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SIMULATION OF BRANCHED BIOLOGICAL STRUCTURES FOR BIONIC INSPIRED FIBRE-REINFORCED COMPONENTS

The load adapted design of complex lightweight bar frame works with nodes and branched profiles is a significant challenge from both the structural mechanical and the manufacturing point of view. The search for novel material efficient solutions increasingly leads to the use of fibre-reinforced composites as they exhibit good specific material properties and a high degree of design flexibility. In order to achieve an optimum design of thin-walled, branched, hollow composite structures, a bionic approach following the top-down principal is pursued and simulations of various Y- and T-shaped models are carried out. The typical characteristics of the ramification areas of selected plant structures are analysed using micro-mirror fringe projection and micro-computed tomography. The scientific findings of plant morphology gained by these analyses are transferred into FE-models for structural analyses and parameter studies. The anisotropy of fibre material, the morphological characteristics of the examined cacti and the technological restrictions of the braiding process are considered in the design process of simulation models. The results show a significant increase of stiffness of thin-walled branched models with bio-inspired design features compared to models constructed according to the state-of-the-art technologies.

Keywords: **bionically inspired composites, lightweight, branching fibre-reinforced structures, braiding technology, thin-walled hollow composites**

SYMULACJA ROZGAŁĘZIONYCH STRUKTUR BIOLOGICZNYCH W INSPIROWANYCH NATURĄ KOMPONENTACH WŁÓKNISTYCH

Bardzo duże wyzwanie, zarówno z perspektywy strukturalno-mechanicznej, jak również produkcyjnej stanowi projektowanie dostosowanych do obciążenia, złożonych, a zarazem lekkich konstukcji prętowych (ramowych) wraz z więzami i rozgałęzieniami z lekkich profili. Poszukiwanie wydajnych rozwiązań materiałowych prowadzi do wykorzystania materiałów kompozytowych wzmacnianych włóknami, gdyż oferują dobre właściwości materiałowe oraz dużą swobodę projektowania. W celu uzyskania optymalnej konstrukcji cienkościennych rozgałęzień kompozytowych zostały przeprowadzone symulacje numeryczne profili w kształcie litery T oraz Y z wykorzystaniem metody elementów skończonych. W pierwszej kolejności przeprowadzono optyczną digitalizację 3D charakterystycznych obszarów rozgałęzień wybranych roślin oraz analizę przy pomocy tomografii komputerowej. Na opracowanie modeli numerycznych z uwzględnieniem anizotropii zastosowanego materiału pozwoliły otrzymane wyniki analiz morfologii roślin, a także uwzględnienie specyfiki wykorzystanej metody wytwarzania, czyli wyplatania. Wyniki pierwszych symulacji pokazują znaczącą poprawę sztywności cienkościennych modeli rozgałęzień bazujących na konstrukcjach inspirowanych naturą w porównaniu z wynikami symulacji konstrukcji tradycyjnych.

Słowa kluczowe: **kompozyty inspirowane naturą, konstrukcje lekkie, rozgałęzienia wzmacniane włóknami, technologia wyplatania, kompozyty cienkościenne**

INTRODUCTION

Aiming at extremely lightweight components for complex technical applications, a wide variety of textile-reinforced composite materials has been developed. Nevertheless, and in contrast to structures found in nature, many technical products do not have load-adapted fibre reinforcement with regard to the spatial flux of force [1-3]. This is a significant deficiency amongst current adapted constructions, such as complex composite profiles and bar frame works, which can be remedied using tailored textile-reinforcement structures and adapted manufacturing technologies [4]. In accordance with the top-down approach used in bionics [5], the development of branched profile structures focuses on promising analogies and solutions which are found in the natural world and can be adopted into technical products. It is expected that the transfer of the outer and inner plant morphology into fibre-reinforced structures will contribute to the optimisation of technical structures. Selected Y- and T-shaped ramifications found in the columnar cacti *Corryocactus brachypetalus* and *Pilosocereus catingicola* are analysed in terms of their morphological characteristics and hierarchical structure (e.g. cross-sectional modifications, ramification angles, support structure arrangement, multi-layer design and gradients between stiff fibres and softer parenchymatous ground tissue) with the aid of fringe pattern projection and micro-computed tomography (μ-CT). In order to gain an in-depth understanding of the complex status of stress in plant structures and significant effects in ramification areas, a detailed 3D model for numerical structural analyses is generated. Additionally, extensive tests for the mechanical characterisation of plant material have been performed. Characteristic bionic features from the investigations of plant morphology together with gained direction-dependent material properties are implemented into FE models which are subsequently used for structural simulations and optimisations. To analyse the influences of bionic features on the occurring deformation and stress status on the ramification area, first, simulations with 2D models are carried out and further refined by more detailed 3D models.

The shoots of this species with 7 to 8 ribs reaching heights of 4 m and diameters of 100 mm [6]. *P. catingicola* naturally grows in the Caatinga savannah in the north-eastern part of Brazil. It is a tree like cactus with one distinct main stem. The ramifications are found from mid-position of the main stem upwards. The maximum height of *P. catingicola* is 10 m with a shoot diameter between 80 and 120 mm and an average number of 4 to 6 ribs [7].

ANALYSIS OF BOTANICAL MORPHOLOGY

For the investigations, the cacti were dissected manually to remove the cortex and the pith. The vascular structure of the ramifications was preserved using an enzymatic maceration technique. The 3D-digitizing system ATOS and the non-destructive, computer based 3D cone beam tomography (μ-CT) are used at the ILK to analyse selected columnar cacti with a pronounced fibre matrix structure and emphasize essential characteristics of the ramification area [8].

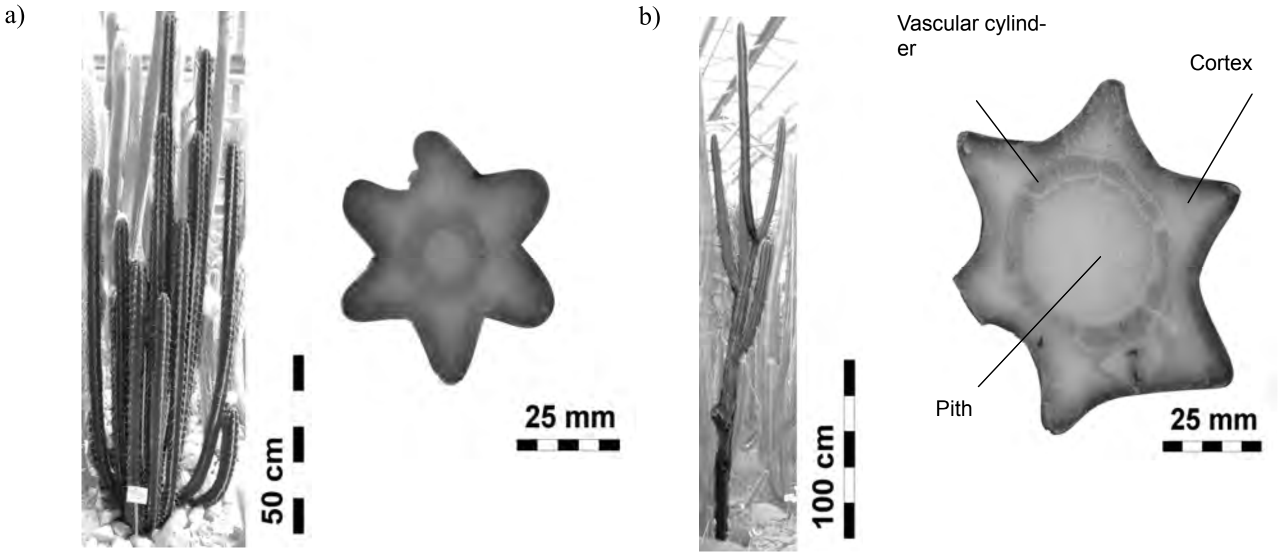


Fig. 1. Cacti *Corryocactus brachypetalus* (a) and *Pilosocereus catingicola* (b) and stem wood cylinder in vertical disks of their stems

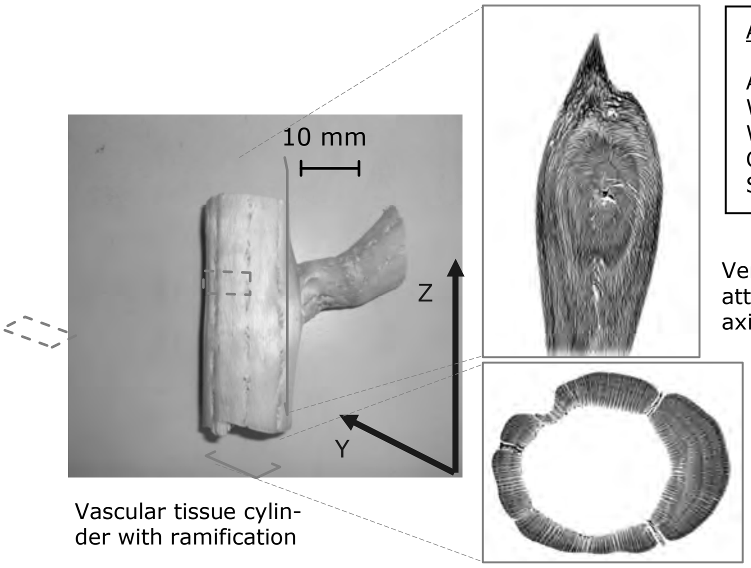
Rys. 1. Kaktusy *Corryocactus brachypetalus* (a) i *Pilosocereus catingicola* (b) oraz przekroje ich łodyg

A choice of suitable variants considering both structural issues and technological feasibility is realised using textile manufacturing processes such as braiding technology.

MATERIAL

Specimens of the two investigated cactus species were obtained from the botanic garden of the TU Dresden. *C. brachypetalus* is a cactus species originally from southern Peru. Its growth habit is shrub like, i.e. all ramifications are situated near the cactus' base (Fig. 1).

Further radiographic studies of the vascular tissue of the branched region are carried out with two specimens of *P. catingicula* to capture a broad spectrum of typical morphological characteristics and to verify the lamella orientation in the branching area found in the *C. brachypetalus*. For this purpose, both ramification areas of vascular tissue are successively irradiated. It has been possible to achieve exceptionally detailed, high-contrast visualisations of their structural properties by a suitable choice of target material and working voltage of the X-ray source as shown in Figure 2.



Analysis parameter of µ-CT

Anode material:	Molybdenum
Working voltage:	60 kV
Working current:	500 µA
Opt. Vergrößerung	2
Schrittweite:	0,3°

Vertikal tomogram of stem-branch-attachement region, rectangle to axis of branch

Horizontal tomogram of stem

Fig. 2. Prepared stem wood and 2D-tomograms of specimen of *P. catingicola*

Rys. 2. Fragment łodygi kaktusa *P. catingicola* oraz tomografia 2D

MATERIAL CHARACTERISATION

Previous investigations of other work groups showed that the lignified vascular tissue - the cactus wood - is the main mechanical support of older columnar cacti [9, 10]. Although it is composed on a microscopic level of the same three cell types as ordinary hardwood: fibers, vessels and rays but its macroscopic appearance does not resemble any typical diffuse-porous wood e.g. beech or birch wood. The axially oriented fibers and vessels are grouped into lamellae. These lamellae are arranged together with the rays in an alternating pericyclical sequence around the stem axis [11]. This rotational symmetry of the anatomy strongly suggests the assumption of orthotropic material properties. Thus the elastic constants of the cactus wood have to be determined in an axial, tangential and radial direction. For this study, Young's moduli in these directions and Poisson's ratios were measured in uniaxial tension tests on flat test pieces. The specimens for the tests were cut out of the cactus wood of unramified segments near the branching of the same cacti that were analyzed in the µ-CT and 3D laser scanning (see Fig. 3). The tension tests were performed on a ZWICK/ROELL testing machine with a 1 kN force transducer and optical deformation measurement with the ARAMIS 3D System of GOM. To guarantee quasi-static loading conditions, the tests were performed at a testing speed of 1 mm/min.

The Tables 1 and 2 summarize the measured Young's moduli and Poisson's ratios for the two investigated species. For *C. brachypetalus,* only test pieces in the axial-tangential plane could be prepared due to the small wall thickness of its cactus wood. This and the anisotropic material behaviour are the reasons why the shear moduli of the investigated cacti cannot be tested and calculated yet.

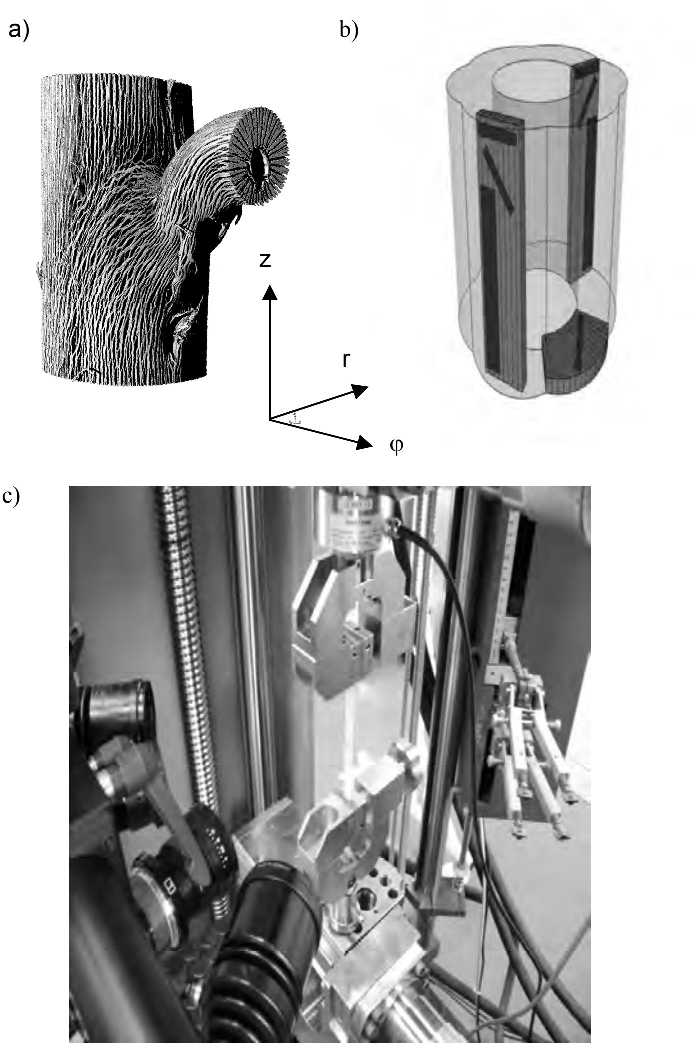


Fig. 3. 3D image (µ-CT) of columnar cacti (a), cutting plan for test pieces (b) and uniaxial tension test with optical measurement (c)

Rys. 3. Obraz 3D (µ-CT) fragmentu kaktusa (a), plan przygotowania próbek (b) i badanie wytrzymałości na rozciąganie wraz z urządzeniami do pomiarów optycznych

TABLE 1. **Measured values of cactus wood *P. catingicola***
TABELA 1. **Otrzymane wartości kaktusa *P. catingicola***

Ez	(10.55 ± 1.92) GPa	νφz	0.61 ± 0.14
Eφ	(0.57 ± 0.07) GPa	νrz	0.40 ± 0.12
Er	(0.88 ± 0.13) GPa	νrφ	0.42 ± 0.03

TABLE 2. **Measured values of cactus wood *C. brachypetalus***
TABELA 2. **Otrzymane wartości kaktusa *C. brachypetalus***

Ez	(7.68 ± 1.20) GPa	νφz	0.46 ± 0.12
Eφ	(0.12 ± 0.01) GPa	νrz	n.a.
Er	n.a.	νrφ	n.a.

n.a.: not analysed yet

The arrangement of the fibres in radially oriented lamellae is reflected by the fact that the radial modulus is higher than the tangential one (see Fig. 4a). It is remarkable that the determined values are in the same range as the Young's moduli and Poisson' ratios of spruce wood (*Picea abies*). In the comparison of *P. catingicola* and *P. abies*, the only significant difference is found in the tests with a transverse contraction in the tangential direction. It is likely that the unusually high Poisson's ratios in these tests are caused by the alternating arrangement of the wooden lamellae with the broad parenchymatous rays (see Fig. 4b).

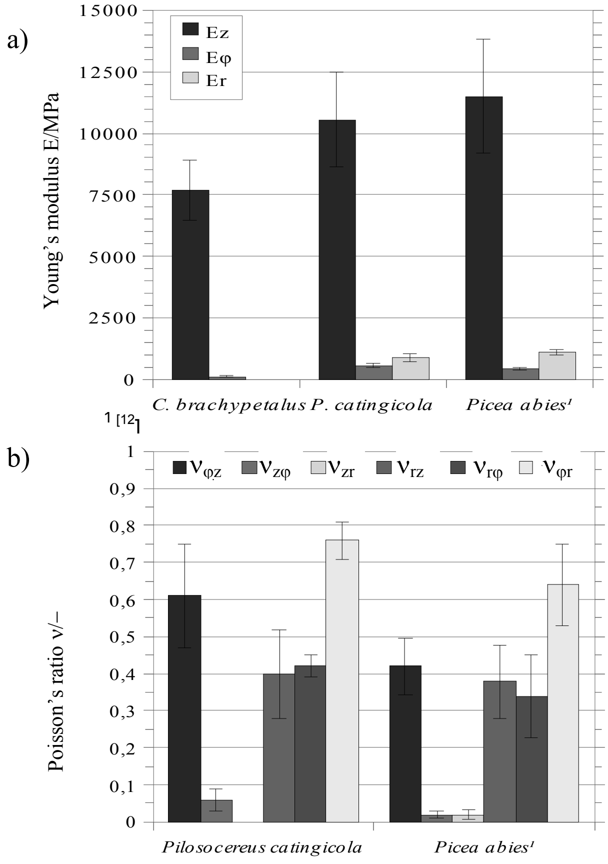


Fig. 4. Material properties of analysed wood of selected plants

Rys. 4. Wartości materiałowe analizowanych fragmentów wybranych roślin

The minor compression stability of these rays resulting from thin, unlignified cell walls under compression stresses resulting from transverse contraction leads to a very high transverse deformation and thus to Poisson's ratios much greater than 0.5.

Besides the high variation of the measured values due to growth conditions, another challenge is the preparation of adequate test pieces because the length of the test pieces is limited by the tube wall thickness of the vascular cylinder, especially in the radial direction. The high Poisson's ratios in the tangential direction leads to the assumption that the pressure inside the ray cells (turgor) is one factor for the mechanical performance of the cactus wood. It can be hypothesized that the transverse contraction increases the turgor and thus increases the stability of the wood with progressing deformation and leads to a visco-elastic material behaviour with high damping ratios.

REVERSE ENGINEERING AND MODELLING

The gained knowledge regarding the morphology and growth forms of specimens of branched columnar cacti *C. brachypetalus* and *P. catingicola* are used to model characteristic geometric features, for instance grooves and angles in branching areas [8]. For effective use of FKV in engineering applications with a branched hollow structure, selected morphological features are examined. According to that, an indentation shows a significant effect on the stress distribution at the notch area of a loaded structure. With a superimposed load, it dominates the stress in the lateral area which is caused by the lateral acting force. A circumferential notch as at the branched support structure of the investigated cacti (see Fig. 5), is not composite-appropriate. In addition, the restrictions of braiding technology require elongated fibre guidance in the lateral region. An improved storage of the roving in the branching region is achieved with the shoulder-like shape.

These selected features were compared to typical designs in parametric studies to determine the influence on the stiffness, stress distributions and principal directions. The FE models were generated with 4-node Thin-Shell-Elements, thereby the deformation behaviour of a thin-walled hollow shaped structure can be sufficiently represented within the first simulations. The element normal corresponds to the thickness of the shell elements and the element orientation corresponds to the axis of a branch or axis of the stem (see Fig. 6). The variable element orientation in the ramification area corresponds to the lamella orientation of the bionic antetype (see Fig. 5). The simulation of Y- and T-shaped branching shell models are computed with layers of symmetric laminates of a 0.3 mm thickness and a suitable choice of element orientations. The growth conditions for the investigated cacti in the greenhouse are known. In order to focus on the influence of the biological design variations, superimposed loads are not considered in the initial simulations. The shown FE model is clamped on both sides of the stem end and is loaded with a force of 100 N at the end of the ramification leg.

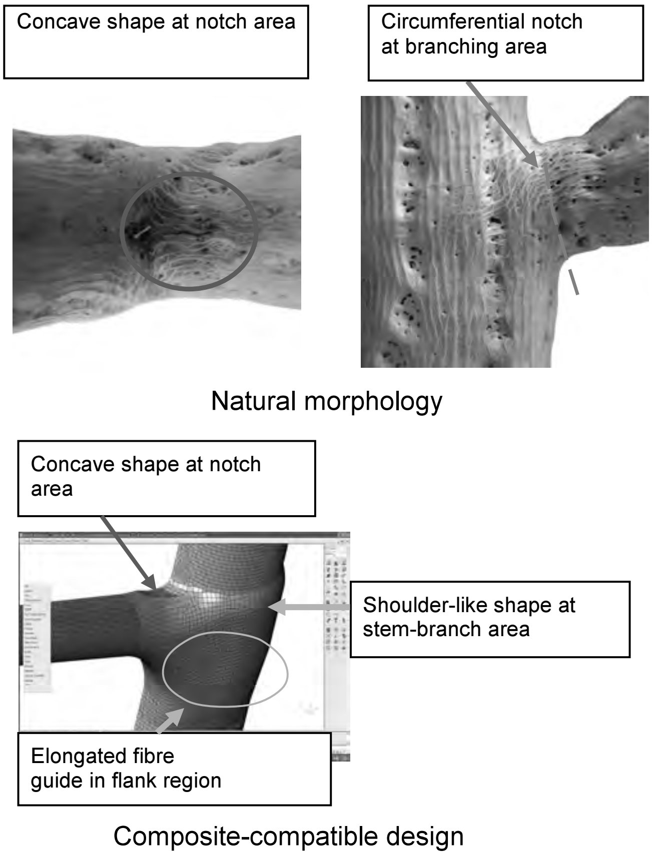


Fig. 5. Natural morphological design and derived design with relevant technological restrictions of braiding process

Rys. 5. Konstrukcja naturalna i konstrukcja otrzymana w procesie wyplatania z ograniczeniami tej technologii

The ramification area of the models is concave shaped on the upper side between the tensile loaded areas corresponding to the concave shaped design found in some species of columnar cacti. This enables a shift of maximum tensile stress from the groove region to lateral areas.

DISCUSSION

The branched structure is modified according to the morphological attributes of the branched area of the investigated columnar cacti. The shoulder-like shape beside the ramification and the concave shape in the middle of the upper side of the ramification results in a shift of maximum tensile stress to the lateral areas and in an increase of stiffness. Design features can be derived from the first simulations for bionically inspired thin-walled, hollow-shaped composite structures. As a further result of these studies of Y- and T-shaped branching, a fibre orientation of ±20 degrees has proven to be beneficial for stiffening. The results of the first comparative studies show a significant reduction of the tensile stress in the ramification area with a simultaneous decrease of deformation by about 65 % of the bionic inspired variants in comparison to the traditional variants (see. Fig. 7).

The complex 3D-stress status, as it is existent in the ramification of the biological antitype, cannot be represented by the thin-shell model. For this reason, a 3D volumetric FE model has to be generated with the directions of volume edges according to the lamella orientation of natural stem wood. The directional dependent material properties of the investigated columnar cacti will be used for these simulations.

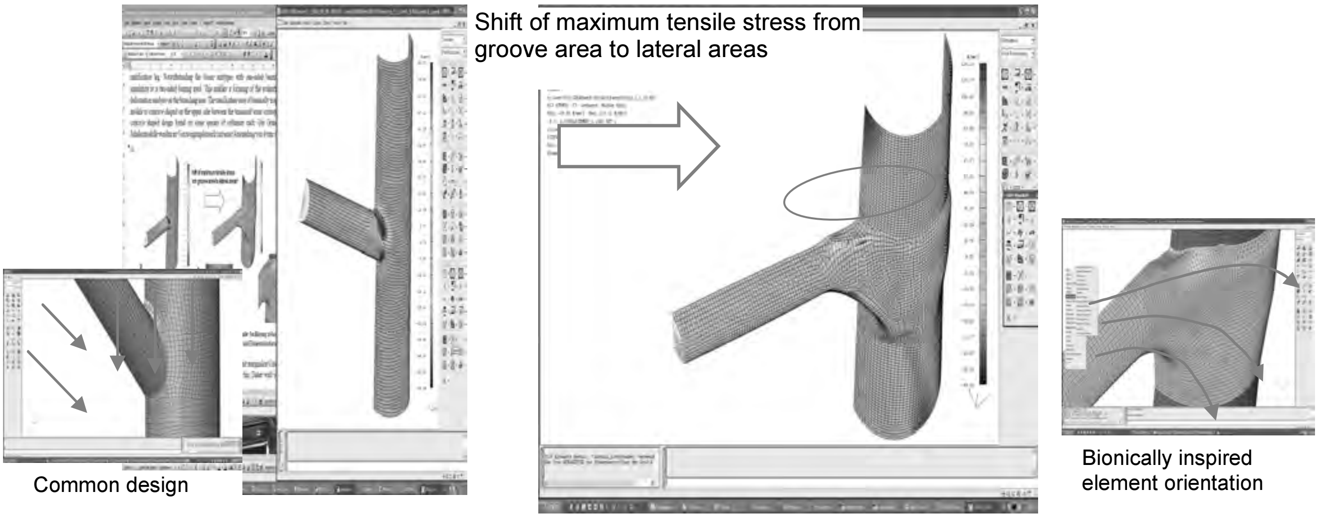


Fig. 6. Influence of element orientation and bionically shaped geometry in groove area of ramification of FE shell models

Rys. 6. Wpływ orientacji elementów oraz kształtu geometrycznego w miejscu rozgałęzienia modelu powłokowego FE

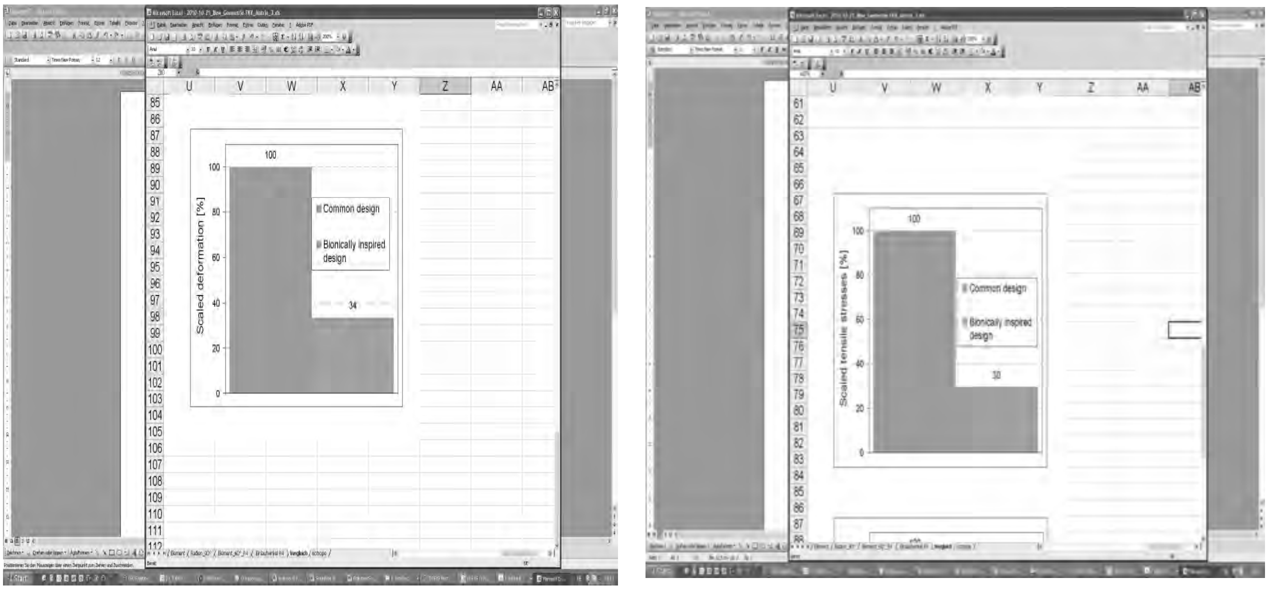


Fig. 7. Influence of bionically inspired geometry on deformation and tensile stress of branched, thin-walled, hollow structures

Rys. 7. Porównanie odkształceń i naprężeń w rozgałęzieniach wykonanych z cienkościennych struktur z wykorzystaniem geometrii inspirowanej bionicznie oraz tradycyjnej

SUMMARY AND OUTLOOK

The analysis of bionic structures offers a great potential for the efficient material design of lightweight structures in composite design. The influence of the inner and outer morphology on structural behaviour as well as the orthotropic material properties of cactus wood is being investigated with extensive analyses of the branched structures of columnar cacti *C. brachypetalus* and *P. catingicola* using fringe pattern projection as well as μ-CT and uniaxial tension tests with optical deformation measurement. The gained data and the results of parameter studies are used to generate thin-walled FE models with bionically inspired shapes including improved geometries of the ramification area. A 3D FE model with preferential directions according to the lamella structure of the analysed branched cactus wood is generated for the investigation of its complex structural behavior. Future technological implementations of advantageous variants into fibre-reinforced components are being carried out with adapted braiding methods and infiltration techniques.

Acknowledgements

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