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Review of modern methods of timber strengthening

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ABSTRACT:
The aim of this review paper is to present modern methods of strengthening timber structures. The first part of the article discusses the characteristics of timber. It needs to be strengthened for several reasons, as described below. The following points describe the strengthening of the components with the use of steel and composite materials. The focus is placed on composite bars, strips and sheets. The materials industry is particularly interested in composites. The work showed their general characteristics and analysed how to use them to reinforce the structure in the best manner. The analysis of the conducted studies suggests that the application of the aforementioned elements is reasonable, and scientists are planning additional research in this domain.

KEYWORDS:
composites; glue joints; load-bearing capacity; reinforcement; timber structures

1. Introduction

Timber is one of the oldest construction materials. It is a resilient building material, but by its nature it degrades more quickly than other materials [1]. Many timber structures have endured for hundreds of years. These are often historic buildings which require appropriate strengthening. The search for innovative approaches to the strenthening and restoration of timber elements, which would ensure the preservation of their authenticity, is therefore of paramount importance.

Strengthening of timber elements is required for a variety of reasons. These include changes in the use of the building, increases in the live load values, changes in the static pattern or the occurrence of damage. They are used to increase the load-bearing capacity or stiffness of the beam compared to its initial load-bearing capacity or stiffness. A repair is an action that restores the section to its original resistance, stiffness or geometry [2].

Damage to wooden structures may occur as a result of the combined action of a number of factors. As a natural material, wood is particularly susceptible to the effects of biological factors. The action of plant or animal organisms leads to its destruction. These include insects, fungi, bacteria and mould. More detailed information can be found in [1]. Due to the flammable nature of wood, it is dangerous for a fire to break out. In a relatively short period of time, a fire can cause enormous damage to the entire structure.

In addition to these factors, there are other causes of damage to wooden structures, such as the natural process of material decay, temperature changes that cause alternating shrinkage and swelling, the presence of material defects, improper use of the object and lack of regular diagnostics. Human errors have been classified as design errors (concept, calculation, drawing), manufacturing errors, installation errors and operational errors [3]. Each of these factors have a negative effect on the operation of the structure, and the occurrence of several of these factors simultaneously results in catastrophes.

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The purpose of this paper is to be an introduction to the subject of the strengthening of timber members. Strengthening methods and materials will be on display. The methods currently in use are outlined in the remainder of this article.

2. Strengthening using steel elements

The use of timber and steel elements for the strengthening of timber structures is a method which is well known. New wooden elements (planks, beams) and steel elements for strengthening were used in traditional carpentry methods. They were attached to the object to be strengthened using mechanical fasteners: nails, screws, bolts [4]. This is an approach that has now been modernised.

For the time being, engineers are still in favour of adhesive bonding. Adhesive bonding is the joining of two materials by means of a bonding agent (glue) that cures and bonds the components.

2.1. Strengthening with steel bars

Bonding steel bars with synthetic resins is a common method of strengthening wooden beams [2]. The principles of strengthening selection are followed as in the design of reinforced concrete elements. Timber beams can be single or double reinforced. There is a limit to the degree of reinforcement of 1.5 % and 3 % respectively. The quality of the reinforcing steel must not be lower than the A-II quality. Grooves in which bars are to be placed should be approximately 1.5 mm - 2.0 mm wider than the diameter of the inserted bar [3]. Masłowski and Spiżewska are the authors of a paper on this issue. The bars are inserted into the pre-drilled holes and glued to the wooden element with resin-based adhesive. The result is a beam where the bonded steel resists tension and the timber resists compression. An example of a reinforcement cross-section is shown in Figure 1.

This issue has been the subject of analysis in the work of Jasienko et al. [5]. Fir beams strengthened with 12 mm diameter steel bars were used for the tests. The analysis concerned the issue of the anchoring length of such a bar. Conclusions on the redistribution of forces between the timber and the glued-in bar are also presented.

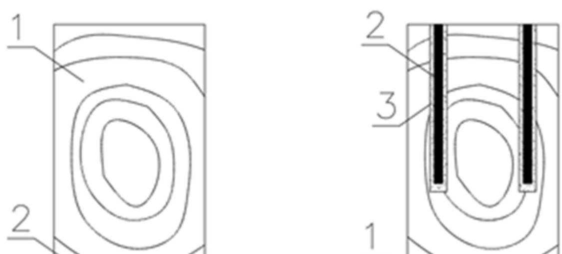

Fig. 1. Example of steel strengthening (1 – timber element, 2 – steel elements, 3 – glue system) (own study)

2.2. Strengthening with steel plates

Bonded plates are as popular as bars. The result is a section with much greater rigidity and load-bearing capacity when the plates are glued into the beam. The height of this plate should not be less than half the beam height or exceed 75 % of this value [2]. Figure 1 shows an image of such a solution.

A collective paper [5] has also addressed this type of strengthening. The tests were carried out on pine beams (old and new wood) strengthened with steel plates on the upper surface (B10) and on the side surfaces (B13). The strengthening has been bonded in place along the entire length of the element. As a result, there was a significant improvement in load-bearing capacity, stiffness and a reduction in strain values.

There are advantages and disadvantages to using steel to strengthening structures. Steel is a strong material that can increase the strength of a component at the expense of its weight. Another aspect to consider is the difference in the thermal expansion of the two materials [6]. Wood is not a moisture resistant material, and a damp environment is conducive to corrosion.

3. Strengthening using composite elements

Composite materials are materials that are formed by the combination of at least two component materials. As a result, the resulting product is characterised by better or new/additional properties [7]. A composite can be either a material that is used for the strengthening of a structural element as well as for a newly constructed strengthened element (e.g. a timber beam reinforced with steel bars).

Fibre Reinforced Polymer (FRP) is the most commonly used composite material for the repair and strengthening of timber structures. Composite materials consist of two phases: continuous (matrix) and dispersed (reinforcement). Depending on the type of dispersed phase used, the following are distinguished: particle, dispersion, fibre (continuous, discontinuous, oriented, random), laminates, sandwich panels [8].

Fibre is present in the form of reinforcement in composites used for structural reinforcement. It is designed to increase the strength properties of materials. The following types are distinguished on the basis of the internal structure of the fibres [9]:
- ‘monofilament’ – occurs in the form of a single thread;
- ‘tow’ – occurs as a group of parallel fibres;
- ‘yarn’ – occurs as a strand of many separate fibres;
- ‘roving’ – occurs as a group of fibres (tow) or multiple strands (yarn).

Fibre-reinforced composites are most commonly based on carbon (CFRP); glass (GFRP); basalt (BFRP); aramide (AFRP). They are also manufactured as hybrid materials, which are made up of more than one type of the aforementioned fibres.

Strength parameters vary depending on fibre used. These properties are not significantly enhanced by the resulting composite matrix. The warp is the binder (adhesive) which protects the reinforcement against the damage and ensures proper load distribution. Thermosets and thermoplastics are the two main types of resin for this purpose. The most commonly used binder is epoxy resin (a thermosetting resin) [10]. Composites are used in the form of strips, sheets, bars, prestressing tendons or prefabricated elements [11].

3.1. Strengthening using composite sheets

Sheets and composite strips are also available as alternatives to steel plates. Composite sheets are woven fabrics that are manufactured as unidirectional, bi-directional or multi-directional structural reinforcement materials. Unidirectional fibres are defined as those fibres in which the structural fibres arranged in the main direction are stabilized by non-structural fibers arranged transversely to them [12]. Bidirectional are where the construction fibres are arranged perpendicularly in two directions. A multidirectional material has a complex structure with fibres arranged in more than two directions.

Adequate preparation of the component to be strengthened is necessary in order to have a guarantee of the fusion of the two structures. The timber surface should be sanded and cleaned. The fabric is later bonded to the structure using an epoxy-based adhesive. Various options for the location of this strengthening are currently being explored by researchers. The placement options for the composite are shown in Figure 2.

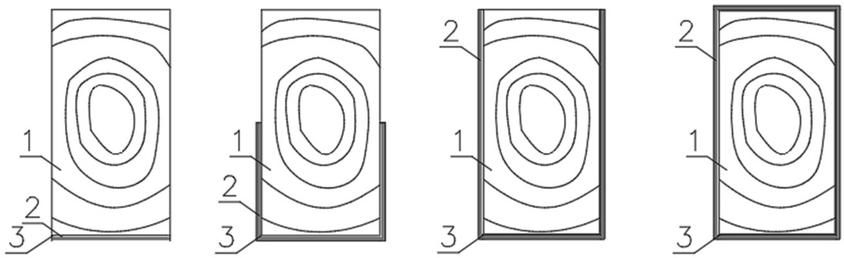

Fig. 2. Example of reinforcement with composite sheets (1 – timber element, 2 – composite, 3 – glue system) (own study)

Corradi et al. [13] carried out tests on beams strengthened with CFRP carbon sheets. The impact of knots, the most serious type of defect, was the main focus of the researchers. The four-point bending test was carried out on 36 fir beams (small and large). Unidirectional carbon fibres are used in CFRP mats. Epoxy resin was used to bond the composite to the timber element. The local strengthening method in use has demonstrated the ability to withstand high tensile forces using a small joint length. Compared to the reference beams, a reduction in load capacity of 34 % and 41 % was observed for the small and large beams, respectively. The local strengthening of the CFRP reduced these values to 22.5 % and 19.6 % respectively.

The research conducted at the Kielce University of Technology [14] involved beam strengthening using glass, aramid, and carbon fibre mats. Pine beams were subjected to four-point bending. The load was two concentrated forces at a distance of one third of the length of the beam between the axes of the supports. When using a single layer of fibreglass sheets, the increase in load bearing capacity was 20 %, for aramid matting it was 48 % and for carbon fibre matting it was 37 %. Tests were also performed for a CFRP composite laid in two layers. In this case, there is a 51 % increase in carrying capacity.

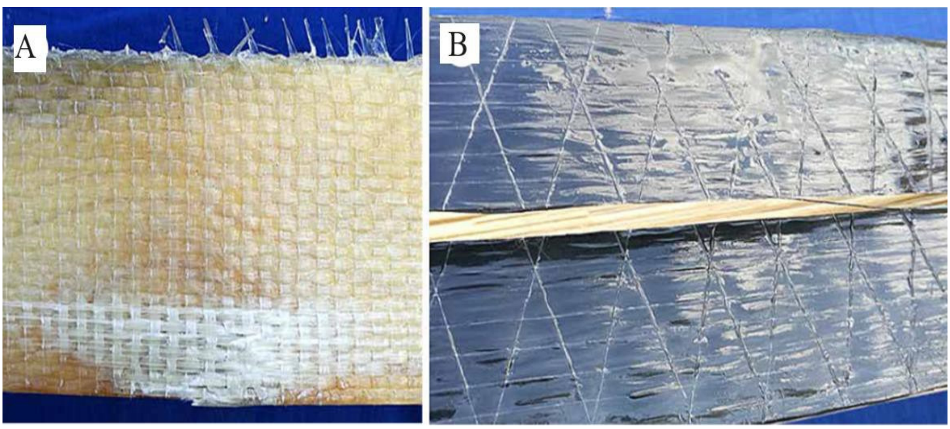

Fig. 3. Fibreglass (A) and carbon fibre sheets (B) used for strenghtening [15]

In [15] the flexural strength of timber members strengthened with composite mats was investigated. Solid C24 grade pine beams subjected to four-point bending were the subjects of the study. The tests have been carried out in accordance with the standard [16]. Reference beams (BD) with cross-sectional dimensions of 80 × 80 mm and a length of 1.6 m. They were strengthened with glass fibre reinforced sheets (BDG) and carbon fibre reinforced sheets (BDC). Figure 3 shows the composites. The photo shows a view of the damaged beams after the survey had been completed. In the tension zone, the sheets were glued to the underside of the beams. Beams strengthened with glass sheets demonstrated enhanced load-carrying capability relative to the reference beams by 15 %. Carbon mats have increased load-bearing capacity by 48 %. The deflection value (at maximum force) more than doubled as the load capacity increased. In [17] they continued to study glued wooden beams. Two different methods were used to place the composite material. The average flexural strength increased by 35 % due to the U-shaped strengthening. This value is increased by 30 % for a mat glued to the underside of the beam.

Garcia et al. investigated pine beams strengthened by basalt and carbon composite materials [18]. Experiments have been carried out on beams strengthened with sheets arranged in a "U" shape. The average section dimensions were 78 mm × 155 mm, and the beam length was 1.090 m. The test was performed with a single loading point. Basalt fibre composites are used in a wide range of weights, while unidirectional and bidirectional fabrics are used for carbon fibre composites. Compared to unidirectional fabrics, bidirectional fabrics give better results. Using unidirectional strengthening made from basalt fibres gives higher strength compared to carbon. There has been an observed growth of the stiffness of the beam as the weight of the fabric rises.

The article [19] gives conclusions on the compressive and flexural strength of the timber component. Smaller (20 mm × 20 mm × 300 mm) and larger (40 mm × 40 mm × 300 mm) specimens were subjected to three-point bending. A carbon fibre composite was wrapped around the wooden beams. A significant increase in compressive and flexural strength was observed with the strengthening applied. Beams with smaller cross sections will increase the compressive stress values, while larger specimens will reduce them.

3.2. Strengthening using composite strips

Composite strips usually take the form of flat laminates or meshes. Constructional fibres are laid in them unidirectionally and multidirectionally [9]. Strengthening can be achieved by the use of composite tapes. These can be positioned inside the cross-section [20] as well as outside [21]. In this case of external reinforcement, band compression was also used.

Halicka and Ślósarz examined the compression of wooden beams using carbon strips [21]. Four-point bending was performed on C24 grade timber beams with a section size of 14 cm × 20 cm. The compression forces were 30 kN, 60 kN, 75 kN and 90 kN. The utilization of amplification has resulted in an increased bending capacity by approx. 13 % and reduced deflection by approx. 20 % - 40 %, depending on compression.

Bakalarz [22] has been the author of a study on the strenghtening of glue-laminated beams. The undersides of the full-size beams (45 mm × 200 mm × 3400 mm) were affixed with 1.4 mm thick CFRP tapes. The Aramis optical system [23] was used to monitor deflection and deformation values. The load-bearing capacity of the beams was increased by 38 % thanks to the composite material used. There has also been an increase in the values of the global average modulus of elasticity by 11 %. The author emphasises the fact that the method used is suitable for the strengthening of existing structures.

In the paper [24], the problem was extended by the author to include an analysis of strain, stiffness and plasticity distributions. Carbon sheets strenghtening is also at the heart of the study. The laminates were glued into the cross section (two layers in the E Series) and also external surface (F Series). The F series beams showed better mechanical parameters than the E series beams. The effectiveness of the reinforcement was analysed in relation to the reference beams (Series A). A view of the elements belonging to each series is shown in Figure 4.

Strengthening studies using sheets and strips made of carbon and aramid fibres have been carried out by Brol and Wdowiak-Postulak. Preliminary tests on small samples have been carried out by the researchers. The main research involved repairing 130 year old pine beams. The span of the columns was 4.5 m and the average beam cross section was 21 cm × 25 cm. Carbon fibre strips were bonded to the underside of the beam as part of the repair. As a result, 80 per cent of the load-bearing capacity was restored in one beam and 58 per cent in the other. The complete research findings have been presented in the publication [25].

(A) (E) (F)

Fig. 4. A view of the reference and strengthened beams [24]

In his doctoral thesis [26], the author analysed the deformation and the load-bearing capacity of beams reinforced with CFRP strips. Approximately 100 year old pine beams with a section size of 12 cm × 22 cm and a length of 4 m were tested. The beams were divided into 7 series according to the defect present. The validity of the reinforcements in use has been established and there has been a demonstrated increase in load capacity of between 21 % and 70.9 %. New timber beams have also been the subject of testing. It was determined that the original load-bearing capacity and stiffness of the beams could be restored.

The article [27] also examined historical beams. The structural elements have been in use for over 200 years. The dimensions of these beams are on average 75 mm × 140 mm × 1288 mm. Nine beams were tested, six of which were strengthened with CFRP strips. Composite with 45 mm wide were glued to the tension surface of the beams. Analytical and experimental analysis has been carried out. Errors between the results reach up to 19.7 %. This is due to material defects in the wood and to significant differences between the reference beams and the strengthened beams.

CFRP strip strengthening has been tested in the laboratory of the Wroclaw University of Technology [28]. Approximately 100-year-old pine beams were tested. The cross-sectional dimensions were 120 mm × 220 mm and the test piece length was 4 m. The elements were strengthened along their entire length, in various configurations (series B-F). An increase in carrying capacity of up to 79 % was observed. The stiffness obtained in the tests takes on a value that is higher than the theoretical value.

3.3. Strengthening using composite bars

Composite bars are a modern replacement for the steel bars used today. The way in which such a strengthening is applied and the appearance of it are very similar. The bars are made of fibres arranged unidirectionally and embedded in a matrix [9]. The most common are those with a circular cross-section, and they come in many dimensions (diameters). Figure 5 shows a coil of basalt fibre reinforced composite bars.

Glued laminated spruce was analysed by Raftery and Kelly [29]. The average moisture content of the beams is approximately 18 %. Basalt bars with a diameter of 12 mm have been used. The tests were carried out on non-strengthened (control) beams, strengthened beams, artificially broken beams and repaired beams. Two strengthening systems were used. Composite bars were glued from below (group B) and from the side (group C). The research was carried out in accordance with EN 408. Four-point bending tests were performed on the beams. Stiffness was increased by more than 10 % through the use of 1.4 % strategically placed strengthening. The ultimate moment capacity increased by an average of 23 % compared to the reference beams (Group A). Basalt bars gave significantly better results than glass bars. The use of basalt bars to repair timber elements was effective. Restoration of mechanical strength and stiffness was shown by the analysis.

Fig. 5. Basalt bars (own study)

The method for the repair of laminate beams is presented in [30]. For this purpose, glass fibre reinforced polymer (GFRP) bars with a diameter of 6 mm and 12 mm have been used. In order to increase bonding with epoxy adhesives, the surface of the bars had a sand coating. The samples of the beams had two dimensions in height: 190 mm and 215 mm. Bars measuring 12 mm in diameter were conventionally inserted into two grooves (reinforcement degree of 1.39 %). Two 6 mm diameter bars were placed in three grooves (1.04 % reinforcement) as the second method of strengthening. For the higher beams, the percentage of reinforcement was respectively: 1.04 % and 0.92 %. The strengthenieng scheme for the lower beams is shown in Figure 6.

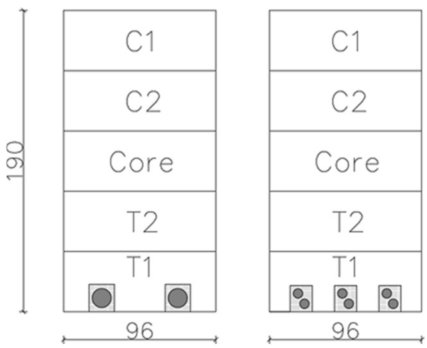

Fig. 6. Distribution of strengthenieng for a laminated timber beam (based on [30])

Beams strengthened with 12 mm diameter bars showed a higher number of cracks than those strengthened with 6 mm diameter bars. In spite of this, the percentage of local stiffness that was recovered was higher for the cracked beams. Global stiffness restoration was better than local stiffness. In each case, significant stiffness and bending moment strength were recovered.

The paper [31] addresses the same issue. Tests were first carried out on undamaged samples and then on artificially damaged samples. It was observed that the cross-section of the groove influences the mechanical properties of the beams. The first series of slots had a 16.7 mm by 16.7 mm square cross-section. The hole in the second series of beams was the same depth and width, with rounded tops. The efficiency of the applied bars has been enhanced by altering the groove geometry in which the glass bar strengthenieng was placed.

Rajczyk and Jończyk carried out studies on bonded spruce wood beams, bonded in layers, with a strength class of C24. The cross-section of the beams was 7 cm × 16 cm and the length of the element was 1.2 m. The strengthening used was basalt epoxy bars with diameters of 7 mm and 9 mm. They were placed in different configurations in the compression and tension zones. Components were subjected to a four-point bending test at 100 kN load. The study does not present results for not strengthened beams, but it does present results for the individual series, as shown in the table in [32]. It has been observed that beams with the highest percentage of reinforcement to achieve the highest failure force values and the lowest deflection values. In the authors' study, these were samples in which both bar diameters were used in both beam working zones.

The method of strengthening with prestressed GFRP bars is presented in [33]. The study was carried out in five groups, using different means of strengthening. In three groups a single GFRP bar was placed (in the centre and below the horizontal axis of symmetry). One group was additionally strengthened with a CFRP sheet. An increase in the average strength of the strengthened beams was achieved as expected. In relation to the control group the following results were obtained. The bar placed at the bottom of the section increased average strength by 3.5 %, while the bar placed in the centre increased it by 4.3 %. The bar in the middle of the section and the carbon sheet glued to the underside gave the best results. The percentage was 9.5 %.

Four-point bending tests on timber beams are described in the article [34]. Control tests were carried out on an unstrengthened and a strengthened beam (two series of 3 elements). The first was strengthened using one GRP bar and the second using two. Each of the beams tested was different – three bar diameters were used. As with the other studies already cited, the strengthening proved effective. The increase in load capacity is a range of 20 % to 30 %, for stiffness it is 24 % to 60 %.

The paper [35] describes previous studies on strengthening also with GRP bars.
In one study [36], basalt and glass bars were used for near-surface-mounted (NSM) reinforcement. The bars were 8 mm in diameter. The beams had dimensions of 70 mm × 215 mm × 2.30 m. Four-point bending tests were carried out on four different types of strengthening. Two bars were placed in the rectangular grooves on the bottom and the second series on the sides of the section. The third series is made up of two bars that are fixed at the top in the compression area and at the bottom in the tension area. The last group consists of three bars arranged in rounded grooves on the underside of the beam. The strengthening analysed showed an increase in flexural stiffness of 22 % - 39 % and in ultimate load capacity of 33 % - 69 %. The displacement of the beam in the mid-span has been measured. In relation to the reference beams, it increased by an average of 34 %.

Laboratory tests, theoretical tests and numerical tests on glued laminated timber and solid wood beams are given in [37]. The analysis looked at strengthening with compressed steel, basalt and glass bars. The bars were 10 mm in diameter. They were glued in on the sides and underneath (3 bars in section). The increments relative to reference beams are shown in Table 1.

Table 1
The results of prestressed bar reinforcement tests (based on [37])

		Max load capacity	Stiffness
Steel	Solid beams	19.55 %	8.11 %
	Glued beams	34.41 %	13.15 %
BFRP	Glued beams	31.12 %	9.91 %
GFRP	Glued beams	29.04 %	9.70 %

There are many advantages to using composites. These are lightweight, which means they do not add significant load to the supporting structure. They are corrosion resistant, unlike those made of steel. The advantages of composites are the ease with which they can be processed and the possibility of adapting their shape to the geometry of the component to be strengthened. Transporting composite materials does not present many difficulties – the strips and sheets are transported in rolls. Composite bars are coiled and the length of the bar is not important when transporting.

4. Summary

Many types of strengthening have been studied by scientists. The works presented indicate that joints using mechanical fasteners are being displaced by adhesive joints. Well-known steel reinforcements are also being replaced with composite strengthening. This is due to the development of the materials industry, which makes it possible to obtain expected material properties. The studies presented so far indicate the validity of the strengthening described. They are carried out at the local level, as well as across the entire span of the component. This is true for both solid wood beams as well as glued laminated beams.

The analysis of the results obtained shows an increase in the load-bearing capacity of structural elements, an increase in stiffness and a reduction in deflection. Glass and carbon fibre strengthening are the most common.

The article shows the advantages and disadvantages of using steel and composites in strengthening of timber elements. Attention should be drawn to the problems which can be encountered when examining timber elements. Due to material defects in the timber that cannot be seen externally, the test results may differ from the expected. For this construction material, a large scatter in the results obtained is typical.

There is a growing interest in modern design methods due to the satisfactory results. However, these are relatively new developments and require further research.

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Przegląd nowoczesnych sposobów wzmacniania konstrukcji drewnianych

STRESZCZENIE:
Celem tej pracy przeglądowej było przedstawienie nowoczesnych sposobów wzmacniania konstrukcji drewnianych. W pierwszej części artykułu skupiono się na charakterystyce drewna. Jego wzmacnianie jest

konieczne ze względu na szereg przyczyn, które omówiono w niniejszej pracy. W kolejnych punktach opisano wzmacnianie elementów za pomocą stali oraz kompozytów. Szczególną uwagę poświęcono prętom, taśmom i matom kompozytowym. Widoczne jest duże zainteresowanie kompozytami w branży materiałowej. Przedstawiono ich ogólną charakterystykę oraz przeanalizowano ich użyteczność we wzmacnianiu konstrukcji. Z badań wynika, że zastosowanie wyżej wymienionych elementów jest zasadne, a naukowcy planują dalsze badania w tym zakresie.

SŁOWA KLUCZOWE:
kompozyty; konstrukcje drewniane; nośność; połączenia klejowe; wzmacnianie