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Strengthening of the wooden structures

Szymon Ślósarz

Department of Structural Engineering, Faculty of Civil Engineering and Architecture, Lublin University of Technology, e–mail: s.slosarz@pollub.pl ORCID ID: 0000-0001-7786-7436

Abstract: The paper is a review of the literature on the strengthening of wooden structures. The strengthening methods are classified according to their purpose and specifics. The article deals with both traditional methods commonly used and modern methods involving the use of composite materials. The paper also includes description of studies on various strengthening methods as well as the presentation of their results. The author also refers to the causes of the loss of load bearing capacity, causes of wood degradation and wooden structures durability in relation to operating conditions.

Keywords: strengthening, wooden structures, degradation, durability, carbon fiber tapes, glued wood

1. Introduction

Wood as a cheap and widely available material, has been used for ages for almost all types of buildings, varied from small farm buildings to large churches, in which wood is the building material for the whole structure or only its cover. The glue laminated wood introduced nowadays has become a material for the large span roof structures in halls, e.g., sport complex. The main advantage of wood is its low weight, which reduces transport and construction costs, significantly reducing or even eliminating the use of heavy machinery.

Wooden structures are resistant to temperature variability and operation in constantly wet environments. The most of their damage come from destructive biological interactions in unfavorable, cyclically changing, moisture conditions. Safe use of wooden structures, in which destructive processes have already begun, requires repair or strengthening. A multitude of wooden structures types (i.e., ceilings, trusses, walls of wooden buildings, roof structures, and various complex engineering structures) leads to many strengthening methods including classic carpenter solutions as well as methods based on the use of modern composite materials. This paper describes the mechanism of wooden structures damage, and the most popular methods used for strengthening of such structures. Then the results of laboratory tests of strengthened wooden structures are described.

2. Durability of wood and a damage mechanism of wooden structures

It is well known that the wood structure under optimal conditions has a very high durability of up to several hundred years, as shown in Table 1. The table shows that wood can operate for a very long period of time only in stable moisture conditions, i.e., in a dry or wet state. The problem arises when the wood structure works under cyclically changing humidity conditions, and these are the most common for wooden elements exposed to environmental agents.

Table 1. Durability of some species of wood according to [1]

Type of wood	Durability [years]		
	outdoor	in consistently dry conditions	underwater
common pine	20-85	120-1000	80-500
spruce	10-70	100-900	50-100
larch	20-90	300-1800	80-700

Kozakiewicz [1] stated that the natural durability of wood depends on the environmental conditions, the type of wood (species), its structure and chemical composition. Regarding the durability, wood is classified into three groups [1]:

- very durable wood (e.g., oak, yew, larch, robinia, ebony, eucalyptus),
- wood of moderate durability (e.g., spruce, pine, ash, fir, beech),
- wood of low durability (e.g., maple, birch, linden, willow, poplar).

Usually conifer (spruce, pine, fir) is used to make structural elements. Therefore structural elements are made of the wood of moderate durability and they are subjected to degradation.

The main factors causing the degradation of wood are:

- biological agents: bacteria, fungi, algae, lichens, insects, and others,
- physico-mechanical agents: low temperature, variable humidity, mechanical forces,
- physico-chemical agents: light, radiation, high temperature, fire,
- chemical agents: acids, bases, salts, aerosols.

The most dangerous factors causing the degradation of wood are fungi and insects, especially if the wood operates under cyclic environmental humidity changes. Due to these changes, micro-cracks appear in the surface of the wood, in which fungal spores are deposited. Fungi cause the decomposition of wood tissue which in a direct way leads to a reduction in strength parameters. Insects, however, degrade wood in a mechanical way. The insects' larvae that create corridors under the surface of the element noticeably reduce the cross-section of the element [2].

a) b) c)

Fig. 1. Damage to wooden elements: a) structural elements affected by fungi (photo. Sz. Ślósarz); b), c) structural elements destroyed by insects, (photo. Sz. Ślósarz, A. Halicka)

Considering that humidity is the factor favoring fungal and insect attack, the PN-EN 335:2013-07 standard [3] distinguishes five classes of use:

- **1st class** – wood or wood-like material is under a roof, it is completely protected from weather conditions and is not exposed to humidification; the beetles destroying the wood are the biological hazard;

- **2nd class** – wood or wood-like material is under a roof, it is completely protected from weather conditions, however, high humidity of the environment may lead to periodic, but not constant humidification; the beetles destroying the wood and fungi worsening the wood surface appearance are the biological hazards ;
- **3rd class** – wood or wood-like material is not under a roof and is not in contact with the ground, although it is constantly exposed to weather conditions, or it is protected from weather conditions, but it is under frequent humidified; the beetles that destroy the wood, fungi that worsen the wood appearance and fungi that decompose the wood are the biological hazards;
- **4th class** – wood or wood-like material is in contact with ground or fresh water and thus it is constantly exposed to humidification; the beetles that destroy the wood, fungi that decompose the wood and gray decay fungi are the biological hazards;
- **5th class** – wood or wood-like material is constantly exposed to seawater; fungi that decompose the wood and gray decay fungi are the biological hazard.

Insects and fungi action (biological corrosion) leads to reduction of the load bearing capacity of structural elements by reducing the wood's strength. In addition, the degraded fragments diminish the cross-section area, which together with the decrease of the modulus of elasticity leads to the reduction in the stiffness of structural elements. As a result, the deflections of bending elements grow and the stability of the whole structure decreases. Thus, in a relatively short time, the biological corrosion can lead to make the use of the structure unsafe due to the reduction of the load bearing capacity or loss of structural stability.

3. Traditional methods of wooden elements repair and strengthening

3.1. The essence of repair and strengthening

Depending on the technical condition of the wooden element and its destination, the repair or strengthening may be chosen. Repair is made when the original load bearing capacity of the element should be restored, which has been lost due to destructive environmental impact (fungi, insects, moisture) or mechanical damage. If there is a need to increase the load bearing capacity or stiffness in order to reduce the deflection, the strengthening should be performed. Elements are usually strengthened, when it is planned to increase the loads (e.g., loads on ceilings or roofs).

Every repair and strengthening of a wooden element should be preceded by assessment of the range of the zone, which was degraded by insects or fungi. The whole degraded parts should be removed and hewed, and the "healthy" wood should be left. This is the necessary condition for the effective repair and strengthening. The abandon of removing infected parts results in further degradation progress, including new wood fragments.

Thus, the elements destined for repair or strengthening are of reduced area in relation to the original cross-section because of removing corroded parts. The repair restores the parameters of the primary cross-section, and the strengthening is focused on the increase of the load bearing capacity of the primary element.

Repair and strengthening of wooden elements usually concern the flexure zone (in the span) or shear zone (near the support). The purpose of strengthening of a wooden element in flexure zone is most often not only to increase the load bearing capacity of cross-sections, but also to reduce existing or designed deflection. One of the most common damage to wooden ceiling is its excessive deflection. It may be caused by the loss of the cross-section area due to corrosion, but also creep of the wood under a long-lasting high-value load. In this case, besides strengthening by the increase of cross-section, there is a need to "straighten out" and thus to lift up the floor beams in the middle of their span. Usually this is done by use of actuators, previously basing them on the masonry or special steel frames or beams, e.g., when there is a vault underneath the ceiling.

3.2. Replacement of fragments or entire element

In the case of strong corrosion of wooden element, it may be necessary to replace its fragments, especially in the support zones. Ends of a beam are subjected to infestation with molds and fungi, due to the lack or faulty insulation between the wall and the wood and as a consequence of moisture in the wood.

The replaced part of the element can remain wooden – then the old and the new part are connected by screws (Fig. 2).

Fig. 2. Replacement of the rafter support zone with a new wooden part (photo. A. Halicka)

The replacement with steel elements can also be made. For this purpose, small steel trusses are used (Fig. 3a). The one side of truss rests in the wall in the socket, while the other side is attached to the "healthy" wooden beam. Another way of replacing the support zone is to replace the support piece with a steel beam, e.g., a C-profile fixed to a wooden beam on a set of screws on one side and supported on a wall on the other side (Fig. 3b).

a)

b)

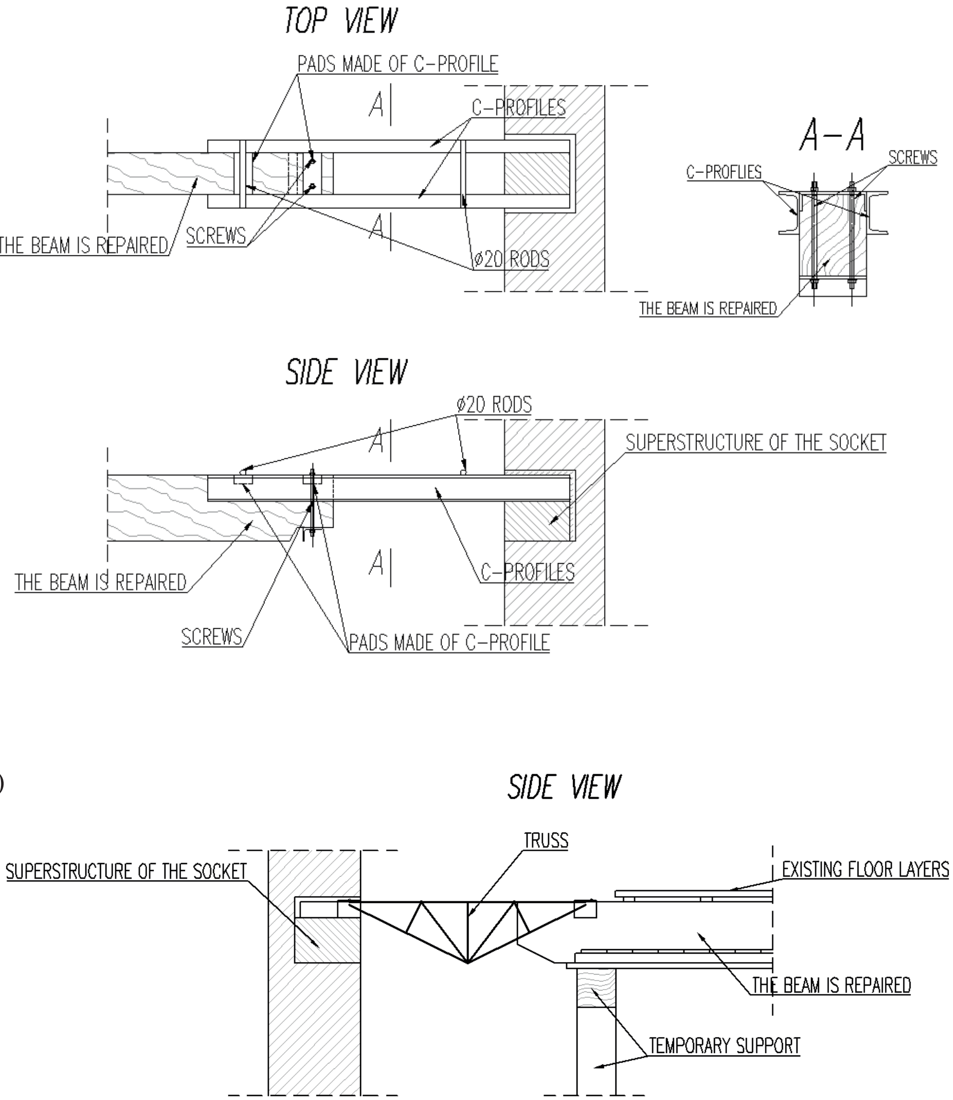

Fig. 3. Replacement of support zones of wooden beams for steel elements: a) truss, b) profiles [4]

In extreme cases, when repair or strengthening to achieve the required load bearing capacity is not possible, additional load bearing elements are introduced, wooden or steel, carrying all loads or loads that exceed the load bearing capacity of left wooden elements (Fig. 4). Another way is to introduce an additional support by undersling the beams in the middle of the span to a wooden beam located perpendicular to the beams (if it is possible to use such a beam).

Fig. 4. Steel load bearing elements taking over the bearing role of original wooden elements (photo. A. Halicka)

3.3. The use of additional wooden elements

The basic and most common way to strengthen and repair existing wooden elements is to increase the area of cross-section by additional wooden elements, which are fixed with mechanical fasteners, usually nails or screws. As a result, the sectional modulus and the moment of inertia of the cross-section increase. The pads can be fixed on the element sides (in the case of strengthening of ceiling beams or beam ends) or on the upper surface as overlays (in the case of rafters and purlins, in which it is allowable to change the height of the beam). In strengthening with wooden pads it is necessary to remember to create the reverse deflection of the beam ceiling made by undercut on the top of the beam and pads.

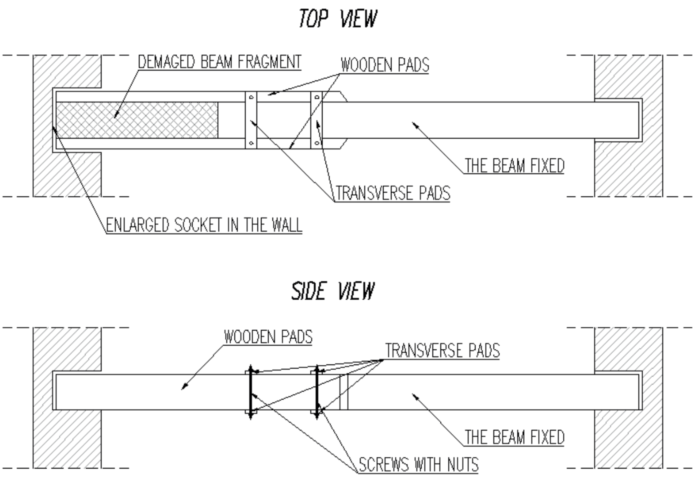

Fig. 5. Strengthening of wooden beams using wooden pads [4]

3.4. The use of additional steel elements

3.4.1. Strengthening the cross-section with steel profiles

Strengthening steel elements are most often used on the side surfaces of the structural member. They can be fastened over the entire length of the element, in order to increase its load bearing capacity, or only on a fragment to replace the damaged part of the cross-section. Linear strengthening is performed by fastening steel elements to the surface of a wooden beam (most often steel elements are placed on both sides and they are twisted together). Connection can be made of screws with nuts in the spacing about 15% of the beam range.

To increase the load bearing capacity, rolled sections are used: angles, C-profiles, and flat bars. Typically, the additional steel element carries the bending moment and the wooden element is treated as not working. The method of linear reinforcement is illustrated in Fig. 6.

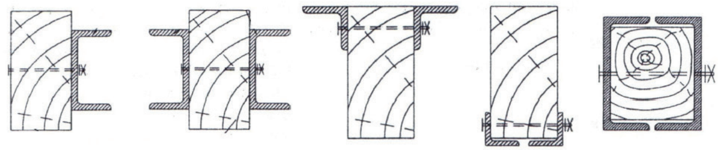

Fig. 6. Strengthening of wooden beams using steel profiles [4]

3.4.2. Strengthening with steel sheets and steel bars

Strengthening of wooden beams using steel sheets and bars consists in making a cutter along the beam into which the epoxy resin is introduced, and the steel bar or metal sheet is embedded into it. This solution does not increase the cross-section, it can be carried out without distraction of this beam surface, which is considered valuable, e.g., for conservation reasons. By the method of gluing steel elements inside beam , both the tensile and shear part in the support zones can be strengthened. The principle is shown in Fig. 7.

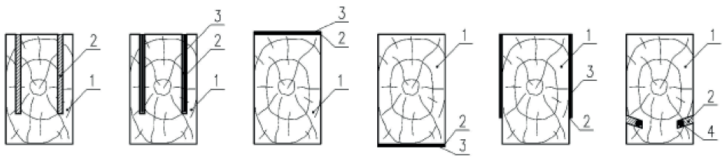

Fig. 7. Strengthening of wooden beams using steel sheets and steel rods [5]; 1-wooden beam reinforced, 2- epoxy composition, 3- metal sheet, 4 –steel rod

In the paper [5], the results of tests were reported, in which the method discussed was applied in different variants (Fig. 7). It was found that the most favorable concerning the increase of the load bearing capacity is the gluing of steel sheets to the side surfaces of wooden beams.

Jasieńko in works [5,6] widely dealt with strengthening of existing beams by steel reinforcement. Similarly to the theory of reinforced concrete, he introduced the steel bars to the tensile zone of a wooden beam. In tests, the deflection of reinforced beams was lesser than the deflection of non-reinforced beams: of about 40% when using single reinforcement (i.e., introduced in a one row) of reinforcement ratio of 1.5% in relation to the cross-section of wood, and 60% when 3% for double reinforcement. The method of steel reinforcement presented in the research [5,6] is shown in Fig. 8.

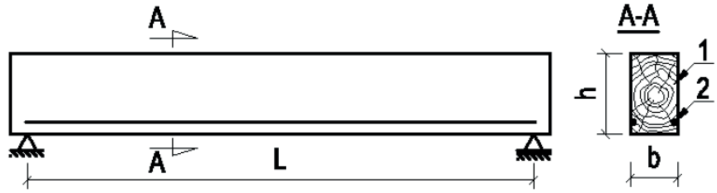

Fig. 8. Strengthening of wooden beams using the reinforcing bars; 1-wooden beam reinforced, 2- adhesive composition with a reinforcing rod, [5]

3.4.3. Prestressing

In the mid-1970s, an attempt was made to transfer the prestressing technology used for concrete elements to wooden structures – prestressing withstands the tensile stress caused by the external load. The steel used for prestressing was a high strength steel. The prestressing was performed by means of wires as well as prestressing steel strips glued to the down surface in the tensile zone. Such a prestressing applied by Peterson [7] resulted in an increase of the load bearing capacity (by approx. 26%), an increase in stiffness and reduction of deflections (by approx. 76%) in relation to non-prestressed beams.

The attempts to introduce preliminary stresses were made by Cyruliński on structures made of the glued laminated wood [8]. It was a structure not only compressed in the tensile zone, but also expanded in the compression zone. The author introduced a special channel routing on the beam sides, ensuring the adjustment of the eccentricity of the compression and tensile forces to the value of the expected operational stresses. The largest increase in ultimate loads of the prestressed-expanded beam in relation to the non-tensioned beam was 48%. The route of the prestressing-expanding bars is shown in Fig. 9.

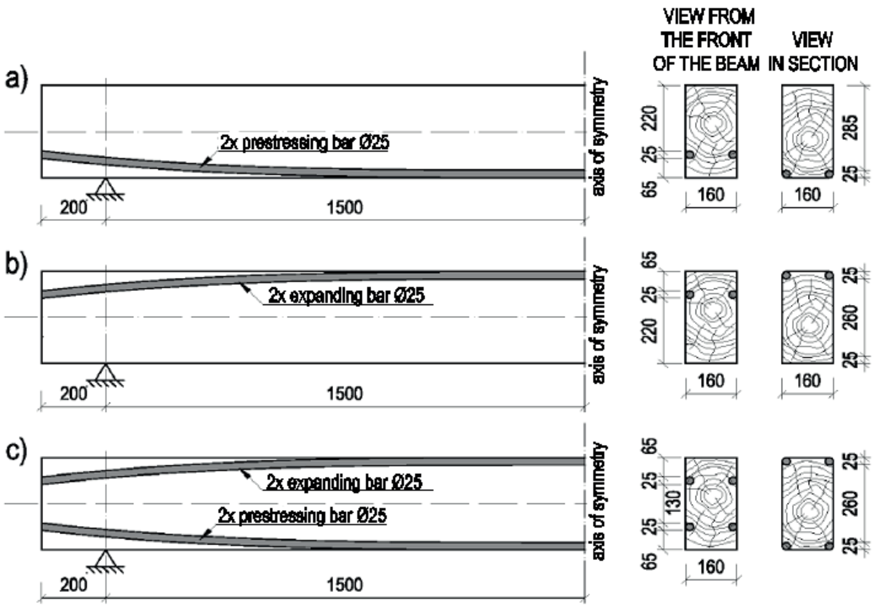

Fig. 9. The course of the routes of prestressed and expanded bars in beams, which were examined by Cyruliński; a) prestressed beam, b) expanded beam, c) prestressed-expanded beam, [8]

The basic problem during the prestressing of wooden beams are the prestress losses. In the wood, with the passage of time, rheological changes occur due to shrinkage and relaxation of wood, which significantly reduce the effectiveness of prestressing. Various studies [9] give a different value of force loss, but they oscillate in the range of 20-25%, which means relatively high losses.

4. Strengthening of wood members using composite materials

The composites (FRP) are used more and more often to strengthen wooden elements. They are materials, in which a matrix consisting of an epoxy resin is reinforced with a fibrous material. Depending on the fibers used, a composite with different parameters is obtained (Tab. 2).

Table 2. Technical parameters of fibers used in composites [10]

Type of fiber	Density [g/cm^3]	Tensile strength [MPa]	Module of longitudinal elasticity [GPa]
E-glass	2.5	2000 – 3500	70
S-glass	2.5	4570	86
Aramid	1.4	3000 – 3150	63 – 67
Carbon	1.4	4000	230 – 240

Research on the strengthening of wooden structures using composite materials has been carried out effectively for both solid wood and glued laminated wood [11-14].

Extensive research in this field was carried out by Nowak [15]. He investigated the influence of the location the composite on the increase of the load bearing capacity of the beam. An important assumption was the insertion of composite to the inside of the beam, which was used to simulate the strengthening of old, antique beams. The tests were carried out on the beams of the 12x22 cm cross-section, using the CFRP tapes, which were glued before loading, both from the top and side of the beam. For comparison, two non-strengthened beams were tested – the A series made of an "old" wood and the G series made of a "new" wood. The scheme of the test is shown in Fig. 10. The beams were loaded to simulate pure bending.

The graph on the Fig. 11 shows the ultimate loads of the tested beams. The largest increase in the load bearing capacity in comparison to series A was recorded for the D series with the tapes on the top and side surfaces (about 79%), while the smallest was for the F series, with tapes based only into the both sides of the beam (approx. 21%).

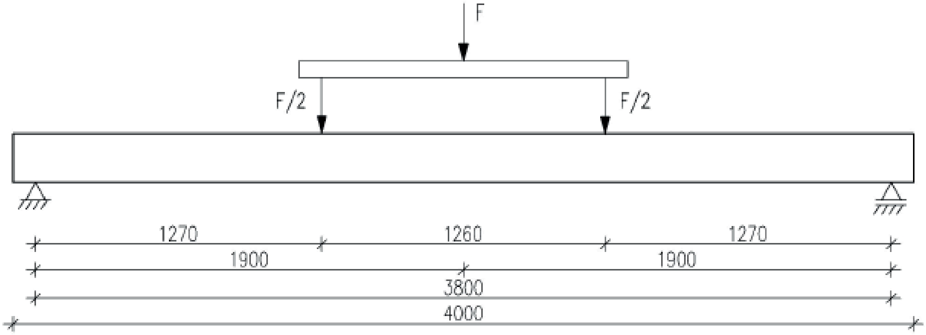

Fig. 10. Scheme of the test stand [15].

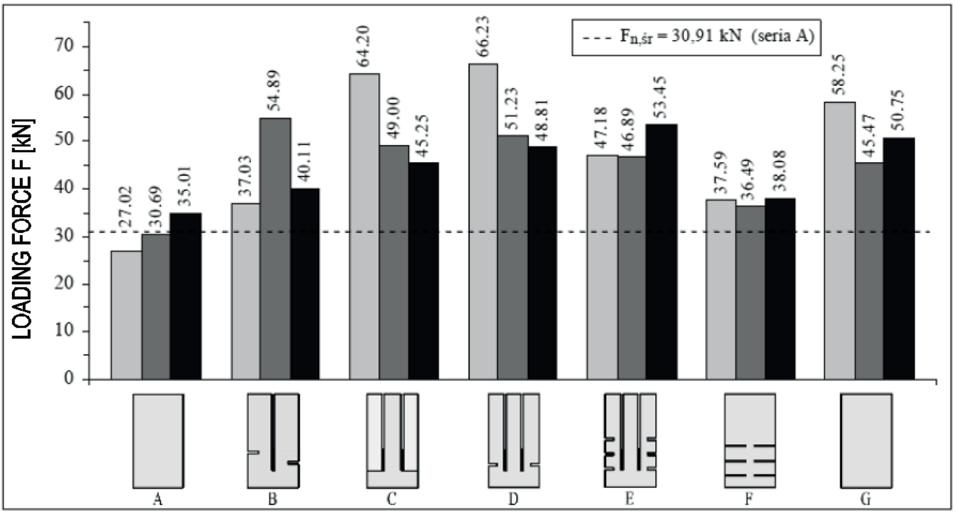

Fig. 11. The results of tests carried out on solid beams by Nowak, [15]

Strengthening of the glued laminated wood using the fiber strips consists of gluing them at the production stage between the last lamellas or on the bottom of the beam. *Brol* [16] performed tests on beams as shown in Figure 12, and obtained an increase in load bearing capacity for GARP strips fastened to the bottom of the beam by 54%, and for reinforcement glued between lamellas by as much as 68% in comparison with non-strengthened beams. He stated that strengthening of the glued laminated wood beams with composite tapes saves even 25% of wood, but the proposed methods are only possible to apply at the production stage.

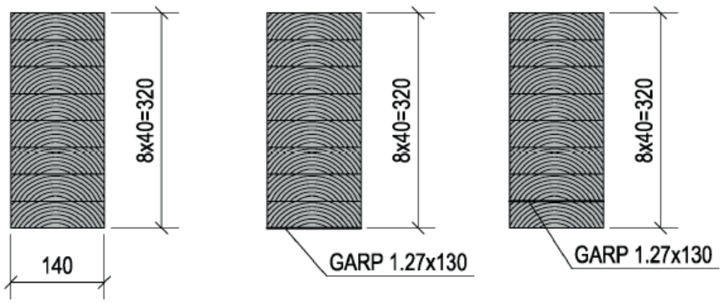

Fig. 12. Types of beams reinforced by *Brol* during the glued wood tests [16]

5. Conclusions

1. The paper presents methods of repair and strengthening of wooden beams in a traditional way and using composite tapes. The main purpose of these methods is to improve the cross-section parameters (depending on the method – increasing the cross-section area, increasing stiffness). In the literature there are studies, which report attempts to introduce initial stresses by prestressing.

2. A common need occurring during the strengthening of wooden beams is the reduction of their existing deflection. It seems that this is possible with use of the prestressing composite tapes. In literature, there is a few case of prestressing wooden beams and typically apply glue laminated wood. There is no case about prestressing traditional wood in current articles so it is a field for further research and analysis.

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