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SHAPE-CHANGING FIBRE-REINFORCED COMPOSITES

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1. Introduction

The increasing trend in the research and industrial utilization of fibre-reinforced composites as structural materials is most likely to continue in the future due to their outstanding properties and still unexploited full potential. While excellent specific mechanical properties can be achieved in the primary loading directions, the weight of composite parts can be significantly reduced by keeping the amount of reinforcement low in the secondary, non-critical directions. This combination of outstanding mechanical properties and light weight is best utilized in industries where both aspects are critical for operational efficiency (e.g. the aerospace, automotive, wind-energy, motorsport and sporting goods industries). The increasing importance of composites is well exemplified by the trend of their usage in commercial aeroplanes. Twenty years ago, composites accounted for less than 20% of the structural weight of commercial aeroplanes, which has increased to about 50% in modern aircraft. Even if the rate of growth of the share of composite parts slows down, the increasing number of modern aeroplanes will require an increasing amount of composites.

Composites are mainly used for their specific mechanical properties, but their value can be further increased by making them multifunctional. For instance, a structural part can be endowed with additional self-healing or integrated health monitoring features. However, there is a more fundamental type of additional functionality that is intrinsically defined by the layup: the shape-changing behaviour of the composite laminate. Materials respond to loads with deformation, usually in the direction of the action (e.g. extension under tensile load or deflection under bending load). However, in some instances, a non-conventional response is more advantageous. For instance, a designed amount of torsion of a bend–twist coupled aeroplane wing or an extension-twist coupled turbine blade can result in a more efficient aerodynamic shape without the need for any additional parts or motors. The principle of the shape-changing (morphing) concept is the same in any application—the utilization of non-conventional deformation as a response to certain conditions during operation. Depending on the nature of the deforming material, the possible means of actuation show a wide variety (e.g. electricity, heat or mechanical loads); nevertheless, each approach aims at achieving the aforementioned irregular reaction. The steadily increasing tendency of the yearly number of new publications in the field shows the increasing scientific effort and interest in morphing (shape-changing) structures.

Based on the above, the aim of my thesis is to combine the two topics by developing and investigating shape-changing composites.

2. Critical assessment of the literature and the aims of the thesis

There are numerous ways to achieve and utilize the non-conventional shape-changing behaviour of materials and structures. The desired deformation can be actuated electrically, thermally, mechanically or even by light, chemicals or pressure. Shape-changing fibre-reinforced composites, however, stand out from the rest of the approaches in the literature in at least two key ways. Firstly, due to the great tailorability of their layup built up from orthotropic plies, composites can possess various intrinsic coupling characteristics between loads and deformations of different modes (e.g. extension–twist or bend–twist). And secondly, the outstanding specific mechanical properties of composites allow for using them in primary load-bearing structures. Shape-changing composites have been extensively investigated in the literature, and there are even examples of their industrial use as extension–twist or bend–twist coupled turbine blades, for instance. However, during my literature review, I identified some unsolved challenges associated with the design and manufacturing of such laminates.

It has been shown that the intrinsic shape-changing and warping behaviour of composites depend on their layups; therefore, these characteristics can be optimized by optimizing the layup. The classical laminate theory (CLT) offers a computationally efficient way to design the elastic behaviour of laminates while providing all the individual coupling terms that are essential for the investigation of the shape-changing behaviour of laminates. However, the available CLT calculators are basic and cannot be used for full-field optimizations of composite layups. There is a need for a CLT-based algorithm that is capable of optimizing the layup of shape-changing laminates.

Many shape-changing laminates have asymmetric layups, and asymmetric layups tend to warp. Warpage is usually unwanted, but it can also be exploited. One way to exploit the thermally induced out-of-plane deformations is to convert the thermal energy into mechanical work by moving weights. Predicting the thermally induced mechanical work capability of an asymmetric laminate is a challenge in itself, but the monostable-bistable transition further complicates the task because of the changing shape of the laminate. The effect of the stability transition on thermally induced work has not been investigated yet. New results in the topic might lead to better exploitation of the thermal warpage of composites.

Mitigating the warpage of asymmetric layups seems to be one of the main challenges in the composites industry. Solving this problem is crucial to make the industry even consider using shape-changing laminates with asymmetric layups. There are three promising warpage mitigation methods that can be part of the solution, but all of them need further investigation than what has already been done in the literature.

Tool compensation is a widely used approach in the composites industry to lessen manufacturing-induced distortions, but it is mostly used to compensate for the warpage of symmetric laminates arising from the complex geometry of the part. In contrast, asymmetric laminates tend to warp intrinsically, regardless of the complexity of the geometry. Since asymmetric laminates can be monostable or bistable, the performance of the tool compensation method needs to be assessed in both stability regions.

Hybrid layups have been used to improve a variety of laminate properties (including some shape-changing characteristics) but have not been studied directly with the aim of mitigating the warpage of asymmetric laminates. The main question that needs to be answered is whether hybridization can lessen warpage and improve morphing at the same time.

As for the third warpage mitigation method – layup homogenization (which is based on the repetition of identical sub-laminates) – the main challenge is to investigate its effects on the coupling performance of composites. The more homogenized a layup is, the more symmetrically it behaves; therefore, homogenization might cause some shape-changing characteristics to diminish while not affecting or even improving another coupled behaviour that does not require layup asymmetry.

Lastly, the novel double-double layup design method, which is based on the homogenization of [±φ/±ψ] sub-laminates, needs to be compared to the current industry standard quad layup method based on strength under complex loads.

The following six points concisely sum up the main aims of the thesis.

1. Develop and validate a CLT-based analytical algorithm that can be used to carry out full-field optimization of shape-changing composites (stiffness) and double-double composites (strength).
2. Investigate the thermally induced mechanical work of asymmetric laminates with particular attention to the range between bistability and monostability.
3. Evaluate the performance of the tool compensation warpage mitigation method on both bistable and monostable asymmetric laminates.
4. Investigate whether hybrid laminates can outperform mono laminates by simultaneously reducing unwanted warpage and increasing the desired shape-changing performance (e.g. extension–twist coupling).
5. Analyse the effect of layup homogenization on the shape-changing behaviour of composite laminates.
6. Investigate whether the double-double layup method can improve the strength of composite structures compared to the industry-standard quad laminates.

3. Materials, methods and equipment

The mechanical behaviour of a composite product is highly dependent on the quality and ratio of the matrix and the fibres as well as the adhesion between the two. Pre-impregnated reinforcement sheets (prepregs) ensure optimal fibre to matrix ratios, which is important for the best possible product quality. As they are high quality and reproducible, only prepreg materials were used in this thesis.

The most likely adopters of shape-changing composites (e.g. the aerospace industry) usually work with the highest performance materials available. In the case of composites, this often means a cross-linked epoxy matrix and carbon fibre reinforcement. Primarily because of this, most of the experiments in this thesis were carried out using carbon-epoxy composites. Also, all materials used were unidirectionally reinforced (UD) as this allows for the best tailorability of the layup. The most used material in the thesis was Hexcel's IM7/913 carbon-epoxy prepreg (Hexcel Corporation, Stamford, USA). Hexcel's S-Glass/913 glass-epoxy prepreg (Hexcel Corporation, Stamford, USA) was used together with the carbon-epoxy prepreg in hybrid composites. Chapter 4.5. of the thesis discusses results of a joint academic–industrial project on double-double composites, for which a different carbon fibre–reinforced material was used than in other chapters (Toray T300/F934, Toray Industries, Tokyo, Japan). The relevant properties of each material can be found in Chapter 3.1. of the thesis.

The design and optimization processes were aided by programming and numerical finite element simulation software. I used the 2017b version of MATLAB (MathWorks, Natick, USA) for the analytical layup optimizations and for evaluating 3D scanning data. MATLAB was chosen for its outstanding ability to handle matrix operations, which is essential for multiple-variable optimizations that are based on the analytical classical laminate theory (CLT). To carry out numerical simulations, I used the 2019 R3 version of Ansys Workbench (Ansys, Canonsburg, USA) with its Composite PrepPost extension.

For experiments that required curved aluminium tools, I manufactured the tools using an MDX-540 4-axis milling machine with 0.1 mm accuracy (Roland DG Corporation, Hamamatsu, Japan). After assembling the laminates and wrapping them in vacuum bags on either flat or curved aluminium tools, they were cured in an autoclave. The ATC 1100/2000 autoclave (Olmar, Gijon, Spain) has two vacuum circuits and four thermocouples to accommodate multiple laminates simultaneously. The two most important parameters of the curing cycle in terms of product quality were the 140 °C plateau temperature (for 60 minutes) and the 7 bar overpressure (the detailed curing cycle can be found in Chapter 3.3. of the thesis). Later experiments were carried out at room temperature (25 °C) resulting in a difference of ΔT=115 °C between the cross-linking temperature and the test temperature. The cured laminates were cut to the exact specimen dimensions with a Diadisc 4200 precision cut-off saw with a diamond cutting disc (Mutronic Präzisionsgerätebau GmbH & Co. KG, Rieden, Germany).

The majority of the mechanical tests were carried out with Zwick's Z005, Z050 and Z250 universal testing machines (Zwick Roell Group, Ulm, Germany). The tests where twisting deformation under tensile load was measured were carried out with a hydraulic Instron 8872 universal testing machine with freely rotating grips (Instron Corporation, Norwood, USA). For accurate strain measurements, the displacements were recorded with a Mercury Monet video system capable of digital image correlation (DIC) measurements (Sobriety s.r.o., Kuřim, Czech Republic). The coefficients of thermal expansion were measured with KMT-LIAS-06-1,5-350-5E strain gauges (Kaliber Instrument and Measuring Technics Ltd., Budapest, Hungary) and a Spider8 general data acquisition device (HBM, Darmstadt, Germany). To analyse the warped shapes of the composite specimens, I used an ATOS 5M 3D scanner with its ATOS Professional 2018 software (GOM GmbH, Braunschweig, Germany) and evaluated the raw data in MATLAB.

4. Summary

Certain materials and structures can demonstrate non-conventional deformations as a result of different actuations. In my thesis, I use the terms "non-conventional deformation" or "shape-changing" to refer to any geometric change that is different in nature from the actuation itself (e.g. twisting deformation under bending load). Shape-changing materials can be advantageous in various applications (e.g. turbine blades or aeroplane wings with improved aerodynamic performance), and thanks to their industrial value, the number of research projects focusing on their investigation and development shows an increasing trend year by year. I started my research by reviewing the shape-changing concepts in the literature, categorizing them based on the nature of their actuation. I concluded that shape-changing fibre-reinforced composites stand out from the rest of the approaches, primarily due to their outstanding specific mechanical properties. In the second part of the literature review, I discussed the main modelling approaches of the elastic behaviour of composites and summarized what the scientific community has achieved in the topic of shape-changing composites so far. Finally, I identified some important and unsolved challenges in the field and set the aims of my thesis accordingly [6].

The coupled behaviour of fibre-reinforced composites (e.g. extension–twist coupling) results from their layup structure. Therefore, to achieve the desired shape-changing behaviour, the layup needs to be optimized. Due to the large number of possible layup permutations, a full-field analysis is usually only feasible using analytical models. The classical laminate theory is well suited to analyze the coupling terms of laminates. As the basis of my thesis, I developed a classical laminate theory-based layup optimization algorithm in MATLAB environment, with which I was able to automatically analyze the shape-changing behaviour of hundreds of thousands of laminates. I used the results of the algorithm (for stiffness and strength) in several chapters [8, 9, 11].

Based on the literature review, one of the major challenges is to mitigate the unwanted thermal warpage of shape-changing composites, as most of these laminates have asymmetric layups, and asymmetric layups tend to warp. Furthermore, depending on the layup and the edge-length to thickness ratio, the warped laminate might not be monostable but bistable, which introduces further challenges.

However, before trying to mitigate thermal warpage, first, I investigated how it can be exploited. The thermally induced out-of-plane deformations can be utilized to perform mechanical work, but I found no information in the literature on how the monostable-bistable transition affects the thermally induced mechanical work of composites. Therefore, I carried out numerical and experimental investigations on this. I demonstrated that the achievable thermally induced work goes through a local maximum and then a local minimum with decreasing edge-length to thickness ratios. In the bistable range, the reduction of the achievable work is associated with the appearance and increase of the second principal curvature of the laminate. This effect is overcompensated by the effect of the increasing relative thickness near the bifurcation point [1, 5].

Next, I investigated three approaches to mitigate the thermal warpage of asymmetric laminates: approaches based on tool compensation, hybrid layups and layup homogenization. Furthermore, I studied how the methods affect the shape-changing performance of laminates.

I experimentally investigated whether it is possible to manufacture monostable and bistable laminates flat with curved tools. The method proved to be effective in converting bistable laminates into monostable laminates and manufacturing monostable laminates practically flat. The unchanged layup structure retains the intrinsic coupled behaviour of the laminates, allowing for the exploitation of thermally induced mechanical work [1].

Hybrid laminates (e.g. carbon/epoxy – glass/epoxy hybrids) consist of plies with different material properties. Because of this, the mechanical, thermal, etc. properties of some of the hybrid layups may be more advantageous than what is possible with mono (non-hybrid) layups. I carried out numerical and experimental investigations to find out whether layup hybridization can increase the achievable shape-changing performance of practically warpage-free laminates. Layup hybridization significantly increased the achievable extension–twist performance. Or from another standpoint, the results showed that a given mechanically coupled performance can be achieved with hybrid laminates at lower thermal warpage than with mono laminates, i.e. the method is suitable for mitigating the warpage of shape-changing composites [2].

The layup of composites can be homogenized by repeating identical sub-laminates on top of each other. According to analytical results from the literature, layup homogenization can mitigate the warpage of asymmetric laminates, which I validated numerically and experimentally. However, the effect of homogenization on the mechanically coupled behaviour of composites has not been investigated yet. I demonstrated numerically and experimentally that the extension–twist performance decreases with homogenization with a similar tendency to the decrease of warpage, but the bend–twist performance is hardly affected in comparison. Furthermore, I showed that depending on the layup of the sub-laminate, layup homogenization can reduce or increase the value of any element of the *[d]* matrix [3].

Finally, I investigated the advantages of a novel layup design method from a strength standpoint by joining an international research group. The so-called double-double laminates consist of 4-ply [±φ/±ψ] sub-laminates that are homogenized through the thickness of the composite. I analytically proved that double-double laminates can have greater strength and thus lead to lighter structures than the industry standard – so-called quad – laminates, which consist of only 0°, 90° and ±45° plies [3, 4].

5. Theses

In the following, I summarize the main scientific results of my research in five theses. In each case, I start with a general description of the results, after which I state the thesis in a concise form. Further details regarding the investigations – on which the theses are based – can be found in the referenced chapters of the thesis.

Composites with asymmetric layups tend to warp with changing temperatures, which is usually an unwanted process. However, out-of-plane deformations can be exploited to move loads, making the laminate suitable for thermally induced mechanical work. By investigating analytically optimized $[45_n/90_n/\text{-}75_n/\text{-}45_n]$ Hexcel IM7/913 carbon–epoxy laminates, I showed that the bistable–monostable transition significantly affects the achievable thermally induced mechanical work (Chapter 4.3.). Experimental measurements of the laminate's principal curvatures showed that moving from the bifurcation point towards the bistable region – as the edge length to thickness ratio of the laminate increases – the second principal curvature converges to zero; therefore, in that region, not only the magnitude of the deformation changes but also the shape (Chapter 4.3.3.). With finite element simulations and experiments, I demonstrated that there is a region where the achievable thermally induced work decreases with the increasing relative thickness of the laminate (Chapter 4.3.4., simulation and experimental setup: Figure 35). Based on the numerical and experimental results, the local maximum of the achievable work is associated with the appearance of the second principal curvature. Based on my results, I concluded that the decreasing tendency of the achievable work from this point is due to the changing shape of the laminate (increasing second principal curvature), which overcompensates the effect of the increasing relative thickness. The end of the overcompensation is indicated by the local minimum of the achievable work near the bifurcation point, from where the increasing tendency continues.

Thesis 1

I showed that by increasing the thickness of fibre-reinforced composites with asymmetric layups, their maximum achievable thermally induced mechanical work goes through a local maximum and then a local minimum as they transition from bistability to monostability. This is because the changing shape of the laminate (the appearance and increase of the second principal curvature) overcompensates the effect of the increasing thickness between the two local extrema [1].

I showed that the thermal warpage of composite laminates with asymmetric layups can be compensated via designed dewarping by manufacturing them on curved tools (Chapter 4.4.1.). The essence of the method is that instead of manufacturing the laminate on a tool with the shape of the final product, the shape of the tool is modified. This alters the initial shape of the composite, which then approaches the desired shape due to manufacturing induced warpage, thus reducing the apparent warpage. Since the method does not modify the layup, the shape of the laminate remains temperature-dependent, i.e. further heating or cooling will result in out-of-plane deformations. This is essential for the exploitation of thermally induced mechanical work. I experimentally investigated the applicability of the warpage compensation method for both monostable and bistable laminates; on analytically optimized [$45_n/90_n/-75_n/-45_n$] Hexcel IM7/913 carbon–epoxy laminates. Based on experimental results, I chose the edge length to thickness ratio of the laminates to investigate the two types of behaviour in their pure forms. Therefore, within practical limits, I investigated monostable laminates with the largest possible second principal curvature and bistable laminates with the smallest possible second principal curvature. The experimental results showed an average warpage reduction of 11.7% when bistable laminates were manufactured on a "bistable shaped" (zero second principal curvature) tool compared to manufacturing on a flat tool, but the principal curvatures swapped places. From this, I concluded that the shape of the tool must compensate for the zero (i.e. hiding) principal curvature, too. Therefore, I also manufactured bistable laminates on a "monostable shaped" tool (where the magnitudes of the two principal curvatures were comparable). I observed an average warpage reduction of 23.3%, but more importantly, I managed to transform the bistable laminates into monostable ones. Since tool compensation provided a transition from the bistable region to the monostable region, the main question became whether the method was effective enough to manufacture monostable laminates flat. I demonstrated that the method is capable of reducing the warpage of monostable laminates by more than 90%, with which the flatness requirement of the ISO 2768 standard (tolerance class K) can be fulfilled.

Thesis 2

I demonstrated that the thermal warpage of both bistable and monostable asymmetric laminates can be compensated by manufacturing them on curved tools. The method is also capable of transforming bistable laminates into monostable ones. Since the method based on geometry compensation does not modify the layup, the shape of the laminate remains temperature-dependent, thereby retaining the feasibility of thermally induced mechanical work [1].

Through finite element simulations and experiments, I demonstrated that hybrid layups can be superior to mono (non-hybrid) layups in terms of their shape-changing performance. First, I numerically investigated the thermal warpage and the extension–twist performance of Hexcel IM7/913 carbon–epoxy and Hexcel S-Glass/913 glass–epoxy mono laminates and their hybrids. The two types of plies differ in a number of material properties, the most important ones, in this case, being the thermal expansion and the stiffness parameters. The idea is that hybrid layups (i.e. using more than one type of ply in the laminate) can achieve thermal and elastic properties that are impossible with mono layups. These complex effects can lead to mitigated unwanted thermal warpage and increased desired shape-changing performance. The aim of the full-field numerical optimization study was to find the layups from each laminate family (carbon–epoxy mono, glass–epoxy mono and carbon–epoxy/glass–epoxy hybrid) that possess the most significant shape-changing capability while remaining practically warpage-free (according to the ISO 2768 standard, tolerance class L) after the cooling stage of the manufacturing process. Based on these criteria and the input parameters (Chapter 4.4.2.), the best hybrid layup outperformed the best mono layup by more than 43%, i.e. it demonstrated that much more twisting deformation at the same elongation. For the best hybrid and mono layups, I experimentally validated the numerical warpage and extension–twist results. After the manufacturing process, I verified the fulfilment of the flatness requirement and the superiority of the hybrid laminate in terms of the shape-changing performance. In a similar numerical optimization study, I also showed that although hybrid laminates might be superior to mono laminates for some types of shape-changing behaviour, it is not a universal tendency. When optimizing the layup for maximum bend–twist performance, for instance, a mono (carbon–epoxy) laminate outperformed all hybrids, although the best hybrid laminate was only 2.5% off from the overall best performer.

Thesis 3

For practically warpage-free laminates that meet the flatness requirement of the ISO 2768 standard (tolerance class L), I demonstrated that hybrid layups can achieve larger twisting deformation under tensile load than mono laminates. The reason for this is that plies of different materials (e.g. carbon–epoxy and glass–epoxy) differ in both thermal expansion and stiffness properties, which in a hybrid layup can lead to mitigated thermal warpage and increased shape-changing performance at the same time [2].

In my thesis, I investigated the effect of layup homogenization on the manufacturing-induced thermal warpage and on two types of shape-changing behaviour of 32-ply laminates (Chapter 4.4.3.). Homogenization of the layup was achieved by repeating identical sub-laminates on top of each other. For $[0_n/90_n]_k$ Hexcel IM7/913 carbon–epoxy laminates (where k refers to the level of homogenization), I proved numerically and experimentally that homogenization can mitigate the extent of warpage by more than 97%. With further numerical investigations, I showed that the $[45_n/90_n/-75_n/-45_n]_k$ laminate – which I analytically optimized for maximal warpage – met the flatness requirement of the ISO 2768 standard (tolerance class L), from a homogenization level of eight. I carried out the extension–twist numerical simulations on $[30_n/90_n/90_n/-30_n]_k$ (also analytically optimized) laminates, and observed an approximately 90% reduction in the shape-changing performance at a homogenization level of eight – similarly to warpage. The reason for the similar tendency is that homogenization reduces laminate asymmetry, and with that, the values of the *[b]* matrix elements. In contrast, I demonstrated a significantly smaller change in the bend–twist performance of $[-30_n/90_n/90_n/-30_n]_k$ laminates with an increasing level of homogenization. However, homogenization even increased the shape-changing performance when the laminates were subjected to the same bending load – a 9% increase in the twisting deformation of the laminate was demonstrated at a homogenization level of eight. Furthermore, I proved with analytical calculations that layup homogenization can reduce or increase the value of any element of the *[d]* matrix, depending on the layup of the sub-laminate.

Thesis 4

I demonstrated that layup homogenization reduces the extension–twist performance of composites following a tendency similar to how it reduces the extent of thermal warpage. The reason for this is that both forms of behaviour require layup asymmetry, but the overall effect of sub-laminate asymmetry becomes less pronounced in the composite with an increasing level of homogenization. However, the bend–twist performance, which does not require asymmetry, can even increase with homogenization. This can result directly from the increase of the d_{16} value or indirectly from the increase of the d_{11} value, which can lead to increased twisting deformation through larger deflections. Furthermore, I showed that depending on the layup of the sub-laminate, homogenization can reduce or increase the value of any element of the *[d]* matrix; therefore, a general tendency can not be identified [3].

I carried out analytical strength analyses of double-double (DD) laminates by joining the international research group of Prof. Stephen W. Tsai (Stanford University, USA), the pioneer of the DD method. By the time I started working on the topic, a large amount of information had already accumulated on the laminate design method through analytical, numerical and experimental investigations. DD laminates consist of 4-ply [±φ/±ψ] sub-laminates, which are homogenized through the thickness of the composite, and they have several advantages over the current industry-standard quad laminates, which consist of only 0°, 90°, 45° and -45° plies and obey the 10% rule (a minimum of 10% of each orientation). In my thesis, I compared the two layup design methods based on maximum strain and first-ply-failure (classical laminate theory). I carried out the strength calculations for characteristic complex loads of two structural components using the material properties of Toray's T300/F934 carbon–epoxy prepreg. In the case of quads, I investigated multiple families based on the number of plies in the laminate (Chapter 4.5.). I demonstrated for both structural components that a more than 5% increase in strength was achievable with DD laminates, even when compared to the theoretical optimum of quad laminates. Furthermore, I highlighted that DD laminates can be homogenized effectively, while quads usually require layup symmetry due to their thicker sub-laminates, which further increases their disadvantage in the case of tapering, for instance. According to the analytical results, DD laminates require lower thickness than quad laminates in order to withstand complex loads; therefore, the weight of composite components can be reduced with the novel layup design method. In a comprehensive optimization process, aspects other than strength have to be considered, too (e.g. stiffness, buckling stability or ply-drops), which can further increase the advantage of double-double laminates, based on the results of the international research group.

Thesis 5

I proved that depending on the loading, double-double laminates can achieve greater strength than quad laminates, which can result in lighter structures. The main reason for this is that in double-double laminates, any fibre orientation can occur; therefore, the direction-dependent mechanical properties of the reinforcing fibres can be exploited more effectively [3, 4].

6. List of my publications

[1] **Vermes B.**, Czigány T.: Thermally induced mechanical work and warpage compensation of asymmetric laminates. Composite Structures (under review, submitted on 21st June 2021) IF=5.407 D1

[2] **Vermes B.**, Czigány T.: Improving the extension–twist coupling performance of practically warpage-free laminates via layup hybridization. Composites Science and Technology (under review, submitted on 17th September 2021) IF=8.528 D1

[3] **Vermes B.**, Tsai S.W., Massard T., Springer G.S., Czigány T.: Design of laminates by a novel "double-double" layup. Thin-Walled Structures, 165, 107954/1-107954/8 (2021) IF=4.442 D1

[4] **Vermes B.**, Tsai S.W., Riccio A., Di Caprio F., Roy S.: Application of the Tsai's modulus and double-double concepts to the definition of a new affordable design approach for composite laminates. Composite Structures, 259, 113246/1-113246/11 (2021) IF=5.407 D1

[5] **Vermes B.**, Czigány T.: Kompozitok hővetemedésének kihasználási lehetősége. in 'XXIX. Nemzetközi Gépészeti Találkozó (OGÉT 2021). Cluj-Napoca, Romania (online)', 144–147 (2021)

[6] **Vermes B.**, Czigány T.: Non-conventional deformations: Materials and actuation. Materials, 13, 1383/1-1383/26 (2020) IF=3.623 Q2

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[11] **Vermes B.**, Czigány T.: Layup optimization and ways to improve the manufacturability of coupled composites. in '22nd International Conference on Composite Materials (ICCM22). Melbourne, Australia', 4667–4673 (2019)

[12] **Vermes B.**, Thompson A., Belnoue J., Hallett S., Ivanov D.: Mitigation against forming defects by local modification of dry preforms. in '18th European Conference on Composite Materials (ECCM18). Athens, Greece', paper ID: 188729353 (2018)

[13] **Vermes B.**, Czigány T.: Development of microcapsules. Materials Science Forum 885, 31-35 (2017)