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TIMBER STRUCTURES REPAIR WITH WFRP (WOOD FIBRES REINFORCED POLYESTER)

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ABSTRACT

Considering the degradations that occur in timber structures, including aging processes, a remedial measure, able to mitigate these degradations affecting both structural timber system and wood itself includes the use of a composite system with an innovative application technology.
Polyester resin, with its viscous liquid aspect, impregnates the wood, being absorbed on a 1.5…2.0 mm depth, function of environmental conditions. The interface composed of the impregnated wood becomes a distinct composite material – wood fibres spatially reinforced polyester WFRP, which have higher physical and mechanical properties than wood. This new composite may be created by laying on impregnated wood a coat of wood fibres, also impregnated with polyester resin.
The remedial system may be applied both for total and partial fractured timber structural elements and consists of creating some pockets with diameter measuring 6…10 mm in which are introduced some pins obtained by impregnating a bundle of wood fibres with polyester resin. The extremities of the pins from wood fibres are moulded on the surface of the structural element, in any direction, and then impregnated with resin. Finally, the damaged zone of the wood element spliced with layers from wood fibres, all impregnated with polyester resin, form a spatial cleat, whose sizes are determined by design calculus.
This type of intervention assures a complete rehabilitation of the timber structural element, both from mechanical and geometrical point of view and also maintains the esthetical and historical value of the structure.

Keywords: *Timber structures, Repair technology, Composite materials, Wood fibres reinforced polyester*

1. INTRODUCTION

1.1. General information

The study of composite materials and their effectiveness in industrial processes is following an ascending trend, both on national and international level. Considering the information databases presently available, a detailed analysis of bio-composite materials and their application domains may be carried out. In European Union, the distribution of products involving composite materials shows that construction domain is situated on the second place with approx. 320 thousands of tones, [1].
Wood fibres are basically of cellulosic nature and are extracted from trees, straw, bamboo, cotton, hemp, jute, sugarcane and other sources. Depending on the desired fibres characteristics, the species that is best suited is chosen and the required fibre processing (chemical treatment, heat treatment, mechanical "brushing" or refining, etc.) is carried out.
For timber elements' rehabilitation, of great importance are the involved materials` structures: wood, jute fibres and unsaturated thermo rigid polyester – NESTRAPOL 450, the two latter being used to obtain the hybrid composite material proposed herein.

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1.2. Some aspects concerning wood

Wood is a natural fibrous composite material, as a combination of cellulose long fibres bonded together by lignin. Cellulose fibres ensure the strength of wood, while the lignin plays the role of matrix which stabilizes the fibres into the material`s structure [2-4]. The tree`s chemical structure is the result of biosynthesis reactions of natural polymers: cellulose, lignin, hemicelluloses and their transformations.

The chemical composition of wood structure`s main components are:

– cellulose: $\mathbf{nH\ (C_6\ H_{10}\ O_5)\ OH \rightarrow (n\text{-}1)\ H_2O + H\ (C_6\ H_{10}\ O_5)_n\ OH(C)}$: 42 to 45%, a natural polymer being the main component of the vegetal cellular membrane. The structural unity of cellulose macromolecule is constituted by the anhydrous-D-glucose. The vegetal cell membrane represents a mass of different types of Carbon hydrates that basically constitute a cellulosic fibres reinforced plastic gel, the proportion between the two components presenting little variations. Cellulose is a polymer with rigid chain and quasi-crystalline mono-phases fibrillar structure. Cellulose biosynthesis inside the plant is limited by the influence of steric formations and the vital activity of the cell.

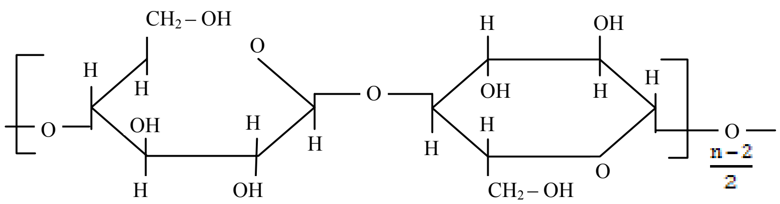
– hemicelluloses is responsible for the biodegradation, micro absorption and thermal degradation of the fibres as it shows least resistance, whereas lignin is thermally stable but prone to UV degradation [4].

– lignin: $\mathbf{n(C_{10}\ H_{12}\ O_3) + 1/2\ nO_2 \rightarrow nH_2O + (C_{10}\ H_{12}\ O_3)_n\ (L)}$: 18 to 33%, is the main aromatic component of vegetal tissues and integrates a group of chemically bonded amorphous macromolecular combinations. The lignin complex presents some characteristic functional groups series: metoxil, hydroxyl and carbonyl.

2. CONSTITUTIVE MATERIALS OF WFRP

2.1. Jute fibres

Jute fibres belong to "vegetal natural fibres" group in which the main component is represented by cellulose, whose structural unit is [5]:



where structural elements are bonded between them, in a chain, by aid of oxygen bridges 180 degrees rotated to each other.

Chemical composition and the moisture content of jute fibres is 61.1 to 71.5 Wt% cellulose, 13.6 to 20.4 Wt% hemicelluloses, 12 to 13 Wt% lignin and 12.5 to 13.7 Wt% moisture content.

Jute fibres present some advantages as being ecological, fully biodegradable, abundantly available and renewable, with reduced costs, non-abrasive nature and safe handling, giving the possibility to be used for repairing timber elements. It also presents good workability with reduced energy consumption, reduced density, factors that are extremely important for being accepted on the markets with high material consumption, as construction industry.

The disadvantages of these types of materials are the limited thermal stability, strength decreasing with increasing humidity and the variation of the material quality depending on the growth season of the plant, which considerable affects the possibility of use these fibres for reinforcing polyesters. High humidity absorption of vegetal fibres and the presence of voids in the interface (porous surfaces) decrease the mechanical properties and reduce the dimensional stability of composite materials reinforced with these types of fibres.

The physical and mechanical properties of jute fibres are the reduced density of about 1.3 g/cm^3, the fibre length of 1500 mm to 3700 mm, Young Modulus of 26.5 GPa; tensile strength of 393 MPa to 773 MPa and elongation of 1.5 to 2%.

2.2. Polyester resin

Unsaturated polyester resin, NESTRAPOL 450-60, is an unsaturated polyesters solution in a monomer, with the role of reactive solvent, to which co-polymerization forms a reticular structure – polymers hardening [6].

Unsaturated polyesters have linear structure, with few lateral chains which have in their structure dicarboxyl acids and diols. Some of the raw materials used in polyesterification contain double chemical bond (-C = C-) which give unsaturated character and come from the (α-β) unsaturated dicarboxyl acids – maleic anhydride, easy to be synthesized in comparison with unsaturated diols.
To obtain the polyester chain, polyesterification of dicarboxyl acids with the diols and adding the diepoxy anhidride is done.
Polyesterification is a chemical reaction to reach the equilibrium and represents the main chemical reaction [7]:

$$HOOC - R - COOH + HO - R_1 - OH = HOOC - R - CO - OR_1 - OH + H_2O,$$

which continues while the water is removed, as secondary product.
Unsaturated polyester resin, NESTRAPOL 450-60, is of orthophthalic type, with high viscosity and reactivity, having maleic anhydride, phthalic anhydride and propylene-glycol components.
Hardening of these resins takes place by co-polymerization of monomers having double chemical bond in the unsaturated polyester chain.
Cold hardening on unsaturated polyester resin is frequently applied for manual processing for repairs and is ensured by using a redox system formed by cobalt salt – ketone peroxide. In this case, the polyesters have longer gelling time and the hardening process proceeds more slowly.
Post-polymerization of hardened resin with cobalt accelerator substantially shortens its maturation period.

2.3. Wood fibre reinforced polyester

Vegetal fibres reinforced composites may be considered in the frame of composite materials in which the fibres ensure the strength and stiffness of the material and unsaturated polyester resin represents the matrix, which transfers the stresses between fibres and throughout the composite. The matrix also re-distributes the stresses in the composite when some of the fibres are broken.
The criteria of choosing the jute fibres for repairing timber construction elements are based on the similar mechanical properties and compatibility of these two materials.
The proposed repair solution is based on the relation between resin/wood and resin/vegetal fibres respectively. Thus, the wood fibres (of cellulosic nature) and polyester resin is considered to have good compatibility because the resin, as it is less viscous, may be absorbed by wood, creating a composite material wood-synthetic resin. This material created at the wood-resin interface has superior shear bond strength than wood fibres-lignin interface. On the other hand, the existence of some degree of compatibility (mechanical, chemical, physical) between the jute vegetal fibres (also of cellulosic nature) and polyester resin, allow the creation of an independent composite material with unitary structure and with a-priori determined mechanical properties. For this type of material, three points bending test were performed, specific to composite material plates, considering that the repaired timber element is also loaded in bending.
Associating wood – synthetic resin for obtaining a hybrid composite, some disadvantages of natural wood, like natural defects, dimensional instability, reduced resistance to photo-bio-chemical attack, may be prevented [9-11].
Producing and processing technologies of hybrid composite material is manual – contact technology.

3. TESTING PROGRAM

The main objective of the testing program is to determine the mechanical properties of the hybrid bio-composite material obtained by impregnating jute fabric with polyester resin and the effect of repair applied to the broken natural timber, using this type of material.
The experimental program is carried out in three steps: three points bending test of the hybrid bio-composite of polyester resin – jute fabric type; the behaviour of the resin/wood respectively resin/jute fabric interface; application of the hybrid bio-composite on two spruce timber elements – both of them being loaded in four points bending, one of them being fractured and the second loaded with a force of 16 kN.

3.1. Three points bending test of the hybrid bio-composite specimens

For the hybrid bio-composite specimens, three jute fabric layers impregnated with polyester resin were used. It is stated that jute fabric is made of untwisted yarns and is of unbalanced type: the warp is represented by one jute yarn, while weft has two jute yarns, the difference between these two being of 55% weft to 45% warp, gravimetrically measured. The rare fabric has 2 × 3 mm mesh size, the small difference of fibres on the two directions being explained by the use of one bigger width strands in warp, and two smaller width strands in weft, the warp loosing some of the fibres quantity during weaving process by friction.

From the hybrid bio-composite plate, of 500 × 360 mm, 16 specimens were cut and processed in accordance to ASTM Standard D 7264-07, "Flexural properties of Polymer Matrix Composite Materials". The specimens` length and the distance are established function of the width of the plate. For the plate, 709 g of NESTRAPOL 450-60 polyester resin and 140 g of jute yarn fabric were used, resulting a reinforcing percent of 20%. The plate was kept in standard conditions, respectively 20 ±1°C temperature and 65% interior moisture, for hardening and maturation of the resin, for 14 days.

The testing equipment is a Computer Control Electro Hydraulic Servo Universal Testing machine with a maximum applied load of 600 kN. The applied loading speed was of 0.5 kN/sec. The specimens were loaded until failure and the force-displacement resulted diagrams were obtained (Fig. 1).

After processing the data, the stresses and strains at failure and the elastic modulus were computed. From the diagram presented in (Fig. 1), it may be seen that, by increasing load, some of the jute strands with smaller cross-sections successively break, fact that is emphasized by abrupt changes in the diagrams. The polyester resin overtakes and redistributes the stresses to the still working strands. Finally, the failure occurs simultaneously by breaking the fibres and crushing of the resin. No detachment or pull out of the fibres from the matrix are observed.

For the tested bio-composite material the results obtained are: maximum normal stress I8 of 78.125 N/mm^2 and the maximum strain of 3.026%. The maximum obtained modulus of elasticity is 4702.702 N/mm^2.

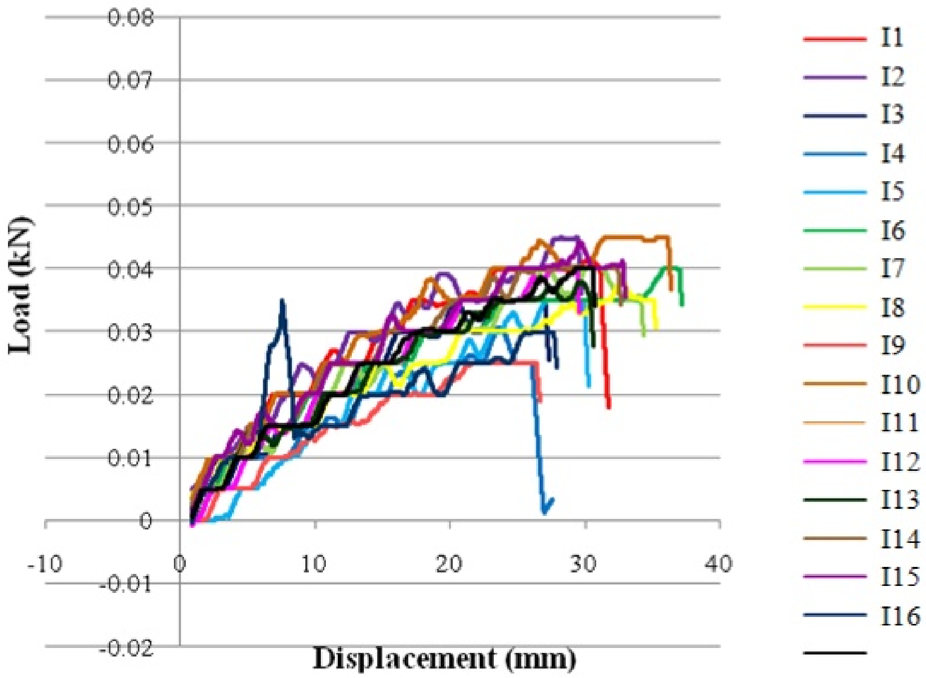
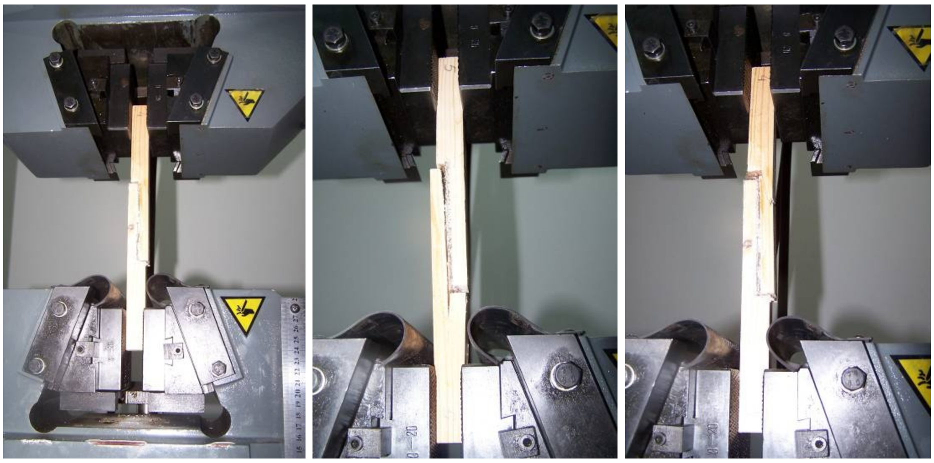


Fig. 1 Load – displacement diagram of the hybrid bio-composite specimens

The mean values of the normal stress, strain and modulus of elasticity are of 63.885 N/mm^2, 2.586% and 3929.168 N/mm^2, respectively.

3.2. Shear bond strength of the wood – bio-composite material interface

The second stage of the experimental program consists of determining the shear bond strength of the bio-composite material to the support (meaning wood). A number of ten specimens of spruce wood were carried out and processed, with the dimensions of 20 × 20 × 300 mm. At the middle third, on a length of 100 mm, the two pieces of wood were bonded together by aid of two layers of jute fabric impregnated with polyester resin, the same material used for the repair technology. After bonding, the elements were pressed and kept into position for hardening and maturation for 14 days. The specimens were tested in tension with an application load speed of 0.1 kN/sec.



a) b) c)

Fig. 2 Wood specimens tested in shear bond strength; a) test setup; b) c) type of failure

The objective of the testing program is to determine the shear bond strength at the interface between wood/bio-composite materials. The experimental results obtained are plotted in a load-displacement diagram, presented in (Fig. 3).

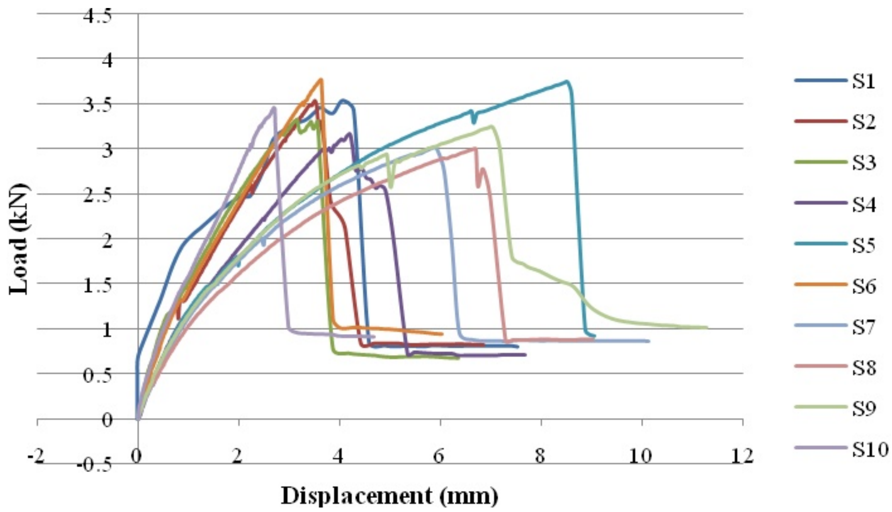


Fig. 3 Load – displacement diagram of the wood/bio-composite material specimens loaded in tension

By the test setup presented here, at the interface between the two materials, shear stresses occur, which describe the mechanical properties of bond strength of the two phases. By processing the obtained results, for the maximum applied load of 3.765 kN (S6) a shear stress of 1.8825 N/mm^2 was computed.

The failure modes are presentd in a detailed view in (Fig. 4).

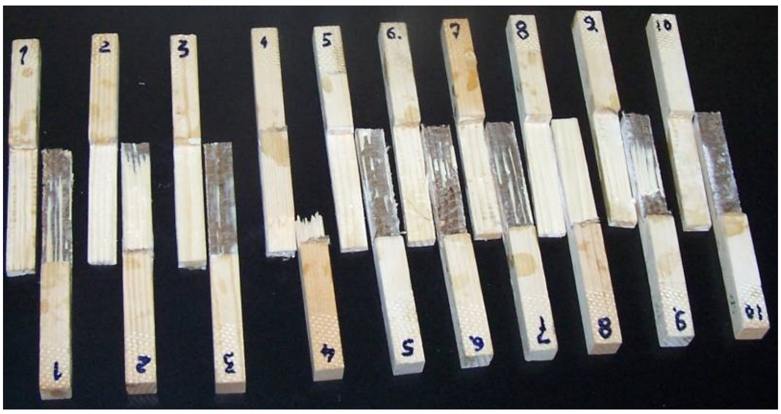


Fig. 4 Failure modes of wood/bio-composite specimens subjected to tension

It may be observed that the specimens failure occurs by pulling out of the wood fibres in the material with weaker matrix (lignin). None of the specimens showed detachement of the wood from polyester resin or from the hybrid composite and also the hybrid composite is not affected by any deterioration. This is due to the fact that the resin gets into the wood`s mass on a certain depth, forming a transition zone between wood and the bio-composite material. The failure occurs by pulling out the wood fibres, see specimens S1, S3, S5, S7 and S9 respectively. When the longitudinal shear stresses in wood are smaller than the stresses at level of the wood/resin interface, the specimens failed in the wood section, see specimens S2, S4 and S8. In only one case the detachment of the composite material from the wood took place because the resin didn`t sufficiently impregnated the wood, specimen S10.
A special behavior was that of specimen S4 where the bonded zone remained intact, while the failure occured in the wood section as a result of the tension stresses paralel to the grain.
As a conclusion, the good compatibility between wood, jute fabric and NESTRAPOL 450-60 unsaturated polyester resin may be emphasized.

3.3. Four points bending test of timber beams repaired with WFRP

The third step of the experiments consisted of assessment of the effect of the proposed repair method on structural timber elements using the hybrid bio-composite material. Four timber beams with the cross section of 45 × 150 mm and the length of 2600 mm were used. The testing device has the roller supports at 2400 mm distance and the loads are applied symmetrically to the beams middle cross section, at 800 mm between them.
The testing program consisted in two stages:
First stage – the four timber beams, G1 to G4, were loaded in bending until failure occurred, for estimating the ultimate force and the maximum displacement.

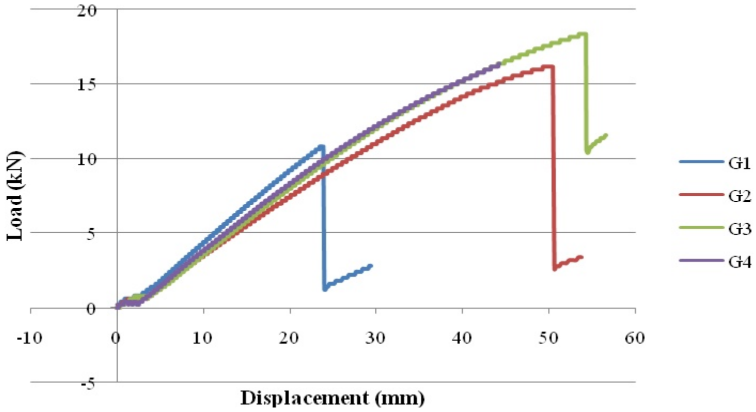


Fig. 5 Load – displacement diagram for timber structural elements

The high no homogeneity of the wood led to choosing for continuation of the experiment only two beams with almost identical evolution: G3 beam loaded until failure and G4 beam loaded until reaching 16 kN, a load level where some of the wood fibres started to brake, but the failure of the element didn`t occur. The loading speed was of 0.1 kN/s. In (Fig. 6) are showed failure modes of each timber beam, in the order in which they were tested.

Fig. 6 Four points bending test of timber beams; test setup and failure modes

The second stage consisted of repairing the two G3 and G4 beams by applying a bio-composite system on a length which covered the deteriorated zone with 100 mm one side and another and for the G4 beam the system was applied on the entire zone of maximum bending moment, with 100 mm one side and another, (Fig. 7).

The repair technology of the G3 beam consisted in filling the cracks with polyester resin and straightening the beam to come as closely as possible to the initial shape. The detached parts of wood were fixed with steel nails. After 24 hours, on the cross section's height, along the beam, some 6 mm diameter holes were drilled every 200 mm starting from 50 mm from the repaired zone ends. Through these holes some bunches of jute yarns (24 strands) were introduced and left 100 mm outside the holes on both sides of the element. The yarns were then impregnated with polyester resin and the extremities of thus obtained pins are moulded on the surface of the structural element, previously covered with polyester resin, in any direction. By introducing these impregnated yarns, the resin filled the holes and was absorbed in the wood mass, as described in the previous paragraph, creating some pins with the role to overtake and transmit the stresses from the wood to the hybrid bio-composite.

Fig. 7 G3 and G4 beams repaired with the bio-composite system

On the surface thus prepared, the timber element was wrapped with three layers of jute fabrics, impregnated one after the other with polyester resin using the manual "contact technology". To keep the jute layers in the desired position, after impregnation, each layer was tighten with jute strands and slightly tensioned for ensuring a uniform contact between the timber element and the layers of impregnated jute.

The repaired element was loaded in bending, in the same conditions as previously and the load-displacement diagrams were recorded. In (Fig. 8) the diagrams of the timber element and the repaired one are comparatively presented.

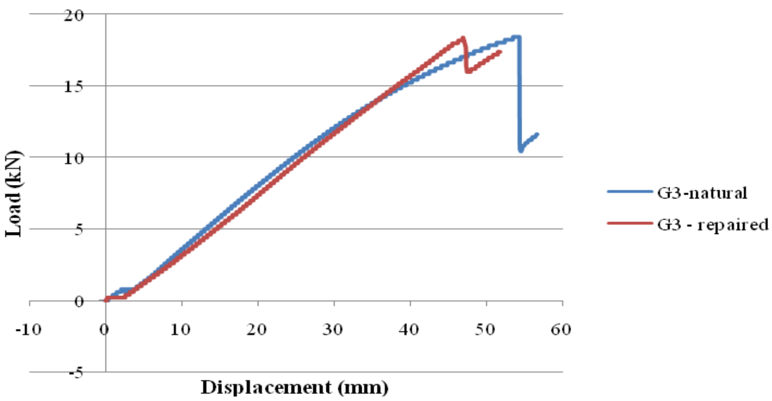


Fig. 8 Load-displacement diagram for G3 beam

By applying the system proposed herein, it may be stated that the hybrid bio-composite completely restores the behaviour of the timber beam in bending by overtaking the stresses and releasing the deteriorated wood. The maximum load at failure recorded for the G3 beam both for natural timber and the repaired element is of 18.4 kN. The maximum displacement of the repaired beam corresponding to the maximum load is of 46.827 mm, compared to 54.185 mm of the natural timber beam. The failure occurred in the applied bio-composite material.

In the case of G4 beam, by associating timber with the hybrid bio-composite, the bearing capacity of the timber element was obtained. The applied technology is the same as for the G3 beam. In the original timber element, for the 16 kN load a 43.218 mm displacement is recorded. For the repaired beam, the failure occurred at 25.8 kN with a corresponding displacement of 69.774 mm, (Fig. 9). It may be seen that in the two situations, G4 natural and G4 repaired, the beams work basically in the same way until the loads reaches 10 kN with the corresponding displacement of 23.6 mm. With load increasing the natural timber element enters the elastic-plastic domain, while the repaired G4 beam reaches the non-elastic domain at a load of 20 kN with a corresponding displacement of 46.165 mm. The loading was stopped when the displacement exceeded the available space for the deformation to take place.

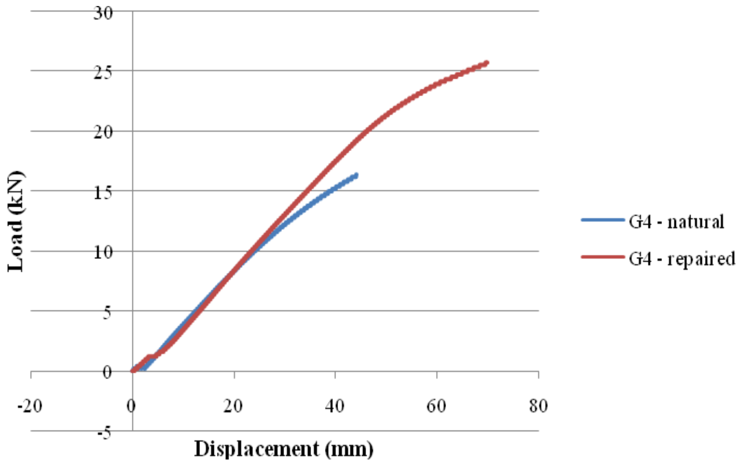


Fig. 9 Load – displacement diagram of G4 beam

By processing the obtained data, the contribution of the hybrid bio-composite made of three layers of jute fabric is significant, considering the 30% increase of the load bearing capacity of the timber element.

3.4. Conclusions of the experimental program

Considering the results of the tests carried out some conclusion may be mentioned:

- the hybrid bio-composite applied in three layers on the broken timber structural elements has the capacity to restore its initial bearing capacity;
- analysing the fracture modes it may be considered that resulted stresses describe more the adherence of polyester matrix both on wood and vegetal jute fibres;
- repaired specimens demonstrate how, in a first stage, the wood split in the initial broken section, the failure of specimens occurring mainly in the hybrid bio-composite;
- it also may be observed the high compatibility between wood and the hybrid bio-composite material.

4. CONCLUSIONS

Considering the biodegradable and renewable character of the wood fibres, they became an important alternative for creating composite materials used in construction domain.

The bio-composite material "unsaturated polyester resin – jute fibres" give the possibility to repair damaged structural elements untill restoring the original bearing capacity and, on the other hand, to considerably increase (30%) the load bearing capacity in the case of undeteriorated structural timber elements. By associating wood – jute fabric reinforced polyester the stiffness of the structural timber element also increases with a 15% percent.

In the repair method proposed herein, the pins have the role to replace steel bolts currently used for wood joints. The advantage of the composite pin is to restore the natural wood structure by removing local stress concentrations surrounding the holes. As demonstrated in the work by tests conducted on wood – WFRP, the proposed repair technology doesn`t induce supplementary stresses in the initial structure. By stress analysis may be stated whether the restoring of bearing capacity of the element is desired or increasing the load bearing capacity of the element is necessary. The repair solution proposed is efficient and easy to apply for highly damaged structural timber elements.

Due to the similarity of the structure of wood and respectively jute fibres reinforced composite, the unsaturated polyester matrix ensures the adherence between the component materials as for wood itself.

As a concluding remark, this type of material may be successfully applied for rehabilitation of hystoric structures, for structural timber elements which are difficult to replace. This type of intervention does not induce supplementary stresses in the original element, and doesn't significantly influence the behaviour of the entire structure.

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