3D woven fabric with cross rib as a composite reinforcement

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Abstract A woven 3D composite is a new type of an advanced construction material. A prototype of three dimensional (3D) textile based on combination of a flat textile with two intersecting tunnels with a rectangular cross-section was constructed and the feasibility of this type of weaving was studied. Prototype of 3D woven fabric was made.
Based on 3D textiles preforms composites for the mechanical trial was made. Composites used for strength tests were made using a vacuum infusion method. The basic elements of the composite, that is the flat part and the element with the rib, were selected for testing. This selection resulted from a complicated process of making a composite based on the entire fabric. A 3D composite, created through the lamination of two flat fabric, was also made for comparison. The study compared the material strength with and without rib reinforcement. Tensile and bending test was made. The analysis of the third composite was aimed at demonstrating the purpose of implementing the complicated weaving process.
The laminate reinforced with 3D fabrics made from a unified weaving process is characterised by the best mechanical properties of the tested variants. The results can be considered to be encouraging.

***Keywords*— bendning test, composite, flax fibres, 3D textile.**

I. INTRODUCTION

Three-dimensional (3D) fabrics play an important role in the development of advanced composites reinforced with textiles. These fabrics are used as shaped elements ready for impregnation with resins, or as thicker materials with structural durability, which - following impregnation - gain a high durability against interlaminar shearing — that is better than in conventional laminated products [6].

Three-dimensional woven fabrics possess a third dimension — thickness (the dimension relative to the Z axis), which is significant in relation to dimensions X and Y. The yarns are interwoven with each other in all three directions X (longitudinal), Y (transverse), and Z (vertical) [1]. According to Chen, structures that have a fundamental dimension in their thickness direction, that is formed by a layer of fabric or yarn layering, are generally referred to as three-dimensional (3D) textiles [6]. 3D fabrics can be understood as thick multilayer fabric with a simple regular form, o as structure made of more complex shapes — that is, multilayer fabrics containing hollow spaces [9]. Khodar defined woven 3D products as fabrics, whose constituting yarns are to be arranged in a tripartite-perpendicular relation [5,10,11].

What we currently define as three-dimensional fabrics may have a generic 3D shape, a more complex internal structure, or both of these features. Besides weaving methods, 3D textiles can be made via means of knitting and breading or by obtaining non-woven fabrics [5].

Strengthening a composite with 3D fabrics can overcome problems related with thickness and low interlaminar strength, which are typical of traditional laminates using 2D fabrics, and have been known for many years. At present, the application of 3D textiles in composites is not only aimed at improving their mechanical properties, but also at reducing production costs and integrating a greater amount of functions in the component [2].

A woven 3D composite is a new type of an advanced construction material. In the case of technical textiles, most of them are used in specialised markets (i.e. aviation and automotive industries) where the requirements concerning durability and efficiency of textile composites are high. The most important applications of fabric-based composites are as stiffeners for Joint Strike Fighter air inlet panels, Beech Starship aircraft wing joints and carrier's cones. Reinforced layered fabrics are also used as floor plates for trains, and hard skeletons for delivery vans and fishing boats. Composites based on 3D fabrics have found application as tapes, fan blades in gas turbines or helicopter blades; while on the military market they are used - among others – as reinforcement of vehicle armours. In addition, they are used in the construction industry or in the sports goods market [5].

A potential market for the introduction of fibre composites is the urban furniture industry, whose goods are expected to have high durability. Urban elements are subjected to intensive usage and are exposed to high and low temperatures. Urban furniture, left unattended, is often vandalised.

3D fabrics were designed in order to increase the mechanical strength of seats and tops of urban furniture, allowing to withstand greater forces than traditional products, thus improving the lifespan of the furniture. The proposed shape is a flat fabric reinforced with two intersecting tunnels with a rectangular cross-section.

II. Design of a 3D fabric

A. *Combination of a flat textile with two intersecting tunnels with a rectangular cross-section*

The proposed 3D fabric envisages the combination of a flat textile and two intersecting tunnels with rectangular cross-sections. The proposed design's notion sees the span-reinforced composite panel as able to carry higher loads, thus allowing the elimination of certain steel or wood (frames and joints) elements in the production of furniture. By employing a composite product as a seat/table top, the weight of the product is lowered and its mechanical strength increases, which could potentially favour the assembly of such furniture within urban spaces, bus stops or stadiums. The shape of the seats and tops can be any, though they are most frequently square or rectangular. As a result, the furniture is easy to arrange and set up in both a closed and open space. For the purpose of creating a prototype, a square shape was adopted.

The virtual model of a 3D fabric depicted below, has been reinforced with two intersecting ribs (Fig. 1). The designed ribs have the form of tunnels with square cross-sections. In principle, the rib's inner canal should be empty, to reduce - among others - the mass of the composite. 3D fabric with a tunnel will full structural filling would be easier to produce (i.e. using an orthogonal loom). Such a structure would, however, lead to problems at the fabric laminating stage — the resin could have difficulty infiltrating into the depths of the fabric, thus not all fibres would be impregnated. Moreover, the occurrence of large areas of resin only would be a danger, which would have a weakening effect onto the structure. The rods inserted into the tunnels will allow to preserve the rectangular rib shape. In the case of filled tunnels within a woven structure, the use of a void could deform the originally established shape. The designed fabric is asymmetrical — the left side is a flat fabric, while on its right side there are convex ribs in the aforementioned cross shape (Fig. 2). It is a homogeneous product characterised by a differing thickness in specific places.

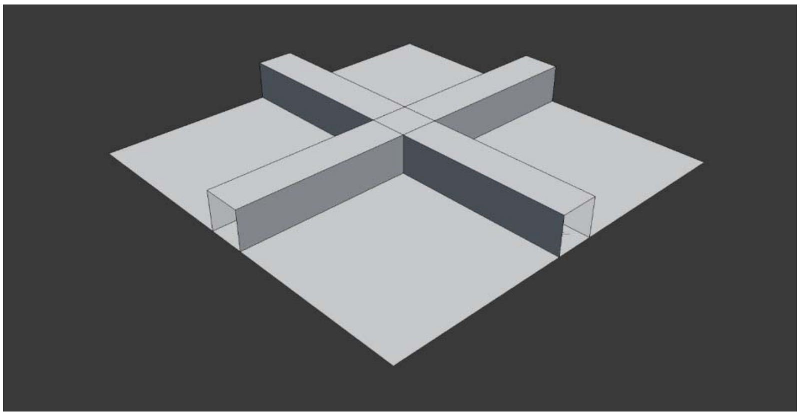

Fig. 1. Virtual 3D fabric model

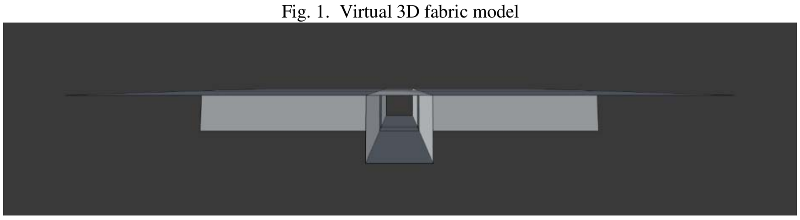

Fig. 2. Virtual 3D fabric model

B. *Material*

In the case of trials for strength tests, based on the conducted analysis of flax yarns, yarns of 100 tex linear mass were used as a warp, and 2000 tex roving as a weft. Roving of a mass of 2000 tex is characterised by a high breaking force fluctuate at around 120 N. The 100 tex yearn was considerably thinner and had a larger twist, allowing for it to be properly tensed and stretched over the frame. Its strength was about 4N.Both yarns were produced by the Safilin company.

C. Manufacture of a 3D fabric

With the currently known technologies it is not possible to manufacture such a fabric on a mechanical loom. To be able tomake ribs in both directions, three warp systems would be necessary: 1) lower layer warp — co-creating both the flat element and the tunnel walls located on the left side of the fabric; 2) upper layer warp — participating in the weaving process of the flat element and the convex part of the horizontal tunnel (creating an overlay equal to the width of three tunnel walls); 3) a warp creating the tunnel perpendicular to the direction of the warp. A fabric made on a mechanical loom equipped in a three warp system would still fail to meet the criteria. At the intersection of tunnels, inside the ribs, there would be non-woven threads ofweft and warp, that would impede the introduction of moulds. As a result of this, it was necessary to develop a method offabricating the fabric, that would reproduce the project as faithfully as possible. The design required the mounting of three warps systems onto the frame: the lower layer warp, the upper layer warp and the warp making a tunnel in a parallel direction tothe warp. The warp forming the vertical tunnel should be mounted so that the threads lay parallel to the walls of the mould. The creation of a parallel tunnel in regard to the weft is possible by making an overlay in the upper layer and then joining the upper and lower layers. The size of the overlay in the upper layer should equal to three widths of the rods wall, a fragment equal to the width of one wall of the rod should be woven in the lower layer. The weaving of the flat part with the vertical tunnel should be carried out in accordance with the study report (Fig. 3). By retaining the set order, the fabric's growth is the same forthe flat textile and the tunnel.

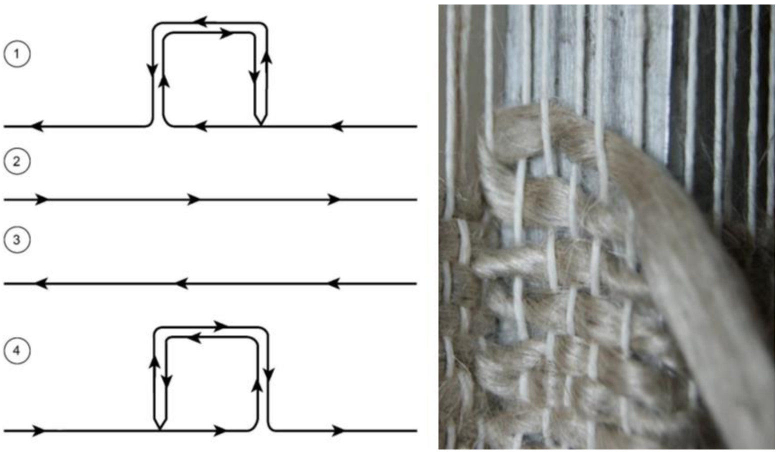

Fig. 3. Weft intromitting cycle for a flat textile with a vertical tunnel. Numbers 1 to 4 refer to the next steps in weaving the vertical tunnel. The left photo shows weft intromitting –step 1.

Fig. 4. Flaxen prototype of the 3D fabric based on a combination of a flat textile and two intersecting tunnels with rectangular cross-sections

D. Manufacture of a composite

Composites used for strength tests were made using a vacuum infusion method, employing a vacuum pressure to press in the resin for the lamination of a textile product. The dry materials are laid on a previously prepared surface and covered with a rigid or flexible film membrane, which is sealed around the perimeter of the mould. A vacuum is produced before the resin is introduced. Only after obtaining a vacuum equal to 1 Bar the resin is sucked into the laminate via inserted tubes. Infusion is considered as a process of closed forms. Vacuum lamination significantly improves the relation of fibre to resin, allowing to obtain a stronger and lighter product. When making the composite, epoxy resins were used.

III. EXPERIMENT

A. Three-point bending of flat laminates of flax fibres

The samples were evaluated for determining the flexural properties under three-point loading (Method A). This is a test dedicated for products made of fibre-reinforced thermoplastic and thermosetting plastic composites. It was carried out in accordance with the norm: PN-EN ISO 14125:2001 Fibre-reinforced plastic composites — Determination of flexural properties.

During the test, the sample - fixed in the form of a supported beam - is subject to bending at constant speed until fracture or until the deformation value reaches the desired quantity. As part of the test, maximum tension stress, modulus of elasticity and deformation on the external surface of the sample are determined. The tested samples were classified into class II materials, and in accordance with the recommendations regarding the types of moulds tested with method A (bending in a three-point system) their length was > 80mm and width 15 ± 0,5mm. The average thickness of the samples is 1,702mm. The tests were carried out on the INSTRON 4485 strength machine in the Laboratory of Strengths of Materials and Structure of the Łódź University of Technology.

During the tests spacing between supports was equal to 80 mm, initial force amounted to 1N and speed of deformation increment was 5mm/min.

The fabric for testing was made of yarns of various linear masses — 100tex warp, 2000tex weft. By studying flat samples in both directions it is possible to analyse the effect of the yarns linear mass on the composite's strength. The experiment was aimed at demonstrating the differences in bending stiffness of the composite along the warp and weft resulting from different linear masses of the used yarns.

B. Three-point bending of 3D laminates

The designed 3D fabric would serve as a reinforcement for seats and table tops of urban furniture. Thus, the ribbed fabric has to be analysed for its mechanical properties. The basic elements of the fabric, that is the flat part and the element with the rib, were selected for testing. This selection resulted from a complicated process of making a composite based on the entire fabric. A 3D fabric, created through the lamination of two flat fabric, was also made for comparison.

The three-point bending test was carried out on three laminates, all 9,5cm wide and 18cm long: flat (P), shaped - reinforcement woven in one single process (K1), shaped - created from two singular fabrics (K2).

(P) — flat laminate of single-cloth flaxen reinforcement with plain weave (Fig. 5);

(K1) — flaxen fabric laminate with a square cross-section tunnel. The reinforcement was made in a uniform weaving process in accordance with the afore-described production method;

(K2) — composite based on two flaxen fabrics (single fabrics with plain weave), which, during the laminating process, were formed into a shape analogous to the reinforcement of composite K1 (Fig. 6).

The study compared the material strength with and without rib reinforcement. The analysis of the third composite (K2) was aimed at demonstrating the purpose of implementing the complicated weaving process.

During the tests spacing between supports was equal to 120 mm, initial force amounted to 10N and speed of deformation increment was 10 mm/min.

Fig. 5. Three-point bending test of a flat laminate

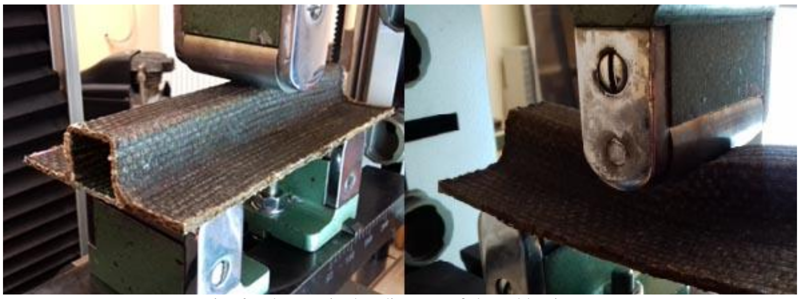

Fig. 6. Three-point bending test of shaped laminates

IV. RESULTS

A. *Three-point bending of flat laminates*

Lower flexural strength is characterised by samples tested for yarns with 100 tex linear mass, warp (Fig. 7). Laminate is characterised by a greater flexural stress along the weft. (63,52 MPa). It is more than three times higher than for the tested samples along the warp line (19,55 MPa). The modulus of elasticity along the weft (5131,52 MPa) is likewise three times greater (Fig. 8). The strength of a material is dependent on the testing direction and the internal positioning of the fabric threads. This is due to the use of yarns with different linear weights — weft (2000 tex) and warp (100 tex). Yarn with a higher linear mass influences better strength properties. In order to obtain uniform results for both axes, the same warp and weft should be used.

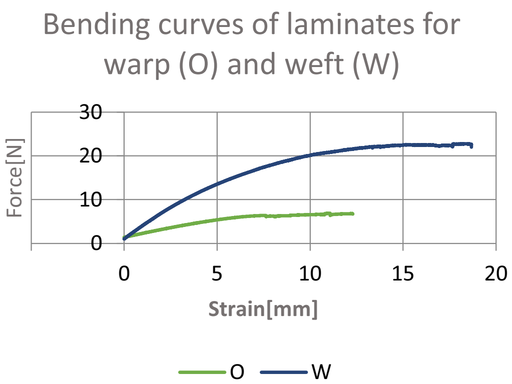

Fig. 7. Graph of bending curves of laminates for average values in both directions

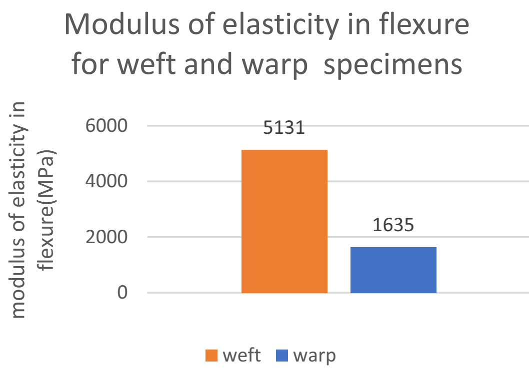

Fig. 8. Average modulus of elasticity in flexure trials along weft and warp

B. *Three-point bending of shaped laminates*

The laminate reinforced with 3D fabrics made from a unified weaving process is characterised by the best mechanical properties of the tested variants (Fmax = 1122.25 N). The laminate formed from two single fabrics was characterised by a significantly lower flexural strength (809,25 N) (Fig. 9).

In the process of 3D weaving the weft threads are interwoven from the beginning so that they are arranged according to the premise. This results in a greater percentage of micro-structural yarn defects, but provides less internal stresses. The fabric formed into a suitable shape at the stage of lamination is subject to an unnatural arrangement of it. In the critical spots, that is at the bends, stresses occur which lower the mechanical strength of the final material. Strengthening in the form of a tunnel leads to an increased stiffness of the composite. The highest load force for the 3D fabric (1112,25 N and 809, 25N) is even several times greater than for a flat one (86,24N). After exceeding the limit of flexural strength, the samples did not break, however the upper support began to dent into the sample. Few cracks in the structure around the working load appeared in both the structures of the shaped laminates and the flat product.

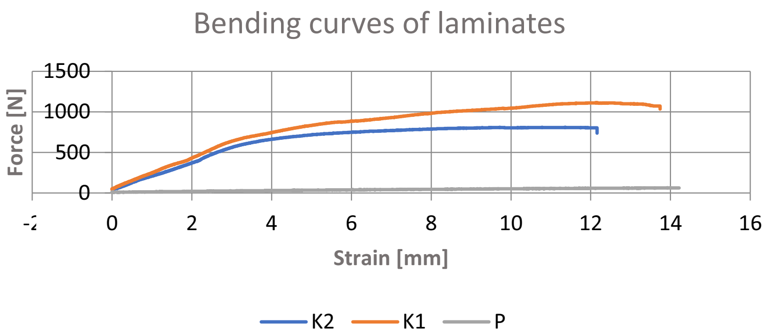

Fig. 9. Graph of bending curves of laminates

V. Conclusion

The bending stiffness of the material along the roving with a larger linear mass (2000tex) is greater than for threads with a lower mass (100tex). With the increasing of linear yarn mass the stiffness of the product increases. In order to obtain similar characteristics in both directions of the study (along the weft and the along the warp) the same yarn should be used in both arrangements.

Higher flexural strength was demonstrated by a laminate reinforces with a 3D fabric made in a unified weaving process. In a 3D laminate made of two fabrics, higher internal stresses occurred in the critical places (wall fractions) which influenced the decrease of the product's stiffness.

Laminate made of a single textile without ribbing demonstrates very low stiffness and poor strength properties compared to both 3D composites. The bending stiffness of a laminate reinforced with a 3D fabric is even several times higher than for a flat laminate. This fact proves that reinforcement in the form of a rectangular tunnel significantly increases the flexural strength of the composite.

Little cracks appeared in the tested composites in the places with the highest load. At the critical moment, when F>F max, the tested 3D composites did not break — the upper support began however to dent into their structure. Composite based on two flaxen fabrics formed in the laminating process is characterized by a lower bending stiffness than a composite based on a shaped fabric made in one weaving process.

The research of polymer laminates reinforced with flaxen fabric described above gives hope for the potential use of these shaped composites in the technical industry. To make this possible, further mechanical tests should be carried out.

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