metals

Review

The Use of CFRP for Structural Reinforcement—Literature Review

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Abstract: Carbon fiber reinforced polymer (CFRP) composites are increasingly being used to strengthen structures and to retrofit existing structures. CFRP composites are used in various industries: construction, automotive, and many others. This literature review has shown that CFRP composites find numerous practical applications. Improving structures by reinforcing them with CFRP composite is an innovative approach in design. This review aims to explore the current state of the art in the types of structures that can be reinforced with CFRP, and modifications to the CFRP composite as an additional aspect to increase the strength of the reinforced structure. It has been shown that regardless of the type of reinforced material, the most critical element in this connection is the bonded joint. Proper surface preparation and the use of an appropriate adhesive are also important.

Keywords: CFRP; composite structures; reinforcement; modernization

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Citation: Pawlak, A.M.; Górny, T.; Dopierała, Ł.; Paczos, P. The Use of CFRP for Structural Reinforcement—Literature Review. *Metals* **2022**, *12*, 1470. https://doi.org/10.3390/met12091470

Academic Editor: Jürgen Eckert

Received: 18 July 2022
Accepted: 30 August 2022
Published: 2 September 2022

1. Introduction

The steel constructions made of thin-walled structures are characterized by smaller material consumption and construction costs in comparison to hot-formed sections [1]; therefore, they are frequently used in industry. That reason triggers a demand for increasing their strength. The traditional strengthening techniques are welding and the use of mechanical fasteners [2], but it is not always possible to use them because of the small thickness of the element cross-section. In that case, an application of Carbon Fiber Reinforced Polymers (CFRPs) is a good alternative. CFRP is a composite material, which consists of a polymer matrix reinforced with carbon fibers. A simple adding of CFRP tapes to the structures allows increasing their strength, which is advantageous, when the change of the load occurs in the construction (e.g., new elements are assembled [3]). A confirmation of the improvement in strength and stiffness of metallic beams bonded with CFRP is acknowledged in various works [4–6]. Many parameters have an influence on the properties of CFRP tapes, e.g., direction of the carbon fibers and resin's specification [7]. The steel is not the only material that can be enhanced. CFRP tapes are used intensively for reinforcement of the concrete structures [8] and an application of them in wooden structures [9] is possible as well. Among different constructions, there are specific examples of strengthening with CFRP tapes, which were introduced in the following works: the roof structure of a historical church by Huster et al. [10], masonry walls by Bastianini et al. [11], and bridges in Poland [12], the UK [13,14], and the United States [15]. This paper aims to study the constructions reinforced with CFRP tapes in order to find the best solution and point to the trouble spots in them.

This article is the first stage of an implementation project on the structural reinforcement of a motor vehicle with CFRP tapes. This literature review aims to explore the current state of the art in CFRP composite reinforced structures. Numerous papers will be presented that describe the research, application, disadvantages, and advantages of structures reinforced with CFRP composites. This review is aimed at preparing a suitable methodology for bending tests of CFRP-reinforced structures, which will be the next stage of the project. A detailed understanding of the topic is an extremely important step in planning the research and methodology. The use of CFRP composites is increasingly popular; however, there are still few works describing how to strengthen structures and structural nodes so that the strength-to-weight ratio is as optimal and favorable as possible, as will be demonstrated in this literature review.

2. Research of CFRP Attributes

The mechanical properties of the CFRP composite depend on many factors, including the percentage of carbon fiber and the type of matrix used. Consequently, mechanical properties vary from one CFRP manufacturer to another. However, mechanical properties such as Young's modulus and tensile strength are several times higher than those of conventional steel. With CFRP composites, as with other polymers, the glass transition temperature value is very important. The glass transition temperature is the temperature at which the transition from the liquid state to the plastic or glassy state occurs. This is manifested by a step increase in the viscosity of the substance. The glass transition temperature for CFRP composites mainly depends on the type of polymer matrix used. The paper [16] presents a study on the effect of elevated temperature on the effectiveness of reinforcing reinforced concrete beams with CFRP-type strips. It was shown that the effect of insolation can cause the adhesive bonding of the reinforced concrete to the CFRP tape to go glassy. A significant decrease in the load-bearing capacity of the structure was observed at elevated temperatures. The cause of the failure was delamination in the adhesive layer. The glass transition temperature is an extremely important property of CFRP composite reinforced structures. The adhesive and the CFRP matrix are polymers, and in the case of polymers, this temperature affects the load-bearing capacity, the strength of individual components, and, thus, the entire structure.

Zhou et al. [17] introduced the results of experimental investigation of the mechanical properties of carbon fiber-reinforced polymer (CFRP) tendons during tension. The conditions of the exposure to room and elevated temperatures were taken into consideration. It was stated on the basis of performed studies, that the stress-displacement relationship remains linear independently of the working temperature. As it was mentioned earlier, the composites consist of two or more materials and for CFRP composites these materials are carbon fiber and polymer. As a polymer, the epoxy resin is frequently used. In work [18], an innovative approach was introduced, where the composition of epoxy resin was modified by adding nanofillers in different percent masses. The test results proved an increase in bending and tensile strength by the content of 2.5% nanofiller. These properties decrease with the increase in nanofiller content in the composite. Steel beams strengthened with CFRP tapes are particularly exposed to the CFRP sheet's creep effect. Zhang et al. [19] introduced an elastic method, which is used to insert the CFRP sheet's creep effect and the steel beam's temperature effect. Computational formulas of interface skid between the CFRP sheet and the steel beam, as well as stresses in the CFRP sheet and steel beam deformations under combined influence of temperature and CFRP creep, were presented. The results showed that stresses in steel beam strengthened with CFRP sheets have the smallest values at the ends of the beam and the biggest values in the middle of the span. Li et al. [20] described thermal damage, which is caused by shearing the CFRP laminates with lasers. Attention was drawn to the fact that the thermal damage weakens the CFRP laminates' strength. During the research, a high-speed camera and numerical simulations were used for estimating the influence of the heat-affected zone (HAZ) width over the ultimate tensile, compressive and bending strength of samples made of CFRP. It was stated that the mechanical properties of CFRP are weakened on account of exposed carbon fibers within HAZ, which are not able to carry the load. The properties of 3D printed CFRP are introduced in article [21]. The aim of the work was to understand the mechanical behavior of printed CFRP elements. Various investigations were carried out, including tension studies, interfacial shear research, and dynamic mechanical thermal analysis. Banon et al. [22] described methods for processing composite materials created by combining CFRP and steel. These materials have different machinability, and as a result, their machining poses some difficulties. The residual stresses of the steel–CFRP components were measured by the borehole method, based on an appropriate formalism for evaluating residual stresses for orthotropic materials, including the calculation of calibration factors by finite element analysis. The finite element method takes into account the actual material layout and mechanical properties of the specimens [23].

CFRP composites are susceptible to local damage during machining due to the applied cutting force and generation of high temperatures. Traditional cooling medium reduces the damage generated by CFRP heat; it is the use of synthetic fluids that significantly affects the environment and public health. Therefore, the paper [24] investigated the performance of CFRP milling in sustainable cooling media, i.e., dry, minimum lubrication, cryogenic liquid nitrogen, and carbon dioxide. In addition, the correct choice of process parameters and lubrification environment affects the cutting mechanism in any metal cutting operation. Wang et al. [25] conducted orthogonal milling tests on CFRP unidirectional laminate disks to study the evolution of cutting properties in a continuum of fiber orientation angles. Experimental results show that surface defects are the main damage to the machined surface and surface roughness increases. Based on these observations, a new milling strategy was proposed that takes into account the fiber orientation angle to avoid surface cavities. This unique approach provides a new way to mill CFRP laminates with a high-quality machined surface. The purpose of this paper [26] was to develop a mathematical model of surface delamination through response surface methodology and to analyze the effects of all individual input machining parameters such as cutting speed, feed rate, and depth of cut on the responses when milling CFRP composites with a solid carbide cutter coated with polycrystalline diamond. The developed second-order response surface model is used to calculate the delamination of machined surfaces under different cutting conditions. Using such a model, significant time and cost savings can be achieved. Sui and Wang [27] conducted slot milling of unidirectional CFRP laminates in four directions with respect to fiber orientation to effectively investigate the machinability of CFRP composites with respect to process parameters and the fiber orientation angle simultaneously. The results show that both the fiber orientation angle and the chip thickness have a significant effect on cutting forces. In the paper [28], an experimental study of CFRP EDM drilling was conducted. Different filler materials and process parameters were investigated. Graphite and carbon black were added to the matrix to increase electrical and thermal conductivity to study their effects on machinability, thermal damage, and surface quality. The machinability of CFRP composites poses many difficulties. Numerous works are being produced on this topic. The authors focus on the selection of suitable cutting conditions.

3. Modification of Carbon Fibers Surface in Order to Increase Mechanical Properties and Interfacial Shear Strength

Improving the properties of composite materials reinforced with carbon fibers by upgrading the interfacial properties of the composite is one of the branches of investigated research subjects among scientists. The efficiency of the composite material depends largely on the interfacial characteristic of the reinforcement and the surrounding material. An interfacial adhesion has a big influence on mechanical properties of composite materials.

Yamamoto et al. [29] developed a new colloidal technique, which consists in synthesis of colloidal polymer, which contains thermoplastic components of nylon resin from nylon powder and surface-active agents or through the emulsion polymerization and next, in absorbing it on the carbon fiber surface through the electrodeposition method. In work [30], an improvement of mechanical properties as a result of colloidal silica absorption on carbon fibers was described. Created Carbon Fiber Reinforced Thermo-Plastics (CFRTP) showed homogeneous strength, because the silica particles acted as spacers between carbon fibers, which stuck to each other thanks to their water repellency in nylon resin. Additionally, mechanical properties of CFRTP remained above room temperature. The research introduced in works [29,30] proved that the surface modification of the composite with colloids improves its mechanical properties and thermal stability. Besides that, it offers the possibility of CFRTP recycling, which is very important these days. CFRTP are exposed to fragile cracking. In order to increase the composite resistance to fragile cracking, the poly (methyl methacrylate) (PMMA) colloids were used, which were absorbed on carbon fibers by the electrospinning method [31]. This operation improved interfacial mechanical properties, such as interfacial shear strength and the impregnation coefficient. Three-point bending processes were done, which confirmed an increased CFRTP ultimate strength. The PMMA colloids were used in work [32] to strengthen a composite made of carbon fibers. The mechanical properties of composite materials are connected with the surface adhesion between composite components. In order to improve the mechanical properties of thermosoft plastics reinforced with carbon fibers, the surface adhesion between them needs to be improved. The polymer colloids were used, which were absorbed on carbon fibers through the electrodeposition. The adhesion between modified carbon fibers and thermoplastic resin was estimated by interfacial shear strength. A thermoplastic reinforced with carbon fiber was synthesized by the use of basic colloidal techniques. The thermoplastic reinforced with carbon fiber can be used as conventional material and can be recycled [33].

Sager et al. [34] researched the interfacial shear strength of carbon fibers covered with nanotubes (CNT) in epoxy matrix. The aim of the use of a CNT coat was the creation of a multifunctional structural composite. The results of the performed test show the improvement of interfacial shear strength, which can stem from the increase in interfacial yield strength. Not only the use of colloids positively influence the mechanical properties of composites made of carbon fiber, but using carbon nanotubes also works well. The compressive strength of polymer composites reinforced with carbon fibers is much lower than their tensile strength; therefore, Wang et al. [35] proposed using CNT in order to improve the compressive strength. The CNT sheets were produced in the form of carbon coils or cables. They proposed a method of wrapping up the CNT carbon fiber, and then impregnating it with the polymer to create a composite. The results showed that the use of CNT sheets around single carbon fibres to increase shear strength improves composite efficiency. In work [36], CNT was used as a modifier of the carbon fiber surface. Godara et al. [37] concentrated on one-way directional macrocomposites made of glass fiber and epoxy resin, where CNT were inserted in three ways: in a preparation for fiber forming, in a matrix, and in the preparation for fiber forming and in the matrix. The interfacial shear strength was researched. It was proved that the interfacial shear strength increases independently of the way of inserting the CNT into the composite.

Liu et al. [38] investigated microchemical interfacial properties of the composite reinforced with carbon fiber (CF) and polyphenylene sulfide (PPS) by the microbond test. The comparative tests were carried out with different loading speed in order to determine interfacial shear strength of the microcomposite. It was proved that the interfacial shear strength increases with the increase in the length of inserted fibers by a speed below 0.02 mm/s and above 0.04 mm/s, but it is constant from 0.02 mm/s to 0.04 mm/s. The tensile strength of one-way directional composites made of carbon fibers was checked in work [39] by taking the interfacial shear strength into consideration. The research was done with the Finite Element Method (FEM) and the influence of the interfacial shear strength on the surrounding fibers was checked, in case of fiber break. Next, the stress concentration factor was determined. The tensile strength of the composites with carbon fibers was predicted using the number of cracks and was compared with experimental results. The optimal interfacial shear strength was talked over, which can provide the maximal ultimate strength of the composites with carbon fibers. Fakhrhoseini et al. [40] modified the carbon fiber surface by the high temperature increase in nano-magnetite on the carbon fibers surface using the iron(II) sulfate as a single nanoparticle precursor. The strong meshing of the contact carbon fiber/epoxide in the form of magnetic nanotubes caused an increase in the interfacial shear strength. Wang et al. [41] proposed an effective and environmentally friendly method of increasing the interfacial shear strength between carbon fiber and resin by the mechanical blocking effect. As a result of chemistry reactions, the fiber structure became irregular. This method increased not only the interfacial shear strength, but also the ultimate tensile strength. Wang et al. [42] upgraded the microconnection method along with proper research device for measuring the interfacial shear strength between carbon fibers and epoxy resin. This method is highly efficient and easy to use, the displacement-load curves show a strong reliability of this method. The CFRP composites are subjected to external loading during exploitation, which causes interfacial creep between fibers and a matrix and, eventually, an interfacial skid. A microscopic behavior of the interface carbon fiber/epoxy resin was researched in work [43] by different shear load levels. According to creep simulation, an initial stress exists for starting the destruction process, above which the interface rips off. Comparably, the ripping off of the interface does not show in the regime of the low stress, where the curve displacement force is drawn and used to determine an energetic barrier since the beginning of creep destruction. Shioya et al. [44] gave a relationship between the ultimate tensile strength of the one-way directional carbon fiber/resin composite strand and the interfacial shear strength on the fiber/matrix wall. It was proved that the tensile strength of the composite strands does not increase monotonously with the increase in the interfacial shear strength, but it showed a maximum on a certain level of the interfacial shear strength. In work [45], the influence of the interfacial fiber/matrix strength on the compression of the composites reinforced with fibers was investigated. The axial compressive strength of the one-way directional composite strands with various values of the interfacial shear strength was measured. The compressive strength of the composite strands does not increase monotonously with the increase in the interfacial shear strength, but it shows smaller values by higher interfacial shear strength.

In Zou et al. [46], a hybrid pre-treatment consisting of laser cleaning and laser forming was introduced to increase the strength of carbon fiber reinforced thermoset composites (CFRTS) and heterogeneous TC4 alloy. Cracking of the CFRTS-TC4 joint occurred between the carbon fibers and polyamide-6 (PA6) resin inside the CFRTS, and the mode of cracking is the rupture of the CFRTS interlayer. The paper [47] describes FRTP and TC4 alloy composites. The laser metal surface plastic coating method and high-speed rotary laser welding technology were applied to improve the quality of the CFRTP-TC4 joint. Another paper [48] describes the bonding of a CFRTP composite to an aluminum alloy. The interface connecting these materials was pretreated by laser microtexturing, anodizing, and a hybrid of laser microtexturing and anodizing. The study showed that the method used produced micro-cavities or micro-roughness on the aluminum surface. As the laser scanning time increases, the size of the micro-pitting or micro-roughness decreases when the laser scanning distance is constant. Another paper [49] also describes a CFRTP-Al joint. A hybrid bonding method was proposed. The method consists of adding PA material to the CFRTP/Al interface and treating the microstructure on the Al alloy surface. Sheng et al. [50] described the joining of CFRTP and stainless steel using a fiber laser. The effect of processing parameters on the quality of the joint was investigated. The results showed that the laser joining process improved the microstructure of the fusion and heat-affected zones in stainless steel. The tensile strength of the joint was strongly influenced by the laser power and scanning speed, but only slightly by the clamping pressure. Jiao et al. [51] also described a CFRTP–stainless steel joint. Fiber laser welding joining parameters were evaluated to investigate the bond between these materials. The effects of parameters such as laser power, joining speed, and clamp pressure on the thermal defect of the stainless-steel surface and the strength of the joint were analyzed.

The above-mentioned articles proved that the surface modification of the carbon fibers causes an improvement of mechanical properties of the polymer reinforced with carbon fiber. Various methods are used for carbon fibers' surface modifications, i.e., electrodeposition, electrospinning, or high temperature increase of nano-magnetite using the right compounds. The influence of the carbon fibers' surface modification is described by the interfacial shear strength. Table 1 provides a summary of this chapter. The effect of carbon fiber modification on composite properties is included.

Table 1. Summary—Effect of carbon fiber surface modification on composite properties.

Article Number	Modifier/Method	Effect on Properties	Comments
[30]	Modifier: PMMA colloids Method: electrospinning	R_m ↑ $IFSS$ ↑ σ_g ↑	Effects occur when the electrodeposition voltage ↑
[33]	Modifier: Polymer colloids containing the same components as the matrix Method: Colloidal techniques, emulsion polymerization without soap or with thermoplastic powder and surfactant.	$IFSS$ ↑ σ_g ↑	Effects occur when the number of adsorbed particles ↑ When the tension ↑ the amount of adsorbed molecules ↑
[34]	Modifier: carbon nanotubes Method: thermal chemical vapor deposition (CVD)	R_m ↑37% and ↑30% $IFSS$ ↑71% and ↑11% E_t ↓9% and ↑13%	Occurring effects depend on the arrangement of the nanotubes
[40]	Modifier: magnetic Fe_3O_4 nanoparticles Method: iron (II) ammonium sulphate as a precursor of nanoparticles	$IFSS$ ↑84.3% SFE ↑ from 58.81 to 64.31 mj/m^2	
[41]	Modifier: amino groups Method: Fenton's chemical reaction	R_m ↑8.39% $IFSS$ ↑277.9% and ↑133.6% compared to unmodified particles.	

$IFSS$—Interfacial shear strength, σ_g—bending strength, R_m—tensile strength, E_t—tensile modulus of elasticity, SFE—Surface Free Energy.

As mentioned above, reinforcing structures with carbon fiber composites results in improved structural strength with a slight increase in structural weight. Thus, if a composite that is modified and, therefore, has better mechanical properties is used to reinforce the structure, the strength-to-weight ratio can be significantly improved.

4. CFRP as the Structure Reinforcement

The CFRP has directional strength properties, which means that the strength properties of CFRP depend on the direction of the carbon fiber distribution and the carbon fibers/polymer ratio. The CFRP is used as the existing structure reinforcement. Constructors often take construction reinforcement by the application of CFRP during designing into consideration.

For both cases mentioned earlier, it is necessary to determine how the construction will work or what its strength properties will be. Szewczak et al. [52], ref. [53] presented the reinforcement of thin-walled cold formed sigma beams with CFRP tapes. An experimental method and a numerical analysis were used during this research. The free supported beams subjected to four-point bending were analyzed. Different variants of the CFRP tape deployment on the thin-walled section were taken into consideration.

Figure 1 shows three-point bending tests on steel beams with a modified cross-sectional shape. CFRP tape was bonded to the beam from the bottom side. In addition, tests were performed on the same beam without CFRP reinforcement. It was shown that the beam with the CFRP reinforcement had significantly higher values for the maximum force that can be loaded on the beam. In work [54], the behavior of thin-walled beams reinforced with carbon fibers (CFRP) was presented. A comparative experimental study of the joint between the steel member and the CFRP through different scales of surface preparation was carried out, and then the behaviour of CFRP-reinforced beams through critical loading with and without CFRP reinforcement was analysed. It was proved that the load capacity increased with the reinforced beams. Szewczak et al. [55] presented the effectiveness of the reinforcement with CFRP tapes and steel tapes in thin-walled cold formed steel beams. The reference beams (without reinforcement) and beams with reinforcement were researched.

The length of reinforcing tapes was 175 cm, various deployments of CFRP tapes were investigated. The studies proved no big differences in deformation and displacement results for the reinforcement made of two different materials. It was noticed that the connection on the steel/adhesive contact was decisive.

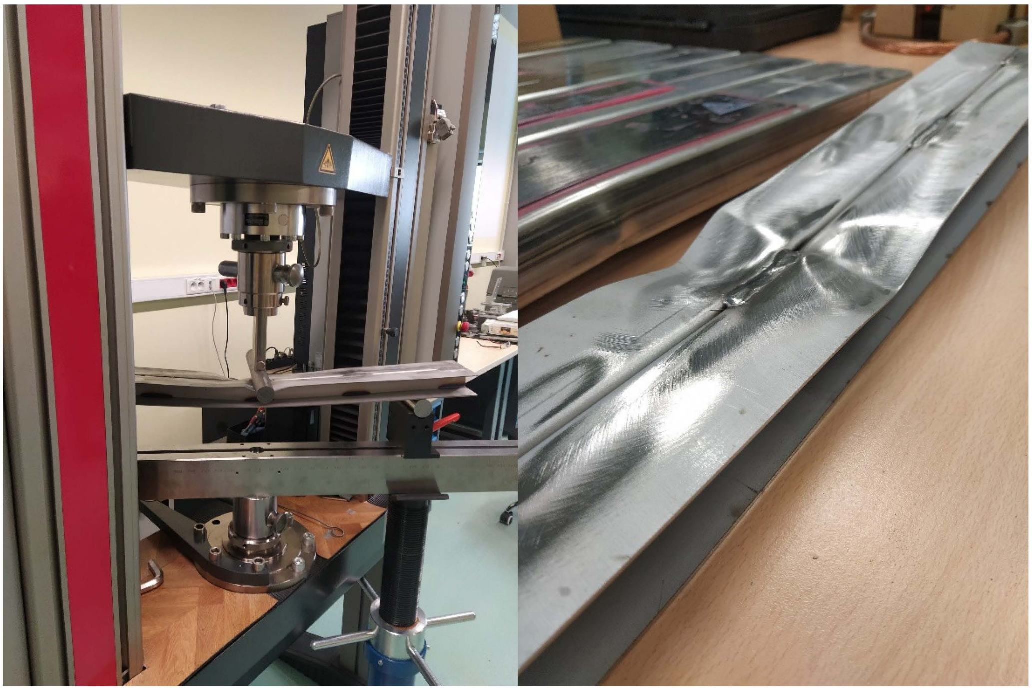

Figure 1. Three-point bending test of a steel section reinforced with CFRP tape.

In work [56], composite steel–CFRP tubes, which contain the advantages of steel and composite, were presented. The experimental studies were carried out, the steel–CFRP tubes were subjected to axial impact. Various geometrical variants of tubes and two different CFRP layouts were analyzed. It was proved, based on the research, that the impact properties of regular load and internal energy's absorption of composite steel–CFRP tubes exceed the properties of tubes made of only steel or only composite. Mamalis et al. [57] presented the results of experimental work on the crash behavior, failure modes, and crash properties of CFRP tubes subjected to static axial compressive loading. CFRP pipes were compressed in a 1000 kN hydraulic press at a very low strain velocity typical of static tests. The effect of laminate properties such as carbon fiber volume content and stacking order on the energy absorption capacity of thin-walled tubes was investigated. Huang and Wang [58] conducted quasi-static tests on CFRP pipes to investigate their response to axial crushing. During the experimental tests, stable progressive crushing processes with brittle fracture modes were observed. Numerical studies were also conducted. The paper [59] investigated the dynamic crushing characteristics of unidirectional CFRP composites under two types of loading, dynamic three-point bending, and axial crushing, using experiment and numerical simulation. Experimental results show that delamination has a critical role in dynamic deformation under bending. Sebaey et al. [60] characterized the impact responses of CFRP pipes filled with polyurethane foam in five different combinations. The CFRP pipes were internally stiffened. In addition, the internally stiffened tubes were filled with polyurethane foam to ensure structural integrity. The specimens were subjected to a dynamic crushing test using an impact hammer with an impact energy of 75 J. The results showed that the peak force, threshold force, and absorbed energy increased after polyurethane foam was applied inside the CFRP composite tubes.

The Figure 2 shows the failure of rectangular tube sections reinforced with CFRP tape. Three-point bending tests were performed. It can be seen that the characteristic failure form is repeated in all the specimens tested. The purpose of this study [61] was to investigate the failure modes and impact properties of double hat-shaped tubes made of CFRP that were subjected to quasi-static axial crushing and lateral bending. In the axial crushing tests, three distinct failure modes were observed: progressive end crushing, unstable local buckling, and mid-length collapse. In contrast, only one mode of progressive collapse was observed during transverse bending testing.

Figure 2. Failure of CFRP reinforced steel due to bending test.

The behavior of modernized steel constructions with steel–CFRP joints subjected to tensile load was investigated experimentally and theoretically in work [62]. Different binding lengths were considered to estimate experimentally the effective joint's length. In order to determine the value of the destructive load, a point stress method was proposed. It was proved that a high conformance exists between experimental results and theoretical results based on point stress method. Columbi and Poggi [63] showed that the mechanical properties of carbon fibers, as well as new joining techniques, give the possibility to use CFRP tapes to strengthen the steel constructions. Experimental and numerical studies were presented, whose aim was the efficiency verification of the application of CFRP plates to strengthen the steel elements. In work [64], results of experimental studies and numerical analyses of static behavior of steel beams reinforced with CFRP tapes were presented. Traditional I-beams were analyzed with different CFRP reinforcement's geometries. The beams were subjected to three-point bending. Rzeszut et al. [65] presented experimental and numerical results of thin-walled beams reinforced with CFRP. A tensile testing of tapes with steel and carbo fiber was carried out. Furthermore, a four-point bending of free supported beams was performed. Special attention was drawn to the critical load capacity's increase with simultaneous displacement restriction by right deployment of CFRP tape. The destruction of the construction adhesive under elevated temperatures, which reflects on the behaviour of steel-CFRP joints, is an important issue when considering the safety of CFRP-reinforced steel structures. Al-Emrani et al. [66] researched experimentally the behavior of composite steel–CFRP elements and performed Finite Element Analyses. They used various combinations of CFRP and adhesive, thanks to which they observed different cracking modes. The composite elements showed different behaviors and a big difference in yield strength and ultimate strength was observed. Lee and Kang [67] introduced a hybrid composite material, which was created by placing the plastic reinforced with CFRP fiber on CR420 plates. The aim of this operation was to increase strength and stiffness in conventional materials. A simulation was carried out, where the differences of specimen's mechanical properties were investigated depending on their deployment. The inner structure of composite material was researched. It was proved that a big number of empty spaces causes the deterioration of mechanical properties of CFRP composites.

4.1. Adhesive Joints

Dang and Lee [68] showed experimental results of static behavior of metal beams connected with CFRP tapes. Special attention was drawn to the weakest link in such constructions, namely the adhesive joint. In work [69], the test results containing the behavior and load capacity of adhesive joints between CFRP laminates and high strength steel elements were introduced. The aim of the study was an adhesive identification able to effectively join these two materials with full exploitation of their mechanical properties. Szewczak et al. [70] did four-point bending of thin-walled sigma beams with adhesive CFRP tapes. The aim of the research was to describe the influence of the adhesive layer's thickness on deformations and displacements in beams. It was proved that the load value, by which a damage appeared in the adhesive joint, decreased with the increase in the adhesive layer's thickness.

Nguyen et al. [71] investigated the mechanical properties of CFRP tape/steel element connection in elevated temperatures (to determine the adhesive glass transition temperature). Specimens with different adhesive joint lengths were researched. It was proved that the destruction mode of the adhesive joint turned from adhesive damage into break damage, when it was near the vitrification temperature. Furthermore, the critical load and joint stiffness decreased considerably in temperatures near and above the vitrification temperature. The effective binding length increased with the temperature. Colombi and Fava [72] described the fatigue properties of tensile steel/CFRP joints. The joints were made of two steel plates and two CFRP tapes, which were connected by epoxy adhesive. Based on the performed studies, it was proved that the detachments appear in the stress concentration points and they spread along the CFRP/adhesive joint and the fatigue limit is insensitive to the strength factor. Bocciarelli et al. [73] researched the debonding strength of axially loaded specimens with double folds between steel plates and CFRP plates. They performed experimental, numerical, and analytical investigations, which allowed verification of obtained results. The dominant way of damaging the specimens was the destruction of the steel/adhesive interface.

Figure 3 shows the sample after the tensile test. The CFRP strip has peeled away from the steel part due to tensile forces.

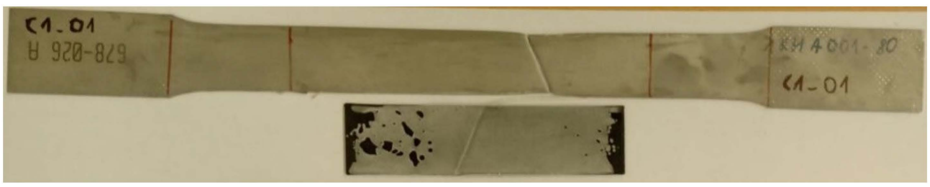

Figure 3. Tensile test on steel + CFRP specimen.

Agarwal et al. [74] researched the influence of mechanical and environmental loads on the behavior of the steel constructions reinforced with CFRP. Initial studies proved that damage in the steel–CFRP joints can appear by merely 15% capacity load during long-term exposition to humid thermal-mechanical loads. Experimental studies were presented, which concerned the influence of the thermal-mechanical load under dry and humid conditions on the steel–CFRP joint. It was proved that the adhesive vitrification temperature should be at least 30 °C higher than the highest usage temperature (steel–CFRP joints' exploitation temperature). Furthermore, it was specified that the steel–CFRP constructions, which are subjected to long-term loading by humid thermal cycles, are destroyed by considerably smaller load capacity than it was assumed [75]. Al-Emrani and Kliger [76] researched the behavior of steel–CFRP elements. An experimental method and Finite Element Method were used. A new type of specimen was developed for researching the influence of various material parameters on the behavior and strength of compound steel–CFRP elements. Based on the Finite Element Method, the types and magnitudes of interfacial stresses were determined. By application of few types of CFRP and adhesives, it was possible to research different cracking modes, a big difference in strength and ductility. In work [77], research results of steel–CFRP specimens under different load levels in room temperature and above and below vitrification temperature were presented. Depending on time, the behavior of the adhesive joint was proved by decreasing the stiffness and strength not only in the temperature function, but also in the time function. Based on material property models, which depend on the temperature and time, the destruction time of steel–CFRP joints was described. Furthermore, the obtained results were confirmed with experimental methods.

In work [78], two polyurethane adhesives were used for connecting steel and CFRP: conventional and hybrid. The aim of using these adhesives was to test the properties of the composites in relation to external environmental factors and high loads.. Despite the different adhesives' behavior, both of them are able to preserve the right strength after the degradation process. In this paper [79], the interfacial fracture behavior of a new titanium-fiber CFRP adhesive bond was investigated experimentally using a double cantilever beam and notched bending configuration. An important element in the combination of steel and CFRP is the surface preparation. The paper [80] presents the sandblasting of a steel surface and then measures the strength of the steel–CFRP joint.

Qin et al. [81] investigated the degradation mechanism of adhesively bonded CFRP–aluminum alloy joints after being subjected to continuous high temperatures. The changes in chemical composition, glass transition temperature, and thermal stability of the adhesive and the CFRP were analyzed. In addition, the failure strength and Young's modulus of the adhesive used were investigated. The results show that the glass transition temperature, thermal stability, tensile strength, and Young's modulus of the adhesive improved. In contrast, CFRP degraded after thermal exposure. The effect of elevated temperatures on the epoxy adhesive used in CFRP reinforcement systems is also presented in Firmo et al. [82] The subject of the study was civil engineering structures. Li et al. [83] investigated the bonding behavior between CFRP and steel using different types of epoxy adhesive and CFRP on failure modes, bond-slip relationships, and bond strength parameters. The results show that due to the use of different materials, some specimens fail due to interface disconnection characterized by brittle failure, while others have cohesive failure or CFRP delamination characterized by plastic failure. Ke et al. [84] proposed a new adhesive for bonding CFRP laminates to steel, and experimental validation was presented to improve the overall bonding performance. The adhesive was shown to have excellent high temperature resistance by dynamic mechanical analysis. The results show that film-adhesive bonded joints fail in the CFRP delamination mode, indicating a stronger interfacial bond between the adhesive layer and adherends than the intra-laminar strength of CFRP. In one [85] study, double and single shear bonded joints were used to investigate the effect of test methods and epoxy adhesives on the joint behavior between CFRP and steel. The test parameters included the type of joint and adhesive and the thickness of the adhesive. The failure mode, CFRP deformation, maximum load, interfacial shear stress, and sliding curve of the joint were compared. The results showed that the joint type influenced the ultimate load, interfacial shear stress, and CFRP strain, but had no effect on the bond-slip relationship and failure mode.

On the basis of the literature review, it was proved that the adhesive is one of the most important aspects in the steel–CFRP joint. It connects both parts.

Figure 4 shows a damaged specimen due to tensile force. The carbon fibers can be seen to have broken. A 'shooting' sound, characteristic of fiber rupture, could be heard during testing. It is necessary to adapt the adhesive to the joint exploitation conditions. In addition, proper surface preparation of the steel-CFRP joint is also important. Various adhesives can be used for connecting the steel and CFRP, e.g., epoxy or polyurethane adhesives. A right adhesive should be chosen depending on required connection properties. The polymers reinforced with carbon fiber are used to strengthen the existing constructions, e.g., their rehabilitation or increasing their strength properties. In addition, designers are considering the use of CFRP as a structural element, as it results in a significant increase in strength while reducing or maintaining the mass value of the overall structure.

Figure 4. Tensile test—steel–CFRP connection.

4.2. Rehabilitation/Modernization

Steel constructions, which are exposed to the influence of environmental conditions, are especially exposed to destruction, e.g., by corrosion. This destruction causes the decrease in load capacity and construction strength. Furthermore, the CFRP application can extend the fatigue life and reduce the crack propagation. Reinforcing the most stressed nodes of the structure reduces the stresses and, thus, the force that contributes to crack propagation. In addition, a number of papers describe studies on the vibration damping and energy absorption of a composite material such as CFRP. These studies have shown that the steel–CFRP combination exhibits significantly better energy absorption properties than either steel alone or CFRP alone. The critical load of the construction can be increased thanks to CFRP reinforcement's application.

In work [86], a problem related to construction rehabilitation using CFRP was formulated, namely a connection between a steel element and the CFRP composite. The construction rehabilitation is considered when the construction is damaged, or it needs an increase in load capacity. The influence of the steel–CFRP joint on its load capacity is an issue that needs special attention. Matta et al. [87] used CFRP composites as external connected laths for strengthening and repairing metal construction elements in buildings and bridges. The result of tensile testing and fatigue testing of steel–CFRP joints was described, which simulate reinforcement and cark's patching scenarios. Based on the performed research, it was proved that the reinforcements made on the ground, which can be characterized by certain inaccuracy, can assure a considerable lightening and load carrying possibility. The rehabilitation of a 40-year-old four-span bride with girders made of prestressed concrete using the CFRP composites was described by Kim et al. [88]. One paper [89] shows how to renovate the 19th bridge. Youssef [90] introduced an analytical model, which allowed predicting linear and nonlinear behavior of various steel beams, which were rehabilitated using CFRP composite. The model is based on differential equations concerning the rehabilitated steel beam behavior. Furthermore, it contains the adhesive behavior representation, which connects steel and CFRP during ripping off and shear. The model was validated using an experimental method. Steel constructions can be strengthened with glass fiber reinforced polymers [91]. RHS beams and I-beams reinforced with GFRP were described in work by Ehsani and Saadatmanesh [92]. It was proved that the nominal load capacity of the beams (using this type of reinforcement) increased considerably. Lepretre et al. [93] introduced experimental studies performed in order to research the application efficiency of CFRP composites for extending the fatigue life of old cracked metal constructions. Specimens that have a single crack coming from the rivet hole were investigated. Experimental results show that an application of CFRP plates can effectively decrease the crack speed growth and extend the fatigue life. CFRP composites are used for strengthening, rehabilitation, or repair of reinforced concrete elements [94]. The CFRP improved considerably the bending strength and shear strength of damaged construction elements. Another article [95] deals with the diagnosis and rapid repair of long-used metallic materials.

Structural retrofitting and rehabilitation using CFRP composite is being applied and numerous studies have been carried out in this area. On the other hand, the aspect of destruction of the CFRP composite retrofitted structures due to external factors acting on it must also be taken into account. Composite patching can be used to reinforce and repair cracked composite structures. In a paper by Soutis et al. [96], a study of bonded external patches of repaired compression-loaded CFRP laminates is described. They presented the repair of a composite structure with composite patching can use mechanical fixation or adhesive bonding, external patching, or flush patching. Various parameters, such as the quality of surface preparation and the design of the composite patch, are very important to ensure a reliable and durable bond. It has been found that the critical failure mechanism is micro-buckling of the carbon fibers. Cheng et al. [97] investigated the tensile behavior of composite structures repaired by gluing external patches. Different variants of patches were used: with different placement order and placed on both sides of the motherboard. The damage development and failure process of the repaired slabs were analyzed and a crack model for the mother slab was proposed. It was found that the high stress concentration along the longitudinal edges of the circular patches and at the transverse edges of the hole leads to early damage initiation in the motherboard. However, damage initiation depends on a number of external factors. Tie et al. [98] experimentally and numerically investigated the low-velocity impact response of CFRP laminates repaired with patches. The study included various patches of different shapes and sizes placed on one side of the parent plates. In the simulation, the damage development and failure process of the repaired plates were analyzed based on the continuum damage mechanics theory and the cohesion zone model. Scarf repairs are used in composite structures when high strength recovery is required or when there is a requirement for a smooth structure surface. Xiaoquan et al. [99] conducted experimental and numerical studies to understand the damage propagation and strength of scarf patch repaired CFRP laminates under uniaxial tension. The tensile strength and damage propagation of scarf patch-repaired laminates were investigated as a function of the change in scarf angle and patch diameter. Sun et al. [100] conducted a numerical study to simulate repeated impacts of patch-repaired laminates. Intralaminar damage was modelled. The effect of impact energy on damage accumulation was investigated, while energy dissipation was obtained from numerical methods. Damage accumulation in patch-repaired laminates is closely related to the development of intralaminar damage.

It has been shown that structures retrofitted with CFRP need to be inspected and if there are defects and damage, remedial steps need to be taken.

4.3. CFRP + Concrete

Polymers reinforced with carbon fibers are frequently used as a construction reinforcement in civil engineering. However, apart from steel construction reinforcement, concrete constructions are very often reinforced with CFRP.

Nguyen et al. [101] introduced reinforced concrete beams' behavior connected with CFRP plates, which formed the floor part of the structure. The influence of the plate length, rebar ratio, and concrete cover thickness on the beams' behavior was described. The attention was particularly drawn to fragile concrete cracking. The most common damage mechanism of reinforced concrete constructions reinforced with CFRP is the peeling off of the composite material. Li et al. [102] researched the CFRP–concrete interface behavior under dynamic load conditions. An experimental method Split Hopkinson Pressure Bar was proposed to the resilience investigations with high loading speeds. Thanks to this device, it was possible to determine the skid factor on the basis of shear research of a single specimen under resilience load. Wan et al. [103] described the influence of water's presence during CFRP application and after its strengthening on the connection between concrete and CFRP. During studies, three different initial levels of water/humidity presence were used. The results were compared with the research of specimens, which worked under dry conditions. It was proved that the presence of water during CFRP application considerably reduces the connection quality. Shahawy et al. [104] investigated the rectangular reinforced concrete beams' behavior connected with CFRP under bending load. The influence of CFRP application on concrete construction reinforcement was presented, and the following parameters were taken into consideration: load under cracking, behavior after cracking, deflections, utilization load, critical strength, and destruction manner. The experimental results showed that the bending strength, using CFRP for the reinforcement of concrete beams, increases considerably. The influence of the rebar ratio on the ultimate bending strength of concrete beams reinforced with CFRP was researched in work [105]. In this case, it was also stated that the construction reinforcement application (CFRP) causes an increase of the bending strength.

A reinforcement of concrete constructions with CFRP exposed to shear force was described in work by Täljsten [106]. Experimental studies were performed, which showed that considering the main cracking directions during compression towards one-way directional fiber is very important. A Near Surface Mounted (NSM) method can be used to strengthen the concrete beams with CFRP laminates [107]. Using this method, a doubling load capacity of concrete beams reinforced with CFRP was achieved, in comparison to conventional concrete beams. The NSM method ensures a considerable load increase in usage boundary state, as well as the stiffness increase after concrete crack. Barros and Dias [108] used the NSM method as well. Four-point bending tests were performed subjected to shear. An Externally Bounded Reinforcement (EBR) method was used too. It was proved that the NSM method is faster and easier to use. The aim of the work [109] was an experimental investigation of masonry-filled RC frames' behavior strengthened with CFRP under cyclic load. A measurement of stiffness, strength, and displacements was done. The specimens, which were symmetrically reinforced, showed a higher cross strength and stiffness. The specimens, whose CFRP tapes (with the same length) were used on one of the internal and external wall surfaces, showed a similar strength and stiffness. Täljsten and Elfgren [110] presented various methods and studies of the CFRP fabrics and tapes application. The aim of the performed research was the investigation of concrete beam load capacity before and after the reinforcement. Furthermore, they used three different methods of applying the fabrics. The experimental results proved that the best effects of concrete beams reinforcement can be obtained by sticking CFRP fabric to the front of the beam. Krzywoń et al. [111] presented experimental test results of the beams strengthened with Steel Reinforced Polymer (SRP) and CFRP laminates. Both materials were compared towards reinforcement effectivity, delamination, longitudinal behavior, application process, and ease of shaping. It was proved that the SRP composites are an interesting alternative for CFRP. In concrete–CFRP, the adhesive joint is the most critical element. The adhesive joint takes a part in carrying the stresses between the rebar and reinforcing tape. The research presented in work [112] showed that modifying the adhesive by changing its composition and the destination surface causes an improvement of adhesive joint properties. Rafi et al. [113] introduced concrete beam studies; the beams reinforced with CFRP and rebars were taken into consideration. It was proved that the behavior of the beams reinforced with carbon fiber is very similar to the behavior of the beams reinforced with the rebars. The deflection of beams reinforced with CFRP was satisfactory on the usable strength level, and the ductile nature of failure of the beams reinforced with CFRP was proved as well. Soudki et al. [114] introduced reinforced concrete beams strengthened with CFRP plates, which were exposed to the influence of a corrosive environment. They considered CFRP plates and tapes. Three beams were kept in room temperature. Eight beams were subjected to the multiple moistening and drying using de-icing agents. After the exposure, the beams were subjected to four-point bending test. Based on received results, the effectivity of the concrete reinforced with CFRP in a corrosive environment was determined. Nawaz et al. [115] present the application of structural light concrete reinforced with CFRP composite. Research was carried out in order to estimate the bending strength of theses beams. The investigation proved that the bending strength of the reinforced beam increased considerably in comparison to the control beam.

4.4. CFRP + Wood

Wooden construction can be reinforced with CFRP composites as well. In work [116], there was presented a behavior of wooden beams reinforced with CFRP composites. Numerical investigations were performed with Finite Element Method, the results were compared with the experiment. Based on the load–displacement relationship, the deformation progress was determined, as well as the stress concentration and damage modes. Five different types of wood were used during the research: Douglas Fir, Yellow Birch, Sitka Spruce, Yellow Poplar, and Northern White Cedar. Kula et al. [117] analyzed the mechanical behavior of wood-like beams. The I-beams were investigated experimentally, and were reinforced with CFRP composite in their weakened zones. During the research, a numerical method was used, and a theoretical analysis was performed. Experimental, theoretical, and numerical studies of the wood–CFRP beams were carried out by Kawecki and Podgórski [118]. The performed analysis included two CFRP reinforcement configurations. The pure glued wooden beams were used as a reference element. It was proved that the negligence of the cohesive adhesive's layer can lead to the revaluation of the total beam's stiffness.

Figure 5 shows three-point bending tests on a beam made of wood-based material reinforced with CFRP tape. In work [119], experimental research of beams bending on a technical scale was presented, in which beams were reinforced with CFRP composite in the tensile zone. The maximum load, deflection, failure mode, stiffness and stress distribution were determined from the tests. The results showed that the proposed reinforcement solution was profitable on account of the strength, stiffness, and construction safety. Socha et al. [120] introduced an experimental and analytical approach to the relaxation problem of the beams made of wood-like materials (Oriented Strand Boards-pressed wood-based composite panels), also the beams reinforced with CFRP tape. Rheological properties of such composites are important and difficult to estimate. A four-point bending test was performed, during which the loading strength reduction was measured. A five-parameter rheological model was used to the rheology description. A considerable stress redistribution was observed during the relaxation of the reinforced beam. The reinforced beams show bigger stiffness and carry bigger loads than unreinforced beams by the same deflection values. The experimental analysis of the beams made of pine wood (Pinus caribea var hondurensis) and reinforced with glass or/and carbon fibers was carried out by Fiorelli and Dias [121]. The ultimate bending strength was determined taking the boundary levels of the ultimate tensile and compressive strength of the wood into consideration. The fiber reinforcement effectivity was confirmed by the increase of strength and stiffness. The beams made of pine wood were described in work [122] as well. The fibers used to reinforce the beam were basalt and carbon. In the case of the carbon fiber, one-way directional and two-way directional fabrics were used. CFRP composites can be used in the rehabilitation of wooden structures.

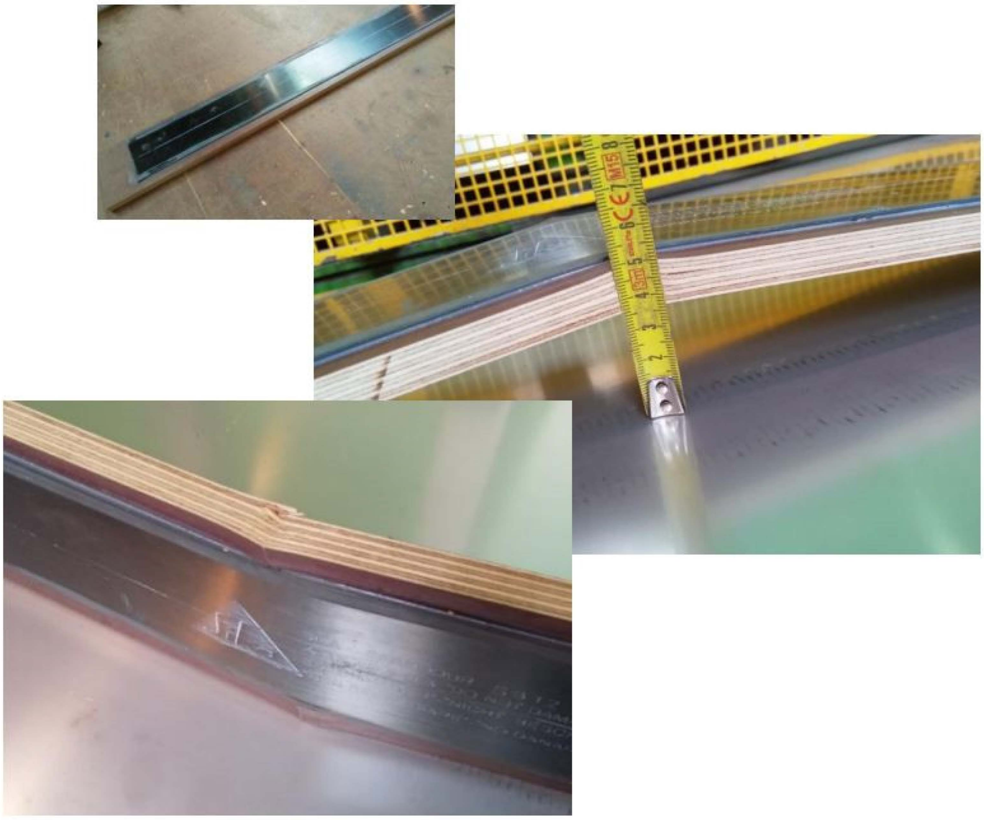

Figure 5. Element made of wood-based material reinforced with CFRP subjected to three-point bending.

Borri et al. [123] analyzed a CFRP composite reinforcement in the existing wooden elements, which were exposed to bending load. A numerical procedure was developed based on nonlinear wood properties (more suitable to use in CFRP reinforcement constructing) of the existing wooden beams. The researched proved that the wooden constructions reinforced with CFRP composite are stiffer during bending. In work [124], the bending strength of wooden beams reinforced with CFRP plates was investigated. A theoretical analysis was performed, and then experimental studies of four-point bending were done in order to determine the load-displacement relationship. Based on the research, it was proved that the wood–CFRP joint strength is higher than the strength of conventional wooden beams, and the average vertical displacement reduced. DE Jesus et al. [125] estimated the influence of the CFRP composite reinforcement's length of the wooden beam on the interphase shear and breaking stresses, which are critical to predict the failure. The research was carried out by the use of experimental methods, numerical methods, and analytical approach. A digital image correlation method was used to determine the impact deformation of CFRP-reinforced wooden beams in work by Liu et al. [126]. The investigation was performed using the drop weight. The properties of dynamic impact resistance were achieved. In order to improve the impact resistance, an axial force was applied to the beams. The near surface reinforcement technique can be used to apply the CFRP composite on the wooden beams. In work by Khelifa and Celzard [127], this technique was used; furthermore, they researched the CFRP-reinforced beams' behavior under bending conditions till their destruction. An application of CFRP composites to wooden celling structures, which are exposed to bending loads, was presented in work [128]. It was observed that this type of reinforcement is promising in case of old historic elements of constructional wood.

4.5. CFRP and Another Materials

In order to improve the beams' properties, which are exposed to the impact load, two methods are used: covering the beams with the composite and using the multicellular cross-sections. The influence of these two methods on the bending strength of the beams was described in work by Huang et al. [129]. The damage during bending and the impact strength of multicellular hybrid Al/CFRP tubes were researched. A three-point bending test was performed and the deformation and response characteristics for the bending force were analyzed, and the energy absorption efficiency was estimated. It was proved that the multicellular Al/CFRP tubes exceed the single cellular equivalents towards the impact strength. A solution review of joining aluminum with CFRP was presented in work [130]. A scope of available methods, processes, and joining mechanisms was described, as well as the properties of these joints. Current methods of joining CFRP composites to metals are, for example, bolting and riveting. These methods are used in aerospace structures. However, the decrease of construction mass is very important; therefore, in work [131], a method of joining aluminum with CFRP using thermal laser process was introduced. A laser beam welding process was used. Su et al. [132] described laser joining the carbon fiber reinforced polyether ether ketone (CFRP-PEEK) with titanium alloy. An influence of focus distance over interfacial joining was researched. An interfacial observation proved that a chemical bond was created in the joint, which caused a creation of a new phase, as a result of materials joining. The auxetic structures are characterized by low stiffness, which restricts their application. In work [133], CFRP composite as a stiffening of auxetic structure was used. An auxiliary composite structure was created, which consisted of corrugated sheets and tubes. It was stated that the structure stiffness depends on the corrugated sheets thickness within the scope of low deformations. The material parameters of the tubes determine the deformations within the scope of high deformations. The structures made of CFRP and aluminum combine the mechanical properties of aluminum with physical and chemical CFRP properties [134]. In order to join these two materials, various methods are used: adhesive joining, and mechanical and thermic methods. A few methods can be distinguished: friction welding, laser welding, ultrasound welding, and inductive welding. Liu et al. [135] proposed a multilayer structure made of Al/CFRP sheets. A magnetic pulse welding was used to join these materials.

4.6. Summary—CFRP as Structural Reinforcement

It has been shown that CFRP tape can be used to reinforce different types of materials. Figure 6 summarizes this chapter on structural reinforcement with CFRP composites. The materials that are reinforced with CFRP composites, the different methods of joining the materials, and the most commonly performed tests on these joints are listed. In addition, it is indicated in which works these aspects have been described.

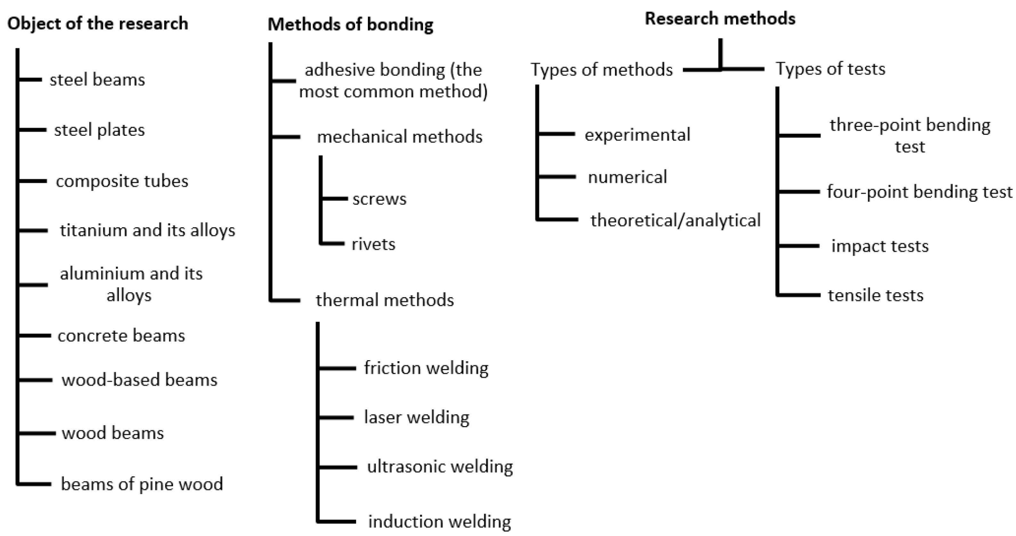

Figure 6. Structural reinforcement with CFRP—reinforced materials, connection between materials, test methodology.

The work presented here showed that, in most cases, the use of CFRP composites has a positive effect on the properties of the structure. However, a number of aspects have been mentioned that need to be paid attention to in order for the structure to work for a long time and be trouble-free.

The results presented in Table 2 show that, despite the numerous problems associated with combining CFRP composite with other materials, the use of CFRP to reinforce structures is beneficial, as the strength properties increase. In addition, it is worth noting that in most cases, CFRP composites are located where tensile stresses act. This is due to the arrangement of the carbon fibers, which achieve their highest strength along the length of the fiber.

Table 2. Improved durability of beams made of different materials compared to unreinforced specimens.

Article Number	Material	Characteristics	Improved Durability Compared to the Sample without Reinforcement
[52]	Thin-walled steel sigma beams	Reinforcement of the lower flange with CFRP tape.	$\sigma_g \uparrow 15\%$
[105]	Concrete beam	Reinforcement with CFRP tape on the tensile flange.	$F_{max} \uparrow \sim 94\%$
[123]	Wooden beam	CFRP tape reinforcing half of the beam—the flange and half the height on each side of the web.	$F_{max} \uparrow \sim 30\%$

5. Application of CFRP

The above sections describe CFRP composite reinforcement structures. In conducting scientific research, it is extremely important to indicate that the investigations carried out will find their application practice. Contemporary engineers frequently use (because they know the advantages of this material) CFRP in designing vehicles, constructions, machines, and in other areas as well. Figure 7 shows the use of CFRP tape and foam to reinforce a motor vehicle structure.

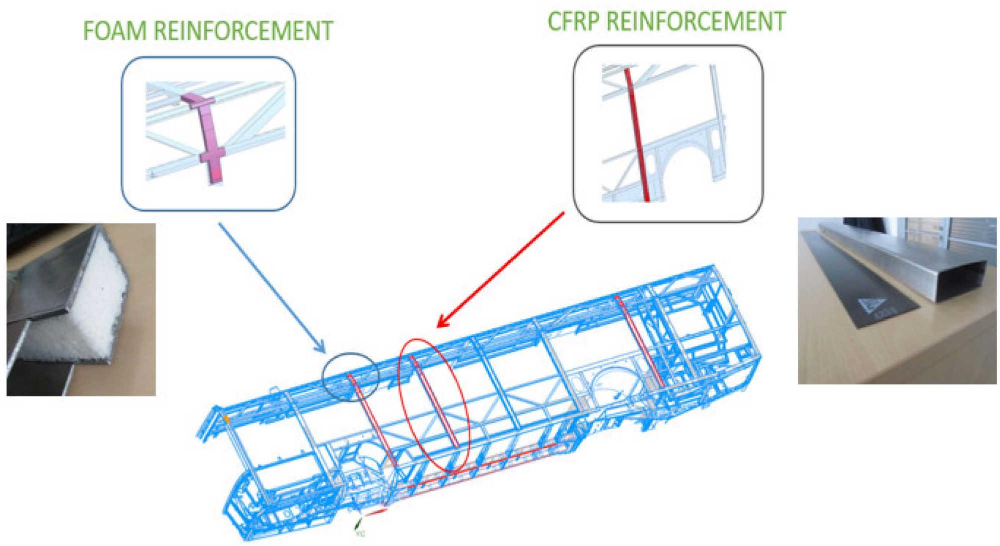

Figure 7. Using CFRP tape and foam to reinforce a motor vehicle.

The application of CFRP tapes by machine tool designing was introduced in work [136]. In case of the machine tools, a high demand for productivity increase exists and a high stiffness/mass ratio of the construction is needed. Furthermore, CFRP composites have a high damping factor, which is particularly important in the construction. The constructions of buses are especially exposed to fatigue because of the used weld joints. Particularly high damages were observed in junctions, which are in the back part of the bus. In work by Fasan et al. [137], research of car elements was presented: springs and external skin of front doors. A complete planning procedure of defining the model of the dynamic CFRP element with a built-in damping material layer was showed. Zhang et al. [138] judged the CFRP life cycle in car application. In their work, the disadvantages of CFRP application to car constructions were presented: there is high energy consumption during processing, materials are dependent on fossil resources, and there are difficulties with recycling. Galves et al. [139] developed a Finite Element Model. The aim was to obtain the forces, which have an effect on the reference junction. Based on performed studies, a new junction was developed by swapping a weld joint for a steel–CFRP adhesive joint. Another paper [140] presents the use of CFRP composites for cables, which are used in bridge construction, among other applications. An application of CFRP composites in designing the cable-stayed bridges was described in work [141]. A new anchoring type—bond and CFRP cable production—and an installation process were developed. Nakamura et al. [142] described an application of CFRP materials to upper stage structures of Japan's launch vehicles H-I and H-II. CFRP composites can be used in space telescope construction [143]. The ultralight and precise CFRP mirrors with layered structure were developed, which consist of layers and core made of CFRP. The CFRP composites can be applied in aviation construction. An active impulse thermography was used as a non-destructive testing method (NDT) to the investigations of aviation elements reinforced with CFRP [144]. A T-shaped stringer was analyzed, which was earlier monitored with ultrasound analysis and laminated with flat plates with internal production defects. The applied method allowed detecting the defects depending on their geometry and localization. Research described in work [145] presents an innovative idea of using the CFRP to strengthen steel pipelines. A request for reinforcing pipelines results from numerous transport line explosions as a result of terrorist attacks and sabotages. After the pipeline reinforcement with the CFRP composite, the deformations reduced by over 30%, using a CFRP band with a thickness of 4 mm. Experimental results showed that foam-filled hybrid structures can change the deformation mode and improve stability during the compression process. At the same time, these hybrid structures can also improve energy absorption compared to their individual components [146]. This paper [147] presents additive manufacturing of titanium with different surface structures for adhesive bonding and direct thermal bonding with fiber-reinforced polyether-etherketone (PEEK) for lightweight structural applications. One paper [148] presents an analytical and experimental study of pre-stressed CFRP in steel structures of water locks.

Numerous advantages of CFRP composites lead to that they are widely used for building new engineering constructions. Furthermore, these composites often improve load capacity and the strength of existing constructions.

6. Conclusions

This paper is a literature review of the use of CFRP as structural reinforcement. The paper describes the properties of CFRP, retrofitting and rehabilitation of structures, and the combination of CFRP with different materials, including the most common ones such as steel and concrete. In addition, examples of CFRP applications are presented. The work is part of an implementation project that deals with the structural strengthening of a motor vehicle using CFRP tapes.

The works cited indicate a cross-section of CFRP-reinforced structures. It has been shown that irrespective of the type of reinforced material, the critical connection points are the same. Furthermore, CFRPs prove to be difficult to machine. It was noted that the cited manuscripts focus either on the bonded connection or on the more difficult machinability of CFRP. It is not only the bonded joint or the mechanical joint that require machinability of CFRP that is the problem, but the bonding of CFRP with other materials in general. There is a lack of a holistic view of this problem, as presented in this paper. The recipient has the chance to learn about the problem and will find detailed information in the works cited.

Author Contributions: Conceptualization, Ł.D. and P.P.; validation, Ł.D., P.P., A.M.P. and T.G.; formal analysis, Ł.D., A.M.P., T.G. and P.P.; resources, A.M.P. and T.G.; data curation, Ł.D. and P.P.; writing—original draft preparation, Ł.D., A.M.P., P.P. and T.G.; writing—review and editing, P.P., A.M.P., T.G. and Ł.D.; visualization, Ł.D., A.M.P., T.G. and P.P.; supervision, P.P.; project administration, Ł.D. and P.P.; funding acquisition, Ł.D. and P.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out/financed under the Applied Doctorate Program of the Ministry of Education and Science realized in years 2020–2024 (Agreement no DWD/4/22/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Ł.D. would like to thank the Ministry of Education and Science for the funding mentioned above.

Conflicts of Interest: The authors declare no conflict of interest.

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