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DESIGN AND APPLICATION OF COMPOSITE MATERIALS IN MECHANICAL STRUCTURES

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Abstract: *Design of machine structures with using composite parts allows to combine different sorts of material, manufacturing technology and thereby control stiffness, strength, dynamic response, weight, as well as the costs, and achieve the products "on request". This paper describes new hybrid composites products based on combination of winding technology with 3D cellular structure and dynamic damping layers. An analytical methods and their effective use for optimization process and a multiscale homogenization on the micro and mezzo scale as well as the FE analysis of the final structure is described. Application of damping layers significantly contributes to the rate of vibration decay and dynamic damping.*
Keywords: *composite structure, dynamic response, multiscale modelling,*

1. INTRODUCTION

During the last decade, performance composite components have been used in an increasing number of different applications, such as sport equipment, transport, marine, energy or machine building. One factor is the decreasing carbon fibre prices, which have created new demands for composite technologies. Some other aspects are going currently in application. Composite technology enables building materials with desired properties, for example rollers or spindles with zero thermal expansion, drive shafts high resonance frequency or machine parts with high damping. Industries can now adopt better materials to produce better performing products, while maintaining efficiencies of productivity and cost. The designers and producers can change material components and manufacturing technology and thereby control stiffness, strength, dynamic response, weight, as well as the costs, and achieve an optimal product.

2. CURRENT AND NEW TECHNOLOGY

2.1. Current technology overview

There are several technologies for the production of machine parts:

- Autoclave processing is the most common method used for curing thermoset prepregs. The curing of thermoset composites involves both mechanical and chemical processes. Mechanically, pressure is applied to remove trapped air and volatiles, and to consolidate the individual plies and fibers.
- Resin Transfer Moulding is a low-pressure, closed mould semi-mechanized process. The process allows fabricating simple low-performance to complex or high-performance articles in varied sizes. The fibre reinforcement, which may be preshaped is placed in the required arrangement in the cavity of a closed mould and a liquid resin of low viscosity is injected under pressure into the cavity, which is subsequently cured.
- Pultrusion is a continuous, automated closed-moulding process that is cost effective for high volume production of constant cross section parts. Due to uniformity of cross-section, resin dispersion, fibre distribution &

alignment, excellent composite structural materials can be fabricated by pultrusion. The basic process usually involves pulling of continuous fibres through a bath of resin, blended with a catalyst and then into pre-forming fixtures where the section is partially pre-shaped & excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product. The profiles produced with this process can compete with traditional metal profiles made of steel & aluminium for strength & weight.

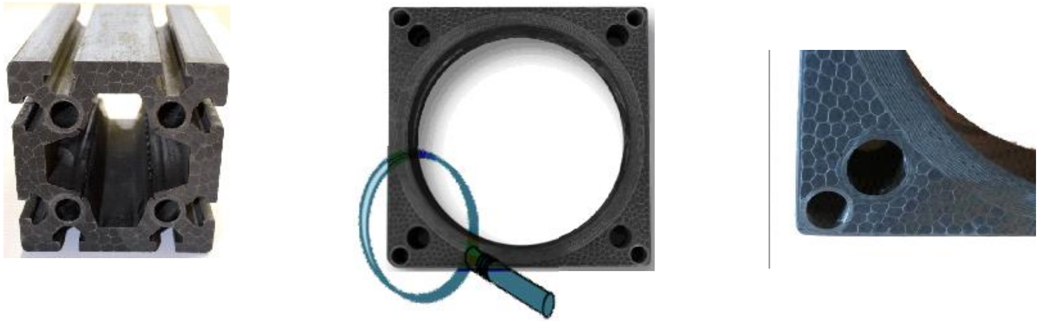
- Filament winding is a semi-automatic manufacturing method for making fibre reinforced composite materials by precisely laying down continuous resin impregnated roving or tows on a rotating mandrel that has the required shape. The mandrel can be cylindrical, round or of any shape that does not have a reverse curvature. The technique has the capacity to vary the winding tension, wide angle or resin content in each layer of reinforcement until the desired thickness or resin content of the composite are obtained with the required direction of strength. A large array of products can be fabricated by this technique e.g. storage tanks, pipes, pressure vessels, rocket engine cases, nose cones of missiles and other aerospace parts.

The specifics of designing of composite structures include the fact that designers should work closely with production technology and they must discard “traditional isotropic” thinking. Czech Technical University in Prague (CTU) closely collaborates with many companies which deal with composite production. The co-author (company CompoTech Plus) has developed its own fibre laying process for structural composite tubes, which is particularly suitable for components that require high bending stiffness and stability. This is called the zero degree axial fibre laying process. Unique application allows using ultra high modulus Pitch carbon fibre to manufacture structural tubes. They can be used in almost any type of high speed industrial machine, such as milling machines, robots and printers. This pitch-based fibre offers higher bending and torsion stiffness than the usual PAN-based fibre and can be cost-effective when used in volume.

As described in [1], a design of composite parts with ultra-high stiffness (for example of machining centre spindle beams) leads to thick-walled reinforcing members characterized by the axially oriented fibres in the direction of maximal loading-flows. However, the low shear static and fatigue strengths of these unidirectional thick structures often limit their application. This is due to the low strength of the composite matrix and the multiaxial stress state. Cracks arise at several points between the fibres (thick-walled pultruded composite flanges), or delamination occur between the laminae (laminated composite plates). An increase in the shear strength is usually produced by various three dimensional (3D) laminate techniques, such as 3D braiding or 3D strengthening (transversal needling). Such technologies can improve or partially eliminate delamination or matrix cracking. However, these techniques lead to a rapid decrease in stiffness in the dominant load direction. Filament fibre winding technology combined with stamping and wrapping with using both high modulus (cell core) and high strength carbon fibers (wrap) was used to manufacture a three-dimensional cell structure.

2.2. Three dimensional cell hybrid structure

A novel type of cell hybrid composite structure was developed by CompoTech Plus in research cooperation with the Czech Technical University in Prague [2]. The main application of these structures is for thick-walled or nearly solid beams with maximum bending strength (spars, wing flanges, etc.) or with high stiffness (machining centre spindle beams). A typical hybrid composite beam consists of the main supporting element (e.g. a central wound composite tube), secondary elements (a corner tubes for connection or integration of the guidelines). Thick parts of the cross section of such typical spindle beam are filled in by a sub-cell structure, as is shown in Fig 1.



a) b) c)

Figure 1: A composite spindle beams cross sections with an integrated guideline formed by 3D cell structure (a) or with a corner guideline connection tubes (b), and a detail of the 3CD structure (c)

This bioinspired structure in its cross section (in the y-z plane) creates sub-cells with a volume fraction of up to 75% axial fibers, see Fig. 2. The sub-cells consist of carbon fiber tows with axial orientation (x axis). The diameter of this bundle is usually between 4 and 8 mm. In the next step, another thin layer is wound around this axially oriented core. The winding is created between 0.2 and 1 mm in thickness. The thickness can be optimized, as the orientation of the winding fibers allows, which can be made from 0 to 89 degrees. The prefabricated bundles are then put into the form, moulded together and subsequently cured into the final shape.

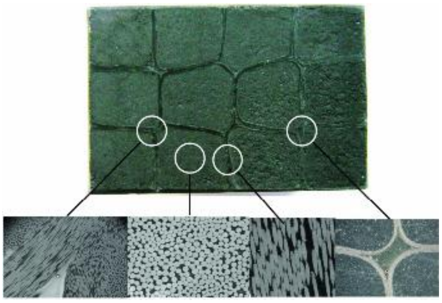
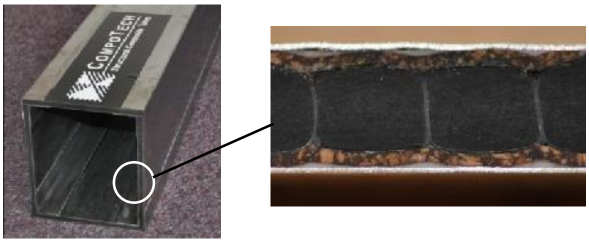


Figure 2: Details of the parts of the 3D composite structure.

2.3. Hybrid structure

As was partially showed above, the design of the more complicated final composite structure can include and conveniently combine different independently produced semi-finished products, which can be "mounted together" by final technological operations, for example stamping in the mould. It allows to include in the structure bearing layers, which transmit loads as well as technological layers to protect the surface (against impact or environment). Special layers of cork or ruber-cork were also tested, to achieve high damping of dynamic vibration, see Fig. 3. Other possibilities are open for structural health monitoring systems (SHM). Authors successfully applied into a composite structure the integrated fibre optic sensors with Bragg grating (FBG). FGB sensors allowed a monitoring of deformation and debonding of adhesive joints, see [2].



(a) (b)

Figure 3: A thin-walled sandwich beam (a) and a detail of its wall (b) containing metal coverings, cork layers and high modulus sub-cell structure

2.4. Properties of high performance structures and their application

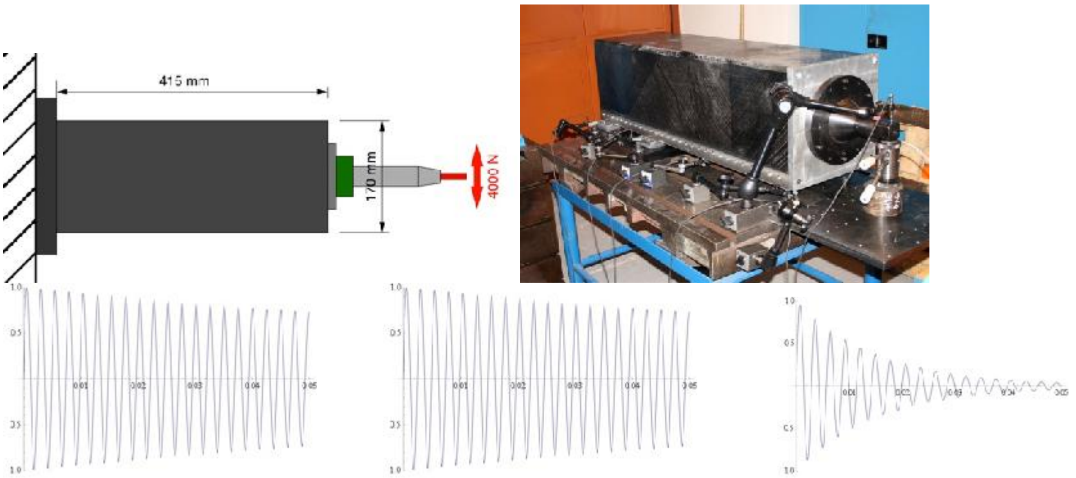
Design of composite hybrid structure „on request" allows to achieve high mechanical and dynamic parameters of the final product.

- For example, an axial fiber placement in the winding technology of tubes and combination of two types of carbon fibres (PAN/PITCH fibers, with positive/negative thermal expansion in longitudinal/transversal direction) enabled the production of printing cylinders, which did not change the outer diameter during a working cycle and changing of temperature.
- Why drill holes when they can be made in the process of manufacturing the beam? Authors have developed the idea of "Winding Holes" and have researched the stresses around these holes to enable secure connection to metal components using the ability of composite fibres to be placed in an advantageous way. No drilling, min. cutting fibres, fewer manufacturing steps, less waste. One example of integrated multi pin joints, which connect the bottom and other equipment with the hydraulic composite cylinder, is shown on the Fig. 4a and Fig. 4b, [3]. Another idea of a connection using the steel rod, which is inside of composite corner tube and screws, is shown in Fig 4c.
- Combination of high strength and high modulus carbon fibers and use of other material layers allows to build "composite dynamic damping" hybrid structures. A high natural frequency is beneficial, but the real benefit to machine builders is the improvement in dynamic damping. Everything vibrates at its own natural frequency and every material has a damping coefficient ζ which is the rate of vibration decay. The developed composite parts have the ability to dissipate vibrational energy. Tests were done by comparing three spindle tubes: with and without a simulated tool (mass of 30 kg), see Fig. 5. Each with the same dimensions and each tested with the same load. It was shown that the graphite carbon damping spindle tube has nearly double the natural frequency,

12 x better dynamic damping and 7 x better dynamic stiffness as steel spindle. It was shown that not only carbon-graphite-damping composites have a higher stiffness and a higher natural frequency, but they also have a lower response at the points of sympathetic vibration. This reduces the response to excitation frequencies and should permit higher accuracy and / or higher cutting speed. The productivity of "removing metal" should be significantly better.

a) b) c)

Figure 4: Integrated loops into the composite tube (a), final hydraulic cylinder (b) and mechanical connection with using of a integrated corner tube (c)



a) Steel Spindle Tube	b) Carbon Fibre Spindle Tube	c) carbon-graphite-damping tube
Natural Frequency = 405 Hz	387 Hz	351 Hz
Dynamic Damping, $\zeta = 0.0025$	$\zeta = 0.003$	$\zeta = 0.03$

Figure 5: Comparison of dynamic response of steel spindle (a), carbon spindle (b) and carbon-graphite-damping tube (c) with the end mass of 30 kg.

3. DESIGN METHODS AND SOFTWARE

3.1. Analytical solutions

The design and comparison of many variants or the optimization process required relative very fast calculation of complicated structures. For this phase of the design process, the analytical methods are more suitable, because they are more flexible for changing of stacking of layers or loading and boundary conditions. Two basic groups of software for designing and analysing fibre layed structures were developed by CompoTech in the close collaboration with the Czech Technical University in Prague.

The first group of software analyses stresses and displacements of cylindrical, fibre layed, laminated composite shells. Two approaches have been developed: The first is simple linear shell theory based on Kirhoff's conditions of shell deformation, known as Classical Laminating Theory (CLT) was modified with own method of unit forces distribution in the cross-sections of tubes. This enables different loads such as bending moment, torque, axial force or thermal load to be solved together. Because this method is based on plate theory, the advantage is a simpler and more precise two dimensional data preparation and the possibility of solving several loading states at the same time. This method is powerful enough for most composite tube applications and has been verified by full destructive tests on test samples. The second approach is based on the theory of the cylindrically anisotropic elasticity. Using Lekhnitski's stress functions, a closed form solution for calculating stresses and displacements was found. The advantage of this approach is the exact and precise calculations of three-dimensional stresses in a fibre layed tube. It particularly enables the analysis of the stress gradients through the thickness of a laminate, which may be very substantial in the form of interlaminar stresses for thicker sections of composite tubes. The disadvantage is a more complicated three dimensional lamina data preparation and the possibility of solving only one load state-bending moment. The company is currently working on the solution using this method for three load states: bending, torsion and axial force.

The second group of software solves and analyses stresses and displacements of fibre layed, laminated composite shells of generally noncircular cross-sections. The principle of this model is the integration of stiffnesses of elements in a cross section. The stiffnesses is calculated as a transformation of (CLT) into a geometric three dimensional expression.

The special software was developed to calculate deflection curves and deformations of the beams or the spars. One dimensional finite element method (FEM) or method of transfer matrix (MTM) is transformed to the numerical program codes. The main advantage is that the way mathematical models are built from elements is identical to the way in which the structure is made, offering accuracy and time saving in pre processing data entry and in transferring results directly into the production code.

3.2. FEM stress state calculation and stiffness and damage prediction

In order to analyse the details of more complicated composite products or taken into account the contacts or joints with other components, FEM software is used on CTU in Prague. In the following, a multiscale modeling of the 3D composite structure is briefly described.

Homogenization on a micro scale. Two main different configurations of the cells can be observed in the cross-section of the 3D structural part, which is hexagonal or rectangular. The idealized geometry of the Representative Volume Elements (RVE) containing the periodic structure with both typical sub-cell shapes is shown in Fig. 6.

(a) (b)

Figure 6: Hexagonal (a) and rectangular shape (b) of sub-cells and periodic RVE models

Computational homogenization on this level can be conceived analytically or with the use of FEM. For an analytical calculation of the unidirectional transversely isotropic structure, law-of-mixture and its empirical variations can be applied in the simplest simulation. A lot of authors have published a number of different more sophistical approaches, see [4], [5]. These formulas usually cannot affect the influence of the interface between fibre and matrix. A more concise estimate of the micro-scale stiffness is provided by FEM analysis with modeling of the fibre interface according [6].

Homogenization on a mezzo scale. The RVE with hexagonal and with rectangular cell shape was modeled in the FE program, according to Fig. 6. The finite element model of a periodic unit cell (PUC) consists of a core and a wrap. It is assumed that the cell contains the homogenized elastic properties of uniaxial oriented fibres tows (high modulus PITCH type fibres). The packaging wrapped around the core can be wound with various angles and thicknesses. High strength PAN type fibres are usually used for this layer. The elastic properties of a PUC calculated on a micro scale level were considered and compared with the experimental measurement of mechanical properties of the 3D structure composite specimens.

The aim of the FE mezzo-scale analysis was to obtain the matrix of homogenized elastic modules according to the Hook's relation between stress and strains tensor transformation:

$$\overline{\sigma}_{i,j} = C_{i,j,k,l} \cdot \overline{\varepsilon}_{i,j} \qquad (1)$$

Homogenization has to be implemented by the boundary conditions. The periodic boundary conditions are assumed on RVE and the displacement of the two opposite boundary surfaces were calculated according periodic condition relations published in [7].

Calculation on a macro scale. A matrix of homogenized elastic modules of PUC was applied to build the final stiffness matrix of the whole hybrid composite structure containing a 3D sub-cell technology. For example, the spindle beams of the machining centre shown in Fig. 5 were calculated, manufactured and experimentally investigated. Another application is depicted in Fig. 3. This beam is composed of thin sandwiches consisting of metal coverings, cork layers and a high modulus sub-cell structure. FE calculations of such hybrid structures based on the multiscale homogenization described above give very satisfied results, and can be used for the construction design of machines. Experimental verification of the FE calculations of static stiffness showed differences up to 10 % in deflections by bending.

4. CONCLUSION

Design of machine structures with using composite parts allows to combine different sorts of material, manufacturing technology and thereby control stiffness, strength, dynamic response, weight, as well as the costs, and achieve the product “on request”. This paper described new hybrid composites products based on combination of winding technology with 3D cellular structure and dynamic damping layers. Multiscale homogenization on a micro scale and on a mezzo scale and final FE analysis on the hybrid material composite structure leads to satisfactory design of complicated machine parts. Analytical methods can be conveniently and effective used in the first step of the design phase and for the optimization process. Experimental investigation, as well as numerical simulations, showed that 3D cell composite structure can be more effective in transferring a shearing force than a classical unidirectional or layered structure. Application of damping layers significantly contributes to the rate of vibration decay and dynamic damping. With using of hybrid composites, parts of high stiffness and very good shear and normal strength can be designed. It was demonstrated on the prototype of the carbon/epoxy spindle for CNC machine centre.

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