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PERSPECTIVES AND SPECIFIC FEATURES OF THE USE OF COMPOSITE MATERIALS FOR STRENGTHENING OF DAMAGED REINFORCED CONCRETE STRUCTURES

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The need for strengthening of existing structures has recently become topical. Composite materials due to their remarkable properties, possibility to adaptation to the design requirements and facilitation of restoration measures are widely used for strengthening. This article is focused on review of restoration approaches with the use of composite materials and specific features of their behavior under various impacts. Study includes analysis of recent studies in the area, identifying gaps of knowledge and perspectives for further research. The most relevant areas of research were distinguished including numerical finite element modelling for parametric analysis, deepening of understanding of composites` linearly elastic behavior, approaches to prevent delamination failure. Further thorough research in this area is strongly recommended to deepen the knowledge and maximize the efficiency of use of composite strengthening systems.

Keywords: RC structures, composite materials, strengthening, damages, efficiency, load-bearing capacity

Introduction

Nowadays strengthening and restoration of existing building structures is an important direction of optimization of project solutions and the most effective use of existing construction funds. Among the most urgent problems is the reliable analysis of the stress-strain state and the choice of the reinforcement system for a specific case (Adamczak-Bugno et al, 2022; Kos et al, 2022; Koteš et al, 2022). There is a number of factors that cause the need for strengthening and retrofitting, including changes in design parameters and requirements, environmental impacts, natural and anthropological disasters, ageing, physical wear, corrosion of concrete and reinforcement, etc (Kos et al, 2020; Kramarchuk et al, 2023; Zeng et al, 2022; Blikharskyy et al, 2021 (a,b), Kopiika et al, 2021).

The widespread use of reinforced concrete (RC) structures, subjected to various external factors, influences and loads causes significant interest in the engineering community in methods of prolongation of their service life, strengthening and restoration. Among the most common strengthening methods could be highlighted the following: the use of external strengthening systems, the use of pre-stressed external reinforcement, composite materials, metal and reinforced concrete cages, etc (Tian et al, 2022).

One of the most common methods of reinforcement, which has proven its effectiveness in many practical projects, is the use of composite non-metallic materials. Due to high strength, resistance to chemical and physical corrosion, special dielectric and diamagnetic properties, low weight and thermal conductivity, composite materials are becoming more and more widespread. This article is summarizing recent research findings in the area of composite strengthening systems for restoration, strengthening and retrofitting of damaged RC structures.

This article is focused on complex review of strengthening approaches with the use of composite materials, their specific features, which should be considered in practical applications. This study includes systematic analysis of recent studies in the area, identifying gaps of knowledge and perspectives for further research.

Materials and Methods

The main method used in the study is systematic collection and synthesizing of previous research regarding the use of composite materials in strengthening systems. Systematic integrated literature review was conducted, aiming to compare research findings and to uncover areas in which more detailed analysis is required. Findings of theoretical and experimental studies were weighed and compared. General patterns, disagreements and relationships were identified, which could further be used for creation of novel theoretical conceptual framework in the issue of composite strengthening systems.

Results and discussion

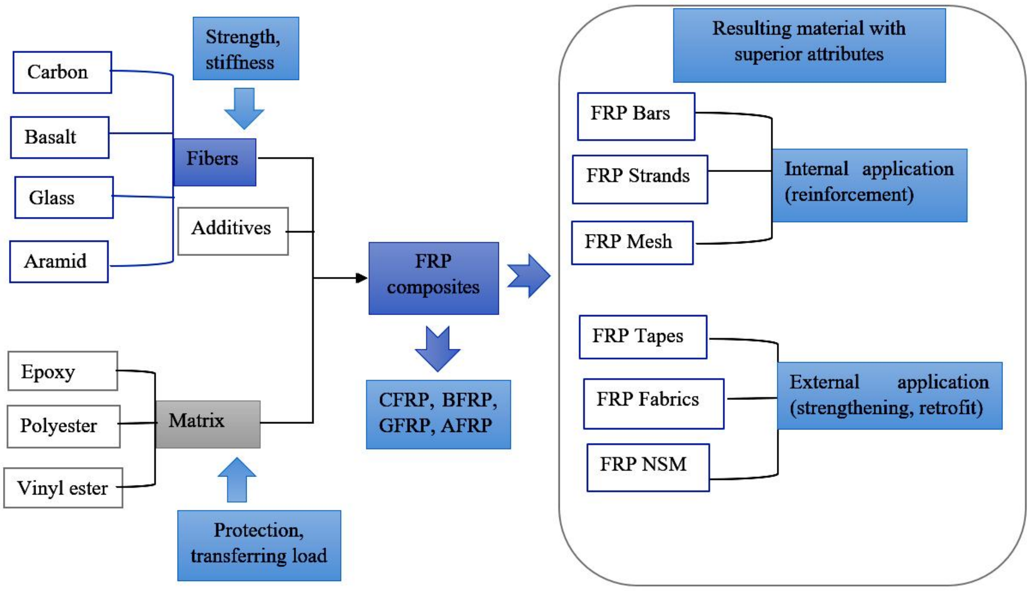
In general case the definition for composite materials is the combination of two or more components which, when united into a system, form a material with improved properties that exceed the sum of properties of individual components (Naser et al, 2018). These materials are widely used in engineering practice in different forms, regarding on the purpose: as thin tapes of 1-2 mm thickness or flexible sheets and fabrics with either uni- or multi-directional orientation of fabrics (Task Group 9.3 FRP, 2001). Composites demonstrate such advantages as high resistance to corrosion, strength-to-weight (efficiency) ratio, durability, tensile strength, rigidity (Mhanna et al, 2021), which has become the reason of their prevalent usage and supplementing of more traditional strengthening techniques (Haya et al, 2021). As was indicated in technical report, states basic concepts of composite strengthening design (Task Group 9.3 FRP, 2001), composites facilitate restoration works in conditions of limited space and can be easily adapted to the design requirements due to wide range of sizes and geometric shapes.

Efficient decision making in design of restoration measures requires complex approach and consideration also disadvantages of composite materials, in particular: generally linearly elastic behavior to failure (unlike other steel reinforcement). Therefore, composite strengthening materials are not characterized by fluidity and plastic behavior. Other peculiarities of their physical and mechanical characteristics include coefficients of thermal expansion, different from concrete, which could be the reason of premature destruction when subjected to impact of high temperatures. Considering comparatively high cost of these materials it is highly important to maximize their efficiency and exploitation (Task Group 9.3 FRP, 2001; Karpiuk et al, 2020). Therefore, composite materials for strengthening goals should be evaluated comprehensively, considering all advantages and potential disadvantages, including mechanical and physical characteristics, manufacturability and durability. All the stated above confirms the necessity of further improvement and development of the practice of exploitation composite materials for strengthening of concrete structures requires a deeper study of the peculiarities of their functioning, clarification of regulatory guidelines based on the practical experience.

The most widely used type of composite materials, used for restoration are fiber-reinforced polymers (FRP). Constituents of FRP materials are high-strength fibers and polymer matrix (see Fig.1). Fibers are specific reinforcing components, providing strength and stiffness characteristics, while the matrix, as a binding component, ensures protection of fibers and load transfer between them (Naser et al, 2018).

There are different types of fibers, which can be used for manufacturing of such composites, varying in physical, mechanical behavior: carbon (CFRP) glass (GFRP), basalt (BFRP), aramid (AFRP), polyethylene terephthalate (PET), etc. As the matrix mainly serve epoxy, polyester, vinyl ester, etc. Therefore, structures, strengthened with different fiber-reinforced polymers have different destruction and cracking mechanism, ability to absorb energy, durability, which also depends on the percentage of fiber content (Manibalan et al, 2023).

Recent research and improvements in science of composite materials and deepening of understanding of their behavior have greatly increased their resistance to external environmental impacts, which caused their wide spread in the field of strengthening of existing buildings and structures. Nowadays, there is already significant practical experience in increasing the load-bearing capacity, stiffness and prolongation of service life by gluing composite systems using epoxy adhesives to the surfaces of damaged structures (Naser et al, 2021). Number of research works (Borysiuk et al, 2019; Kramarchuk et al, 2021) describe the application of such systems in the form of tapes and sheets to reduce the risk of various failure mechanisms for more than 50 years. In particular, Haya et al demonstrated an increase in the load-bearing capacity for bending in RC beams externally strengthened with hybrid CFRP and PETFRP tapes, glued to the stretched face (Haya et al, 2022).



Composition and application of FRP materials

Experimental and theoretical studies have confirmed, that strengthening with CFRP materials has considerable positive impact on the range of mechanical parameters of RC bending structures, such as stiffness and shear strength, crack resilience, deformability and ability to absorb energy (Zhang et al, 2022; Kantarci et al, 2023; Džidić and Mahmutović, 2019). Design of strengthening system and decision making on effective restoration measures is determined by the particular goal of retrofitting. Thus, gluing the tape to the lower face of the RC beam contributes to absorbing blast energy, while the use of diagonal tapes on the side face of beams and U-shaped systems allows to increase shear strength (Jahami et al, 2021). Detailed experimental study, dedicated to assessment of combined shear and bending reinforcement systems using fiber-reinforced polymer (FRP) and textile reinforced mortar (TRM) composite materials confirmed the increase in shear load-bearing capacity and other parameters of behavior under loading (Pohoryles et al, 2021). This was also confirmed by study of Abdalla et al, who indicated a significant increase in the load-bearing capacity for bending and shear when using composite tapes for wrapping RC beams in combination with rod anchors (Abdalla et al, 2022). According to detailed review of existing studies, presented in the work Maazoun et al, FRP materials have remarkable perspectives for increasing the load-bearing capacity under impact loading, in particular, for more plastic behavior and reducing the level of damage (Maazoun et al, 2017). Another studies (Saljoughian and Mostofinejad, 2020; Xu and Huang, 2020) also confirmed the positive impact of FRP composites in terms of the load-bearing capacity of structures subjected to cyclic loading.

Separate research field is dedicated to perspectives of replacing steel reinforcement with composite materials in the future, due to their resilience, durability, light weight and ease of use. As is stated by Nabi et al, although the cost of a structure with composite reinforcement will be higher at the initial stages of construction, the general in general entire life cycle of the structure will be more economical (Nabi et al, 2020). Thus, numerical modeling when compared with experimental data, presented in recent study shows that the use of composite materials for replacing reinforcement in the stretched zone allows to increase the crack resistance of reinforced concrete beams (Pang et al, 2021).

Notwithstanding the long-term practice of use of composite materials, researchers still note a number of specific aspects of their behavior, identifying gaps of knowledge in this area. For instance, FRP materials do not have characteristic yield point and prone to linear elastic behavior, which leads to a brittle failure mechanism of reinforced concrete structures (Mhanna et al, 2022). Also, since the modulus of elasticity of these materials is quite low, structures strengthened with them, tend to increased deflections and opening of cracks. Therefore, specific attention should be paid to operational suitability requirements (Abed et al, 2021).

Žmindák et al have made an interesting observation, that strengthening of beams with composite tapes causes redistribution of stresses in concrete and reinforcement, which was confirmed by FE modeling and experimental tests (Žmindák et al, 2017). Authors (Džidić and Mahmutović, 2019) also claim that for beams, retrofitted with carbon tapes there is a danger of an oblique crack formation, which will cause almost instantaneous peeling of tapes from the concrete and brittle failure. This could be eliminated by wrapping beams with carbon fabrics in the zone of maximum shear forces (Džidić and Mahmutović, 2019). Comprehensive study Blikharskyy et al has indicated that the level of preloading has significant impact on ultimate load, which could be perceived by strengthened RC component, as well as on ultimate displacement (Blikharskyy et al, 2023).

As was mentioned above, the cost of composite materials is rather high, therefore it is highly important to maximize efficiency of their application, which is covered in numerous studies. Thus, it was found that the bending capacity of strengthened beams depends significantly on the orientation of the tapes. In particular, the angle of 45^0 between the longitudinal axis of the beam and the direction of tapes is the most effective and helps to avoid the fragile process of destruction (Murad, 2018 (a,b)). This was confirmed by a theoretical evaluation using numerical modeling and parametric analysis, highlighting the impact of orientation of tapes on the load-bearing capacity and the mechanism of destruction (Al-Bodour et al, 2022). In shear strengthening it is also important to take into account distance between tapes (Halim et al, 2020).

One of the most common problems that arise when using external strengthening systems is a debonding or violation of the anchoring of the composite tape, thus, the further joint operation of the structure and strengthening material becomes impossible. For RC bended structures the most dangerous zones in this aspect are places of stress concentration at the ends of the tape due to shear forces. Another reason of such debonding is the appearance of cracks ("intermediate crack (IC)" debonding). Such unfavorable failure mechanism is considered as the third type of limit state and could cause incomplete use of the potential bearing capacity of CFRP materials (up to 20-30%) (Yang et al, 2021). Gideon and Alagusundaramoorthy have experimentally observed formation of cracks at the contact of the surfaces, confirming danger of such mechanism of destruction (Gideon and Alagusundaramoorthy, 2018). It is important to ensure effective stress transfer between the components of the concrete-composite tape system in the contact zone (Zhu et. al., 2020), since, as noted by Gideon and Alagusundaramoorthy, in this zone cracks, delamination, and disruption of the interoperability of materials are the most common cause of structural collapse (Gideon and Alagusundaramoorthy, 2018). Among other studies, which mention, that delamination is the most typical and dangerous mechanism of failure of RC beams, strengthened with CFRP materials are also Adhikary et al, 2015 and Castillo et al, 2016. Islam et al note that the presence of cracks in a reinforced concrete beam before application of strengthening increases the probability of failure due to delamination and the effectiveness of the use of composites decreases (Islam et al, 2021).

The danger of failure due to debonding has caused increased attention to search of methods to prevent it, which is anchoring of composite materials. Therefore, the number of studies is devoted to effective methods of anchoring of composite materials (Castillo et al, 2016; Castillo et al, 2019; Huang et al, 2022; Yang et al, 2021; Mhanna, 2022; Chen et al, 2018; Yang et al, 2018).

For instance, Yang et al propose to use the technology of "stepwise prestressing", which ensures self-anchoring of CFRP strips, which helps to increase the level of use of FRP up to 81% (Yang et al, 2018). Another efficient approach to prevent debonding is the use of U-shaped transverse reinforcement, which, as stated by Chen et al are more efficient than vertical anchors (Chen et al, 2018). The results of the study by Huang et al indicate that H-type anchors and an increased level of prestressing of CFRP strips not only increase load resistance and plasticity, but also allow to identify critical load levels close to limit states. According to the comprehensive evaluation and use of the FE model, this approach allows to increase the degree of use of composite materials and open new perspective applications (Huang et al, 2022).

Another interesting work, worth paying attention by Castillo et al suggests the use of straight FRP anchors, which are quite effective in cases of complex geometry of structure, when other methods of anchoring are unavailable. Detailed experimental study was dedicated to analysis of various parameters of such anchoring systems in order to maximize efficiency of their use. Authors also describe various approaches to anchor design and indicate promising directions for deepening knowledge on performance of anchoring systems (Castillo et al, 2016; Castillo et al, 2019). Numerical modelling and analysis of input parameters of FRP anchors also confirmed that such anchoring approach allow to reduce the risk of failure according to the third group of limit states (Yang et al, 2018). Study of Mhanna et al identified impact of inclination of the anchors on the efficiency of their use, while the most optimal are small angles. In addition, such anchors also increase shear strength and ductility (Mhanna et al, 2022).

Significant improvement in design of composite strengthening systems can be achieved via effective modeling and calculation methods, which was covered by significant number of researches, enabling reliable assessment of the stress-strain state, strength parameters and residual source of reinforced concrete elements strengthened with composite materials (Alyaseen et al, 2022; Borysiuk et al, 2019; Karpiuk et al, 2020; Naser et al, 2021; Colajanni, and Pagnotta, 2021; D'Antino et al, 2020). Borysiuk et al in their article emphasize the need for the development of accurate and reliable calculation methods that can be adapted for practical needs and take into account operating conditions and the stress-strain state of the structure before application of strengthening system (Borysiuk et al, 2019). In particular, numerical finite element analysis and modelling have confirmed the effectiveness of CFRP materials for strengthening of damaged RC beams (Alyaseen et al, 2022). Similarly, recent research notes that it is advisable to pay attention to the development of special finite element models, allowing to significantly reduce the material and time costs of experimental research. Researchers describe in detail strategies and algorithms for successful analytical modeling of structures strengthened with composites, which are target-oriented and allow parametric analysis (Naser et al, 2021).

Study of Tommaso D'Antino et al presents an analytical model for calculating the shear strength of reinforced concrete structures strengthened with fiber-reinforced composites, which is based on the Mohr model and considers the non-uniform distribution of stresses along the crack (D'Antino et al, 2020). Thus, different procedures for evaluating the influential parameters of the load-bearing capacity of the structure strengthened with composites were described by Colajanni, and Pagnotta. This study also proposes simplified formulation of the analytical model for evaluation of the shear strength based on the comparison of transverse forces perceived by FRP and steel reinforcement (Colajanni, and Pagnotta, 2021). Sensitivity analysis for various parameters of load-bearing capacity and holistic quantitative and qualitative assessment deformation, crack formation and destruction mechanisms were covered by study of Karpyuk et al (Karpiuk et al, 2020). Taking into account the existing evidence about non-linear behavior of strengthened structures, it is important identified the necessity for implementation of specific models for strength modelling, which take into consideration individual loading and failure circumstances (Kopiika and Blikharskyy, 2022).

Conclusions

Detailed literature review was conducted, enabling to evaluate state of the art, identify general trends, perspectives and gaps of knowledge in the issue of composite strengthening systems. On the basis of the conducted detailed research, it can be stated that the use of composite materials for strengthening and restoration of RC structures is a promising direction, reaching arising attention in both scientific research and practical applications. In the context of multiple studies on this topic main trends were identified, including the use of complex theoretical and experimental studies, which enabled cross-validation and refinement of results, numerical finite element modelling for parametric analysis and deepening of understanding of composites` linearly elastic behavior. It is important to highlight specific interest in recent studies to approaches to prevent delamination failure by the use of various anchoring systems. In general, it can be concluded, that the use of composite materials for strengthening and retrofitting of damaged structures is a promising direction due to remarkable physical and mechanical properties, possibility to adaptation to the design requirements and facilitation of restoration measures.

Prospects for further research

Composite materials in restoration tasks provide wide range of promising areas for further research. In particular, important gaps of knowledge which should be addressed in more detail include development and improvement of numerical models, which will automatically conduct parametric analysis and consider sustainability, resilience and robustness requirements. Further thorough theoretical and experimental research in this area is strongly recommended to deepen the knowledge and maximize the efficiency of use of composite strengthening systems.

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ПЕРСПЕКТИВИ ТА ОСОБЛИВОСТІ ВИКОРИСТАННЯ КОМПОЗИТНИХ МАТЕРІАЛІВ ДЛЯ ПІДСИЛЕННЯ ПОШКОДЖЕНИХ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ

Залізобетонні конструкції (ЗБК) широко поширені серед будівель і споруд, що перебувають в експлуатації протягом тривалого часу, тому проблема в їх ефективному підсиленні набуває актуальності. Композиційні матеріали завдяки своїм високим механічним і фізичним властивостям, можливості адаптації до проектних вимог і полегшенню самого процесу підсилення широко використовуються для задач реконструкції. Ця стаття присвячена комплексному розгляду методів підсилення із застосуванням фіброармованих полімерних матеріалів та особливостей їх поведінки при різних впливах. Дослідження включає аналіз публікацій у цій галузі, визначення недостатньо розглянутих напрямків та перспективи подальших досліджень. На основі аналізу ряду літературних джерел було виділено найбільш актуальні напрямки, включаючи чисельне моделювання методами скінченних елементів (МСЕ) для параметричного аналізу, поглиблення розуміння лінійно-пружної поведінки композитів, комплексні експериментально-теоретичні дослідження для крос-валідації і уточнення результатів. Важливо також відмітити значний інтерес до підходів для запобігання граничного стану через порушення сумісної роботи залізобетонної конструкції і композитних матеріалів завдяки застосуванню різних способів анкерування. В статті проаналізовано загальні тенденції в галузі підсилення залізобетонних конструкцій композитними матеріалами, визначено перспективні напрямки для подальшого вивчення цього питання, зокрема розробку та вдосконалення числових моделей, які будуть автоматично проводити параметричний аналіз і враховувати вимоги стійкості, стійкості та міцності. Подальші ретельні експериментальні і теоретичні дослідження систем підсилення із застосуванням фібро армованих полімерів є надзвичайно важливими для поглиблення знань і максимізації ефективності використання композитних систем зміцнення.

Ключові слова: ЗБ конструкції, композитні матеріали, підсилення, пошкодження, ефективність, несуча здатність.