Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

Kompozyty 11: 3 (2011) 187-191

KOMPOZYTY
COMPOSITES

**Werner A. Hufenbach, Maik Gude, Frank Adam, Niels Modler, Thomas Heber, Ole Renner
Ivonne Körner, Daniel Weck***

Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology (ILK), Holbeinstraße 3, 01307 Dresden, Germany
** Corresponding author. E-mail: d.weck@ilk.mw.tu-dresden.de*

Otrzymano (Received) 16.02.2011

EXPERIMENTAL INVESTIGATION OF COMPOSITE-BASED COMPLIANT STRUCTURES

Composite materials with their adjustable, high specific mechanical properties offer the possibility to realise load-adapted, locally functionalised lightweight structures. Here, compliant structures characterised by individually adaptable deformation behaviour are promising applications. Notwithstanding the substantial degree of function integration, competitive serial production of such components can be achieved by the use of composites based on thermoplastic matrix systems in close combination with efficient manufacturing technologies. This paper contributes to the development of composite compliant structures, specifically designed for use in bending dominated applications. The experimental studies including different fibre-reinforcements make allowance for the composite adapted design of a beam structure and the associated load transfer elements. For this purpose, an adapted testing device was designed and installed, and various composite bending structures are compared. The experimental results show the suitability of fibre-reinforced composites with large elastic deformability for compliant structures. Different designs of the load transfer element were tested. Compared to the basic design, an increase of the load bearing capacity of the compliant structure by up to 100 % was achieved. This is facilitated by the aligned design of the composite beam and its associated load transfer elements.

Keywords: compliant structure, fibre-reinforced plastics, load transfer element

BADANIA EKSPERYMENTALNE KOMPOZYTÓW O STRUKTURACH PODATNYCH

Materiały kompozytowe z dopasowanymi do założonych wymagań własnościami mechanicznymi oferują możliwość realizacji dostosowanych do obciążenia miejscowo funkcjonalizowanych struktur lekkich. W tym przypadku obiecującymi rozwiązaniami są „compliant structures” - tzw. struktury podatne, charakteryzujące się możliwością indywidualnie dostosowanego przebiegu deformacji. Pomimo znacznego stopnia integracji funkcji, konkurencyjność seryjnej produkcji tych elementów można osiągnąć poprzez zastosowanie materiałów kompozytowych z osnową termoplastyczną, w ścisłym połączeniu z wydajnymi technologiami wytwarzania. Przedstawiona praca wnosi wkład w rozwój tzw. struktur podatnych wykonanych z materiałów kompozytowych i wykorzystanych w układach z elementami zginanymi. Badania eksperymentalne, w których uwzględniono różne rodzaje włókien wzmacniających, pozwoliły na opracowanie struktury belki oraz powiązanych z nią elementów przenoszących obciążenie. W tym celu zaprojektowano i wykonano odpowiednie stanowisko badawcze służące do porównania różnych struktur z materiałów kompozytowych. Wyniki badań potwierdziły predyspozycje wykorzystania w strukturach podatnych kompozytów włóknistych zdolnych do dużych odkształceń sprężystych. Przetestowano różne warianty kształtu elementów przenoszących obciążenie, a wyniki badań potwierdziły poprawę nośności, w porównaniu z konstrukcją wyjściową, aż do 100%. Było to możliwe dzięki dopasowaniu konstrukcji belki kompozytowej oraz współpracujących z nią elementów przenoszących obciążenie.

Słowa kluczowe: struktury podatne, tworzywa sztuczne wzmocnione włóknami, element przenoszący obciążenie

INTRODUCTION

The constant development of technical components and the optimisation of their mechanical properties are essential in opening new areas of application. Novel composite materials contribute to this topic with their adjustable, anisotropic mechanical characteristics. Fibre-reinforced thermoplastic components made of hybrid yarns offer the possibility to efficiently produce such composite structures in various shapes [1-8].

Function-integration is of major importance in designing competitive lightweight components. For this purpose, the integration of complaint mechanisms into structural parts and components enables low-maintenance lightweight solutions [9-12]. Materials suitable for compliant structures must allow for large elastic deformation of the compliant hinge members and they must especially be able to endure the resulting high strains without material damage. This so-called deformability of the material is described by the ratio of the elastic limit to the Young's modulus. Provided that the cross-section dimensions of the considered structures are comparable, metals exhibit high stiffness and low deformability while polymers show low stiffness and high deformability. Fibre-reinforced composites combine both high deformability and high stiffness. Consequently, fibre reinforced composite materials offer improved possibilities in designing compliant structures compared to homogeneous materials. Especially fibre-reinforced thermoplastic composites like glass fibre-reinforced polypropylene (GF-PP) with their versatile anisotropic characteristics and their capability of high nonlinear elastic deformation are qualified for application in compliant mechanisms. The results of an exemplary endurance test under pure bending revealed a fatigue-free operation of fibre-reinforced GF-PP up to three million load cycles [13].

The efficient design of compliant structures requires adequate analytical methods. For this purpose, a coupled design process is briefly described which involves the "Pseudo Rigid-Body Model" (PRBM) presented in [14]. In the main part of this paper, the results of experimental studies on beams are presented in order to evaluate the suitability of different reinforcing fibres for application in compliant structures. Additionally, different structural thicknesses of the composite beams are considered. Furthermore, the composite-adapted design of the load transfer elements is focussed in order to improve the load bearing capacity of the compliant structures. The results of these investigations confirm the necessity to design the composite bending structure and its associated load transfer elements in an aligned way.

DESIGN OF COMPLIANT STRUCTURES

Mechanisms based on fibre-reinforced thermoplastic compliances transmit motions through structural deformations. Therefore, these systems are characterised by improved precision and reliability. The synthesis of compliant mechanisms is completely different compared to conventional kinematic systems. The amplitude and direction of the acting forces affect the movement and deformation of the compliant structures. Additionally, the kinematic behaviour of the compliant mechanism is influenced by the Young's modulus and the cross-section geometry of the compliant structures. As a result, the structural strength has to be considered additionally in the design process. This leads to a complex and iterative synthesis process for compliant mechanisms.

The calculation of structural behaviour with large geometric nonlinear deformation is accomplished in this coupled design process with the aid of the PRBM. Here, rigid body elements connected by characteristic joints substitute the flexible links. The deformation of the compliant structure is mainly defined by the applied force F and its direction, which is described here by the angle α (Fig. 1). To ensure equivalent force-deformation-characteristics of PRBM and compliant structure, the characteristic radius factor $\gamma = \gamma(\alpha)$ and the characteristic spring constant $K = K(\alpha)$ are introduced. The dependence of the characteristic PRBM parameters on angle α leads to one specific PRBM for each direction of applied force F.

The PRBM enables the efficient analysis of compliant structures. This analytical model allows for a better understanding of the physical connections compared to finite element analysis and offers the possibility to quickly perform parameter studies. Nevertheless, the verification of designed compliant structures by numerical methods is essential in order to check the actual loading conditions in the fibre-reinforced composite.

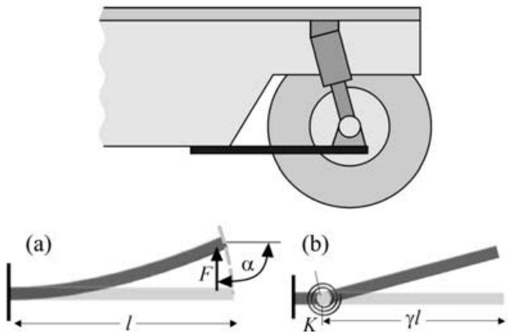

Fig. 1. Chassis component and associated simplified mechanical model of a cantilever beam; (a) applied force F and associated angle α and (b) PRBM with characteristic radius factor $\gamma(\alpha)$ and characteristic spring constant $K(\alpha)$ [15]

Rys. 1. Fragment podwozia wraz z uproszczonym modelem mechanicznym belki wspornikowej (a), występujące siły i odpowiadający im kąt α (b) oraz PRBM z charakterystycznym współczynnikiem promienia $\gamma(\alpha)$ oraz stałą sprężyny $K(\alpha)$ [15]

Besides the design of the compliant structure, which includes the definition of compliant material and cross-section, the composite-adapted design of the load transfer elements is a major topic in order to fully exploit the material strength. The compressive stress due to bending and the shear stress induced by the transverse force are superimposed at the end of the load transfer element as shown in Figure 2a. This complex loading condition causes the failure of the composite beam at an early stage. Experimental studies are performed in order to identify the design guidelines for the load transfer elements of compliant structures undergoing large non-linear deformations.

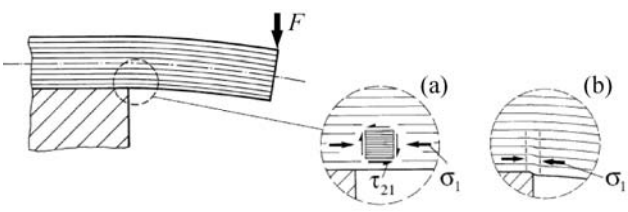

Fig. 2. Superimposed shear and compressive stresses at end of load transfer element; (a) local loading condition and (b) deformation due to shear stress promotes fibre kinking [16]

Rys. 2. Nakładanie się naprężeń ścinanających i ściskających na końcu elementu przenoszącego obciążenie; (a) lokalne warunki obciążenia i (b) odkształcenie spowodowane naprężeniami ścinającymi sprzyjającymi wyboczeniu włókien [16]

EXPERIMENTAL STUDIES

The load transfer into fibre-reinforced structures is favourably performed by utilising large areas [16]. Consequently, compliant structures characterised by large nonlinear deformations may benefit from an adapted supporting radius which ensures a uniform load distribution (Fig. 3).

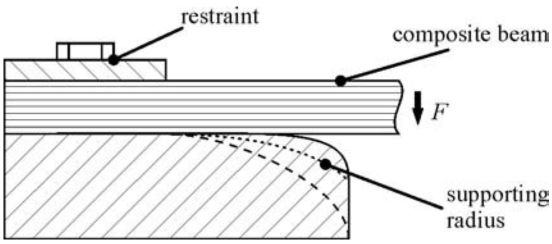

Fig. 3. Load transfer element with adaptable supporting radius

Rys. 3. Element przenoszący obciążenie wraz z promieniem podpierającym

To investigate the influence of this set-up on the load bearing capacity of fibre-reinforced composite beams, a test rig has been designed for single cantilevered specimens (Fig. 4). The flat specimens have a drilled hole at both ends and are fixed to the test rig at one side by means of a flat restraint and a fitting screw. Likewise, the opposite side of the specimen is connected with a cable used to load the specimen. The vertical load application is ensured by the test rig which is adjustable with respect to different specimen lengths. The test rig is installed into a conventional testing machine utilised to pull the cable and to measure the resulting force and displacement. The part defining the supporting radius is easily replaceable in order to study different configurations. Four different parts with radii of 0, 50, 125, and 250 mm are incorporated in the present investigation.

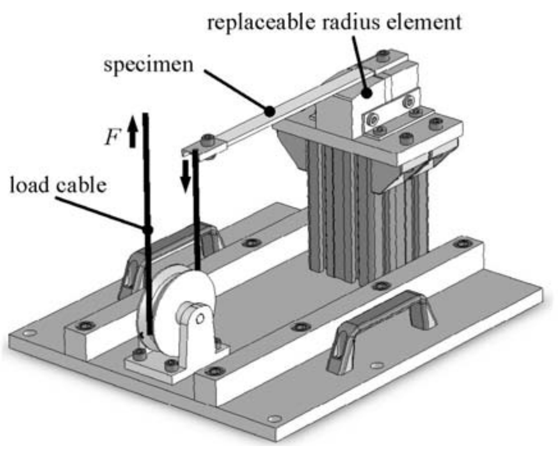

Fig. 4. CAD-model of test rig with pull cable mechanism ensuring vertical load

Rys. 4. Model CAD urządzenia zapewniającego obciążenie w kierunku pionowym

Three different composite materials with unidirectional reinforcement are investigated in the accomplished study. The employed reinforcing fibres comprise carbon fibres both with high tenacity (CFRP-HT) and high Young's modulus (CFRP-HM) as well as E-glass fibres (GFRP-E). The corresponding composite panels are manufactured in an autoclave process. Subsequently, the panels are milled in order to ensure a homogeneous thickness, whereby two different specimen thicknesses *t* (4.5 mm and 9.5 mm) are realised. Afterwards, the specimens are cut by water jet technology to a length of 300 mm and a width of 20 mm. The characteristic PRBM parameters of the considered specimens are summarised in Table 1.

TABLE 1. **Characteristic PRBM parameters of considered experimental configurations**

TABELA 1. **Charakterystyczne parametry PRBM**

	GFRP-E	CFRP-HT	CFRP-HM
t, mm	4.5 / 9.5	4.5 / 9.5	4.5 / 9.5
γ	0,85	0,85	0,85
K, Nm	50.0 / 470.5	148.0 / 1392.6	285 / 2681.5

RESULTS

Preliminary tests with specimens of 4.5 mm in thickness confirm the suitability of CFRP-HT and GFRP-E for compliant structures. Compared to an analogue spring steel specimen, these materials enable 158 and 230% elastic deflection without an additional supporting radius, respectively. The elastic limit load of the specimens is nearly the same for spring steel (100%), CFRP-HT (103%), and GFRP-E (87%). In contrast, the CFRP-HM specimen fails at 50% deflection and 50% force compared to the spring steel specimen. This performance caused by the brittleness of the reinforcing CF-HM fibres is disadvantageous for use in compliant structures.

The experimental results obtained for different configurations of composite specimens are summarised in Figure 5 in terms of mean values of maximum force and associated deflection. The specimens reinforced with high modulus carbon fibres exhibit little deflection until failure because of their high bending stiffness. Therefore, the contact area between the specimen and supporting radius is marginal and the different radii do not significantly change the load bearing capacity or maximum deflection of these specimens. In contrast, specimens undergoing large deformations (CFRP-HT, GFRP-E) can benefit from supporting radii with regard to maximum force and maximum deflection. As an example, the GFRP-E specimens with a thickness of 9.5 mm exhibit an increase in maximum force of more than 100% and a raise in maximum deflection of approx. 30%. The actual shift of maximum force and deflection are dependent on the respective configuration.

Figure 6 shows the corresponding force-deflection relationship for different supporting radii in order to have a detailed view on the GFRP-E specimens with a thickness of 9.5 mm. First of all, a rise in force gradient for increased supporting radii is recognisable, which is mainly caused by the reduced lever arm length. Maximum force and maximum deflection increase up to a supporting radius of 125 mm.

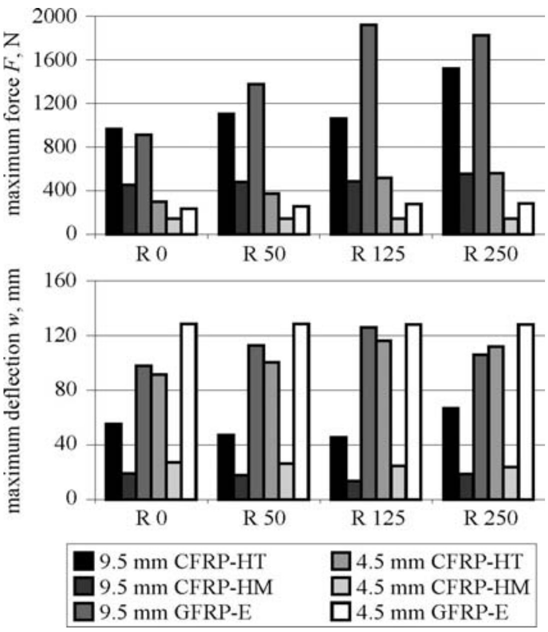

Fig. 5. Maximum force and associated deflection of specimens with different composite materials and thicknesses (maximum deflection of test rig reached for GFRP-E, thickness 4.5 mm)

Rys. 5. Siła maksymalna i związane z nią ugięcie próbek z różnych materiałów kompozytowych i o różnej grubości (maksymalne ugięcie na stanowisku badawczym osiągnął GFRP-E grubości 4,5 mm)

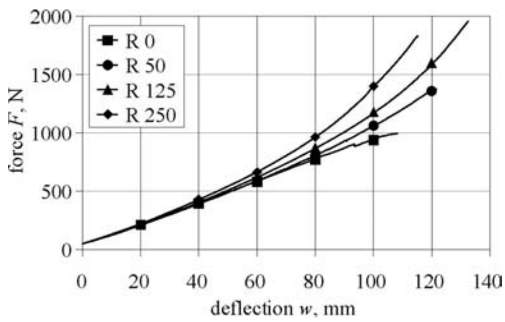

Fig. 6. Force-deflection diagram of GFRP-E specimens with thickness of 9.5 mm for different supporting radii

Rys. 6. Wykres siła-ugięcie próbek GFRP-E o grubości 9,5 mm dla różnych promieni podpierających

To study this behaviour further, numerical analyses were performed with ANSYS WORKBENCH 12.1. The support and the composite beam are modelled using solid elements as deformable structures with linear-elastic material characteristics. The interaction of the two finite element meshes is accomplished by means of a symmetric, friction-afflicted contact. To represent the experimental setup, the composite beam is additionally fixed at the top side in the region of the support. The numerical results reveal that with increasing radius, the maximum compression stress in fibre direction is significantly reduced and a more uniform stress distribution is recognisable (Fig. 7). Additionally, the maximum transverse shear stress decreases. The region with maximum normal stress is moved away from the restraint by utilising a supporting radius. Hence, the stress in the clamping zone decreases and the overall performance of the compliant structure is improved.

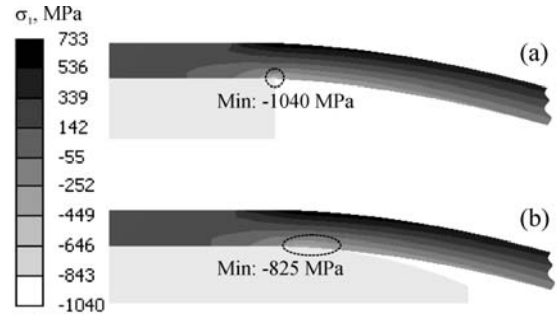

Fig. 7. Normal stress in fibre direction of unidirectionally reinforced GFRP-E specimens (thickness 9.5 mm) at a deflection of 60 mm with supporting radius of (a) 0 mm and (b) 125 mm

Rys. 7. Naprężenia normalne w kierunku włókien dla jednokierunkowo wzmocnionych próbek GFRP-E (grubość 9,5 mm) powstałe w wyniku ugięcia belki o wartości 60 mm dla promieni podpierających o wartości (a) 0 mm i (b) 125 mm

In addition, the maximum force and maximum deflection decrease if a supporting radius of 250 mm is utilised. The deformed GFRP-E specimens with a thickness of 9.5 mm supported by a radius of 125 mm and 250 mm are contrasted in Figure 8. A good analogy between the bending radius of the structure and the supporting radius of 125 mm can be seen in Figure 8a. In contrast, a greater supporting radius causes a new stress concentration at the end of the radius element because the bending radius of the specimen is smaller than the supporting radius (Fig. 8b). Consequently, this structure achieves lower force and deflection maxima. The results reveal that the supporting radius has to be adapted to the characteristics of the utilised composite structure in order to fully exploit the material strength.

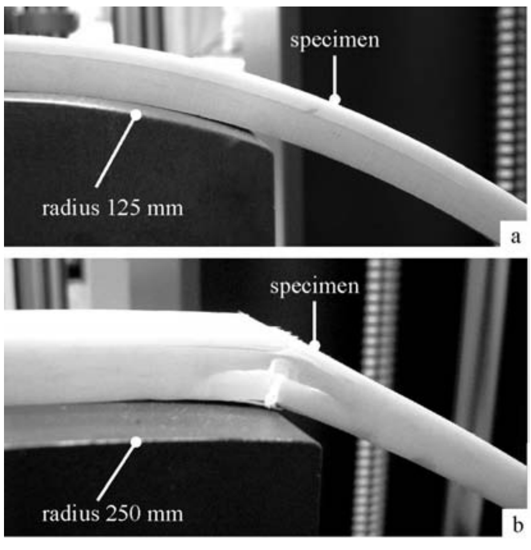

Fig. 8. Deformation of GFRP-E specimens (thickness 9.5 mm) for supporting radius of (a) 125 mm and (b) 250 mm

Rys. 8. Odkształcenie próbek GFRP-E (grubość 9,5 mm) dla promieni podpierających (a) 125 mm i (b) 250 mm

CONCLUSIONS

Compliant mechanisms enable the realisation of function-integrative composite parts. These systems are characterised by improved precision and reliability compared to conventional mechanisms. The iterative synthesis of complex compliant mechanisms can be accomplished by means of analytical approaches like PRBM as well as by using finite element modelling.

To enhance the performance of compliant structures, materials with large elastic deformability are needed. The experimental investigations confirm the suitability of fibre-reinforced plastics with a high ultimate strain like CFRP-HT and GFRP-E for compliant structures. Furthermore, the maximum deflection and force of a composite beam undergoing large nonlinear deformations is improved by means of an additional part with an adapted supporting radius. Such additional parts can be easily integrated into the load transfer elements of compliant mechanisms.

Acknowledgements

The authors would like to express their gratitude to the German Research Foundation (DFG), who funds the Collaborative Research Centre SFB 639 (subproject D2 and E1) at Technische Universität Dresden.

REFERENCES

[1] Abounaim M., Hoffmann G., Diestel O., Cherif C., Thermoplastic composite from innovative flat knitted 3D multi-layer spacer fabric using hybrid yarn and the study of 2D mechanical properties, Composites Science and Technology 2010, 70(2), 363-370.

[2] Badawi S., Development of the weaving machine and 3D woven spacer fabric structures for lightweight composites materials, PhD thesis, Technische Universität Dresden, 2007.

[3] Großmann K., Mühl A., Löser M., Chokri C., Hoffmann G., Torun A.R., New solutions for the manufacturing of spacer preforms for thermoplastic textile-reinforced lightweight structures, Production Engineering - Research and Development 2010, 4, 589-597.

[4] Herzberg C., Zhao N., Rödel H., Konfektionstechnische Fertigung textiler 3D-Preforms für komplexe Leichtbauanwendungen [in:] Chemnitzer Textiltechnik-Tagung, Chemnitz 2009.

[5] Hufenbach W., Adam F., Geller S., Krahl M., Integral solution strategies for the design of fibre-reinforced composites focussing automotive lightweight applications, Proceedings of 2nd International Conference on Advanced Metal Forming Processes in Automotive Industry AutoMetForm 2010, Freiberg, November 2010.

[6] Hufenbach W., Böhm R., Thieme M., Winkler A., Mäder E., Rausch J., Schade M., Polypropylene-glass fibre 3D-textile reinforced composites for automotive applications, Materials & Design 2011, 32(3), 1468-1476.

[7] Hufenbach W., Adam F., Beyer J., Krahl M., Zichner M., Lin S., Hanke U., Development of an adapted process technology for complex thermoplastic lightweight structures based on hybrid yarns, 17th International Conference on Composite Materials (ICCM-17), Edinburgh, July 2009.

[8] Mäder E., Rausch J., Schmidt N., Commingled yarns - processing aspects and tailored surfaces of polypropylene/glass composites, Composites Part A: Applied Science and Manufacturing 2008, 39, 612-623.

[9] Christen G., Pfefferkorn H., Zum Bewegungsverhalten nachgiebiger Mechanismen, Wissenschaftliche Zeitschrift der Technischen Universität Dresden 2001, 50(3), 53-58.

[10] Franitza D., Hufenbach W., Modler N., Modler K.-H., Bewegung durch Verformung - Simulation nachgiebiger Mechanismen aus thermoplastbasierten Faserverbundwerkstoffen, VDI-Bericht Nr. 1966, 389-402, 2006.

[11] Modler K.-H., Franitza D., Landgraf G., Investigations to geometrically non-linear deformable mechanisms, Proceedings of Tenth World Congress on the Theory of Machine and Mechanisms, Oulu 1999, 2, 578-583.

[12] Modler N., Nachgiebigkeitsmechanismen aus Textilverbunden mit integrierten aktorischen Elementen, PhD thesis, Technische Universität Dresden 2008.

[13] Modler N., Modler K.-H., Hufenbach W., Gude M., Jaschinski J., Zichner M., Lovasz E.-C., Margineanu D., Perju D., Cyclic test of textile-reinforced composites in compliant hinge mechanisms, EUCOMES2010 - 3rd European Conference on Mechanism Science, Cluj-Napoca, 14-18.09.2010.

[14] Howell L., Compliant mechanisms, Wiley Interscience, Danvers 2001.

[15] Hufenbach W., Täger O., Adam F., Modler N., Krahl M., Renner O., Advanced manufacturing techniques for textile-reinforced thermoplastic composites considering piezoceramic actuators, Proceedings of the 12th International Scientific Conference on the Contemporary Achievements in Mechanics, Manufacturing and Materials Science (CAM3S 2006), Zakopane 27-30.11.2006.

[16] Franke O., Schürmann H., Analysis of the interaction of adjacent layers of a GFRP-laminate under fatigue loading, International Journal of Fatigue 2010, 32(1), 54-59.

