources or be prevented due to environmental conditions. As a result of the significant increase in environmental awareness observed in recent years, a number of initiatives and legal regulations have been created (both at national and global level) effectively limiting the negative impact of construction activities on the environment, causing at the same time the need for the construction industry to adapt to new operating conditions. The effect of the implemented measures is increased care for the environment, and in the context of materials, for example, a greater share of recycled materials in the production of steel elements – which brings little improvement in the field of material management, without solving at the same time current and especially projected future problems regarding the availability of structural materials, including steel.

One of the material alternatives available on the market for structural reinforcement elements, currently largely realized with the use of steel bars, is non-metallic reinforcement – in particular composite reinforcement (FRP – Fibre Reinforced Polymer) is a material created by combining fibres and resin – individual types of reinforcement vary depending on the fibres used and the type of resin (there are also hybrid solutions used by manufacturers to specific material parameters). Currently, there are four main types of FRP reinforcement on the market based on the use of glass fibers (GFRP), carbon fiber (CFRP), aramid fiber (AFRP), basalt fiber (BFRP). In the article [1] the authors review the properties and potential applications of composite reinforcement in concrete structures, indicating this type of reinforcement as a material can constitute an alternative to the use of traditional steel reinforcement bars in concrete elements, but requires a number of studies and research determination of parameters necessary for safe and responsible design of concrete structures with its application.

Due to the wide range of applications of reinforced concrete in the construction industry – from simple structures such as elements of small architecture or single-family buildings to multi-storey skyscrapers or bridge structures, proper research and popularization of alternatives to steel reinforcement is not only an answer to difficulties in the availability of materials, but also an opportunity to optimize the cost of construction processes.

2 Characteristics of composite reinforcement

The composite reinforcement consists of continuous fibres embedded in a polymer resin. The main role of the fibres is to provide the appropriate strength and rigidity of the composite, while the resin is responsible for connecting the fibres with a proper distance between them, protecting their surfaces from damage and transferring stress to them. To obtain a composite, these fibres are "sunk" in thermosetting resin (polyester, epoxy, vinyl ester) or thermoplastic resin (PEEK, PPS, PSUL) [2].

The physical and mechanical properties of the composite reinforcement target product depend in particular on the type of fibres and resins used to produce them. There are currently four main types of composite reinforcement on the market, which are divided according to the type of fibres used in their production:

- aramid (AFRP),
- basalt (BFRP),
- carbon (CFRP),
- glass (GFRP).

Fiberglass is the most popular type of fibre mainly due to its low cost of production. They are a fully isotropic material and exhibit alkaline properties. The main disadvantage of glass fibers is their susceptibility to moisture and temperature. However, they are easy to process and exhibit high adhesion to most types of resins [3].

Carbon fibers are a group of materials popular in the performance of reinforcements despite the relatively high price. They are produced on the basis of tar or by the process of thermal decomposition of polyacrylonitrile. Carbon fibers achieve the best mechanical parameters among FRP materials are resistant to environmental aggression and temperature changes [3].

Aramid fibers are of organic origin known as Kevlar. They are distinguished by the lowest intrinsic density of reinforcement fibres (at 1400 kg/m^3), which in combination with high tensile strength (of the order of 3 000 MPa) gives a very favourable strength-to-weight ratio. Aramid has a high resistance to environmental factors and elevated temperatures. It is a good terminal and electrical insulator. Fibres are sensitive to UV radiation and have moisture-absorbing properties, which can significantly impair mechanical properties. [3]

Basalt fibers come from molten and then extracted volcanic rocks. They are a relatively new material when it comes to use in fiber composites. With a tensile strength of 2800-3200 MPa and a modulus of elasticity of 85-90 MPa, they are placed between glass and carbon fibers. The biggest advantage of basalt fibers is their very high resistance to elevated temperatures and aggressive chemical environments [3].

Composite reinforcement is created by the process of pultrusion – it is a method consisting in dragging the impregnated fibres through sieves giving them the right shape, then soaking them with resin under conditions of high pressure and temperature. The structure of the composite rod is composed of about 80 percent fibers and about 20 percent resin [4].

The entire process of implementing composite reinforcement in concrete elements consumes significantly less water, energy, fuel – which as a result generates less carbon dioxide into the atmosphere – and therefore more environmentally friendly. In addition, it should be emphasized that the transport and application of composite reinforcement in concrete elements, due to the significantly lower weight of elements compared to steel reinforcement, reduces the number and scale of heavy equipment needed to embed these elements, which also has a positive effect on the environment compared to the use of conventional reinforcement.

3 Analysis of the benefits and risks associated with the use of composite reinforcement

Among the preferred material parameters of the composite reinforcement stands out the tensile strength, which, depending on the type of fibers used (aramid AFRP up to 2540 MPa, basalt BFRP up to 1 100 MPa, carbon CFRP up to 3 690 MPa, glass GFRP up to 1 600 MPa) can reach even more than 3 500 MPa, which for steel reinforcement is less than 700 MPa. At the same time, composite reinforcement, regardless of the type of fibers used for the production of fibers, has a much lower compressive strength than steel reinforcement, so that the material under analysis should not be used in the compression zones of the concrete cross-section.

In addition to strength parameters, composite reinforcement is also characterized by other advantageous parameters. First of all, as a non-metallic material, unlike classic steel reinforcement, it presents corrosion resistance – which predisposes this material to application in aggressive environmental conditions, e.g. elements exposed to aggressive water activity. In view of the above, it is reasonable to consider this material in the context of application in concrete structures erected in ports or docks, where, due to the possibility of numerous mechanical damage to the concrete surface, resulting in the eventual loss of the coating of the element and the occurrence of corrosion foci which may eventually lead to the degradation of the element. The use of composite reinforcement in such constructions, which are often structures of a resistance nature – therefore, in most cases, the elements in question do not work in a compression model – therefore, the use of composite reinforcement in such constructions may prove to be an effective solution to one of the most common causes of failure, which is the corrosion of reinforcement due to contact with water, caused by loss of coating.

Non-metallic composite reinforcement is also characterized by mechanical properties, which are an important aspect in the context of the decision to use this material in the construction industry – i.e. primarily a much lower specific weight than steel reinforcement, which consequently allows less involvement of equipment both in the transport of materials to the construction site and subsequently within the construction site. This type of reinforcement also allows much less laborious cutting of rebar under construction conditions, but on the other hand bending of composite reinforcement under construction conditions is not possible. Another practical disadvantage associated with the use of composite reinforcement is the low resistance of this material to UV rays, which obliges in the case of long- term storage to organize covered areas, limiting the influence of UV rays on the reinforcement elements.

An important aspect, both in the context of design and execution of concrete elements with the use of composite reinforcement, is fire resistance. Currently, composite reinforcement on the market is mostly characterized by unmarked fire resistance, which becomes problematic or impossible in the context of application in concrete elements of buildings requiring determination of the fire load capacity of individual elements of the structure.

4 Analysis of the needs of the construction market in the search for alternative solutions

For more than a century, the construction industry has been based on the implementation of concrete elements reinforced depending on the conditions of the load model of individual elements with individually selected steel reinforcement. As the industry has grown over time and the popularity of reinforced concrete elements as a solution to easily adapt to structural needs, reinforced concrete elements have become an integral part of almost every building

erected over time – from a trace presence in the form of pillars or corrugated beams in predominantly brick structures, to their use as the sole or main structural material in elements with complex structural patterns. Faced with shrinking natural resources of iron ore and other global problems related to sourcing and trading of raw materials, the popularization of alternative methods of reinforcing concrete structures opens up a number of possibilities for both construction site monolithic structures and prefabricated elements:

- the possibility of diversifying reinforcement materials, particularly in conditions of disrupted supply chains, armed conflicts, other circumstances which periodically limit the availability of raw materials necessary for the production of steel reinforcement,
- possibility of optimizing the cost of making monolithic and prefabricated concrete elements by using interchangeable with composite reinforcement interchangeable with steel reinforcement or using hybrid solutions,
- possibility of using material with good parameters in the range of: tensile, high corrosion resistance, low specific gravity,
- the need for detailed – research determination of parameters constituting potential defects of the analysed material, i.e. low shear strength, low resistance to UV rays, fire resistance, classification of parameters according to the type of fibres used.

A very important aspect for the construction industry in the context of the search for alternatives to classic steel reinforcement is also the issue of the purchase cost of non-metallic reinforcement, e. g. composite reinforcement, which should be analysed in detail not only in the context of the purchase price of the material itself, but also in terms of the equipment necessary for transporting both to the construction sites and on the construction site itself, energy / fuels necessary for the production and transport of elements or the labour intensity of the reinforcement processing itself – only after analysing all the above. of issues, it is possible to make a reliable comparison of the actual cost of the basic or replacement material, which for reinforcing steel may be composite reinforcement.

5 Research directions – review

When reviewing the literature on the subject of composite reinforcement – as an alternative to the classically used reinforcement steel, it should be noted that this is a topic widely studied all over the world. Research carried out in different centres around the world focuses on determining the possibility of large-scale use of composite reinforcement as a viable alternative to standard solutions – in terms of determining fire resistance parameters, calculation procedures, working method and model of destruction of concrete elements reinforced with composite bars. Methodology determination of load capacity of reinforced concrete elements FRP (fibre reinforced polymer) and research related to determination of fire resistance of composite reinforcement are two key directions of research on the analyzed material, which after proper and wide recognition will lead to its popularization and ensure proper safety design of structures using composite reinforcement.

A common problem in the design of composite reinforcement in concrete elements faced by designers and constructors in many countries is the lack or scarcity of relevant standards, manuals or guidelines for the design of such elements. Countries that have developed standards for the design of concrete elements with composite reinforcement are the United States, Canada, Italy, Norway, the United Kingdom and Japan [4]. It should be estimated that as the research and popularity of this material on construction sites become more popular, the number of standards or manuals for the design of composite reinforcement should increase and meet the demand of designers in this area. In the paper [5], the authors summarizing the research carried out in many research centres around the world, analyze the problem of

finding a way to properly define calculation procedures for determining the shear load of concrete elements using FRP reinforcement. In the paper, a review of calculation procedures for determining the shear capacity of concrete elements reinforced with composite bars, without transverse reinforcement was carried out. Three groups of procedures have been distinguished:

(I) modifying the designs used for reinforced concrete structures,

(II) modifying the existing design procedures for elements reinforced with FRP bars and

(III) modifying the designs developed based on the analysis of the results of experimental tests and the application of different calculation tools.

In summary, the authors of the study emphasize that determining a universal method of estimating the shear load of concrete elements reinforced with composite bars is difficult due to the complexity of the description of the destruction mechanisms, and on the other hand due to the necessity of practical application of the proposed procedures in the design - to obtain their simplest form.

Studies on concrete slabs with the use of composite elements were carried out by the authors of the article [6], making a research element representing the shape and structure of the bridge span element, in different variants i.e. 3 elements reinforced with the use of carbon fiber composite materials (strip steel plates, mesh, cloth), other without reinforcement at all. The study consisted of fatigue analysis of the samples under load. Studies have shown that reinforcement with CFRP mesh and carbon fiber composite cloth in bridge structures is equally effective in terms of fatigue parameters.

Another extremely important direction of research, besides obtaining the methodology for determining the load capacity of concrete elements using FRP reinforcement, necessary for wide development towards popularization of the analyzed material, is fire resistance. Research and analysis carried out to determine the fire resistance of composite reinforcement elements, as well as to compare the parameters of this type of elements with steel reinforcement, are definitely unfavourable for composite reinforcement. Based on composite reinforcement bridge elements in the United States, thermal simulation has shown that FRP bridge decks are sensitive to elevated temperatures. Compared to steel or concrete bridges, they showed lower heat resistance [7]. Studies carried out towards the detailed determination of the fire load of individual composites, are also aimed at determining fire resistance parameters depending on the type of fibres used, due to the natural parameters of the base material, the most promising results are associated with composite bars based on basalt fibres, which is more broadly inferred by the authors of the work [8].

The issue of fire resistance of composite elements in construction in general has been taken up by the authors of the work [9]. In their considerations, they analyze the possibility of using elements produced in the form of composite as a response to the increasing demands on adaptation of structures to unusual shapes or unique architectural solutions, referring in their work to the necessity of ensuring proper fire parameters of elements built into objects. The properties of composite materials, including the ease of their shaping, can be a convenient solution for shaping facade elements or interior finishing. The authors carry out an analysis which, at the current state of research and analysis, does not lead to conclusions that the use of FRP-based materials provides an appropriate level of fire safety for the architectural elements of the buildings under consideration, indicating further planning of research to broaden the issue. This article confirms that research not only on composite reinforcement, but on building elements based on FRP application in general, towards the determination of fire properties, is one of the most important branches of research of this material.

An important area of research into the properties and potential wide range of applications of composite materials is the use of FRP materials in the repair or revitalisation of reinforced concrete elements, in particular because of the very good strength characteristics of carbon

fibre elements. The authors of the article [10] refer to this issue in their work by considering the use of FRP elements in the repair of building elements and analysing the long-term durability of this relatively new repair method.

6 Plate testing – description of methodology and conducted tests

Research conducted at Bydgoszcz University of Technology. J.J. Śniadeckich in Bydgoszcz on the application of high-strength steel reinforcement B600B and composite reinforcement mainly focus on the analysis of concrete slabs for which reinforcement on the basis of glass fibers was used. The research is based on the literature of the subject and the previously published guidelines for the design of concrete elements with the use of composite reinforcement [4, 11-13]. The analyses cover in particular:

- dimensioning and modelling of concrete elements using the analysed reinforcement,
- determination of load capacity and performance characteristics under different operating conditions,
- determining the principles of stress and strain diagnosis, taking into account the methods of structural dynamics analysis.

The aim of the research is to obtain the methodology for determining the load-bearing capacity of concrete slabs with composite reinforcement (on the basis of glass fibres) by determining on the basis of theoretical analyses and laboratory tests the method for calculating the load-bearing capacity of concrete slabs with composite reinforcement and comparing the results of theoretical model analysis with the results of laboratory tests.

The methodology adopted in the studies, consists in the comparative analysis of narrow plate bands loaded with bending moment. and tensile normal force. In the first phase of the study, narrow reinforced concrete slabs with rectangular cross-section, width 0.50 m and variable cross-sectional height (0.08, 0.10, 0.12) m and length 2.00 m were analyzed. The slabs are reinforced along the long side with longitudinal bars Ø10 and Ø12 mm made of B600B steel and FRP reinforcement in non-metallic reinforced slabs. The longitudinal bars are evenly distributed over the width of the board. The center of gravity of the longitudinal reinforcement is located at half the height of the element.

An example research stand is shown in Fig. 1.

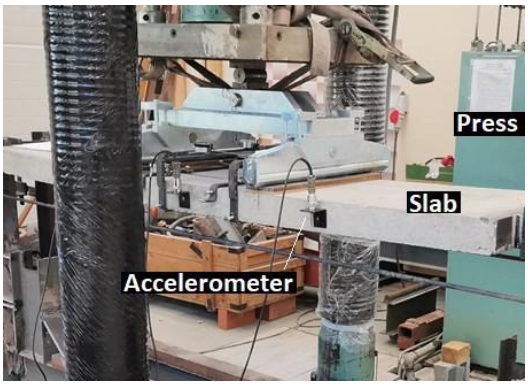

Fig. 1. Research stand with a slab.

The WPM DRMB 600 press with a strength range of up to 6 000 kN was used in the destructive tests. The narrow strips of plates were laid on two supports and then loaded to destroy

In the further part of the study, a comparative analysis of plates using high-strength steel reinforcement and composite reinforcement will be carried out. The aim of this analysis will be to define the methodology for determining the load-bearing capacity of panels with composite reinforcement, analysis of the theoretical model and comparison with the results of the experiment – leading to the determination of the procedure for calculating the load-bearing capacity of panels with composite reinforcement and comparison of the results of the theoretical model analysis with the results of laboratory tests.

7 Conclusion

Non-metallic – composite reinforcement is a material currently used in the execution of concrete works, the reasons for this state of affairs are mainly the still insufficient state of knowledge about the behaviour of this material under different load conditions, exposure to external factors. Research conducted all over the world on this material leads to the creation of an ever larger base of literature on the subject, calculation procedures, results of research and analysis – which in the perspective of a few or a dozen years should lead to the right state of knowledge in the subject, allowing for conscious and responsible design of this type of armament.

Environmental conditions, further global events affecting supply chain disruption or economic issues may force the construction industry to make wider use of composite reinforcement in the near future. When selecting composite reinforcement for individual applications, it is necessary to always take into account the working conditions of the structure and exposure, because according to the analyses carried out, reinforcement parameters vary significantly depending on the type of fibres and resins used, which can have a key impact on the subsequent trouble-free operation of the concrete element.

References

1. I.S. Abbood, S.A. Odaa, K.F. Hasan, M.A. Jasim, Properties evaluation of fiber renforced polymers and their constituent materials used in structures - A review. Mater. Today Proc. **43(2)**, 1003-1008 (2021). https://doi.org/10.1016/j.matpr.2020.07.636
2. M. Szumigała, D. Pawłowski, The use of composite rebar in building structures. Przegląd budowlany **3/2014**, 47-50 (2014)
3. M. Górski, E. Goldmann, Will non-metallic reinforcement be increasingly popular?. Civil Engineer, (2021)
4. A. Nanni, A. De Luca, H.J. Zadeh, Reinforced Concrete with FRP Bars: Mechanics and Design, (Taylor & Francis Group, LLC, 2014)
5. A. Wiater, T. Siwowski, Load capacity for shear of bent concrete elements reinforced with FRP composite bars in the light of selected calculation procedures. Journal of Civil Engineering, Environment and Architecture **34(64)**, 265-296 (2017). https://doi.org/10.7862/rb.2017.98
6. S. Tian, X. Zhang, W. Hu, Fatigue Analysis of CFRP-Reinforced Concrete Ribbed Girder Bridge Deck Slabs. Polymers **14(18)**, 3814 (2022). https://doi.org/10.3390/polym14183814
7. W.I. Alnahhal, M. Chiewanichakorn, A.J. Aref, S. Alampalli, Temporal Thermal Behavior and Damage Simulations of FRP Deck. J. Bridg. Eng. **11(4)**, 452-464 (2006). https://doi.org/10.1061/(ASCE)1084-0702(2006)11:4(452)

8. T. Bhat, V. Chevali, X. Liu, S. Feith, A.P. Mouritz, Fire structural resistance of basalt fibre composite. Compos. Part A Appl. Sci. Manuf. **71**, 107-115 (2015). https://doi.org/10.1016/j.compositesa.2015.01.006
9. U. Berardi, N. Dembsey, Thermal and fire characteristics of FRP composites for architectural applications. Polymers **7(11)**, 2276-2289 (2015). https://doi.org/10.3390/polym7111513
10. S. Amidi, J. Wang, Subcritical debonding of FRP-to-concrete bonded interface under synergistic effect of load, moisture and temperature. Mech. Mater. **92**, 80-93 (2016). https://doi.org/10.1016/j.mechmat.2015.09.001
11. PN-EN 1990:2004/Ap1:2004/A1:2008/AC:2008/Ap2:2010. Eurocode: Basics of structural design
12. W. Starosolski, Reinforced concrete constructions according to Eurocode 2 and related standards, Volume 1 (PWN Scientific Publishing House, Warsaw, 2011)
13. ACI 440.1R-06 (2006), Guide for the design and construction of concrete reinforced with FRP bars, ACI Committee 440, American Concrete Institute