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STATIC AND DYNAMIC TESTING OF TEXTILE-REINFORCED COMPOSITE COMPLIANT STRUCTURES UNDER SHEAR-FORCE-FREE BENDING LOAD

High-performance applications in mechanical engineering and vehicle construction increasingly have to fulfil high demands concerning passenger comfort and the conservation of natural resources. Therefore, lightweight structures made of textile-reinforced composites exhibit a considerable application potential due to their inherently wide-ranging ability for function integration and design freedom. Additionally, the use of so-called compliant elements with specifically adjustable compliances offers the possibility to transmit motions simply by means of structural deformations. For the investigation of the deformation behaviour of such composite compliant hinge mechanisms as well as for the analysis of anisotropism-related coupling effects of multilayered composites, bending free of shear force can be used advantageously. This paper makes a contribution to the efficient cyclic testing of textile-reinforced compliant structures. Thus, a novel kinematic test rig has been developed, which can be utilized for the static and dynamic bending tests of composite (strip shaped) beam specimens. The main unit is a multifunctional six-membered linkage that allows a moment's application free of shear force by providing a pure bending load. The design studies mainly focus on the mechanical adaptation of an appropriate mathematical characterized mechanism to the trajectory of the movable restraint point. Furthermore, basic test results in consideration of the moment, force, and deformation of textile-reinforced compliant hinges are shown and evaluated with the help of computer tomography.

Keywords: textile-reinforced composites, compliant hinge mechanisms, cyclic testing

STATYCZNE I DYNAMICZNE BADANIA WŁÓKNISTYCH KOMPOZYTOWYCH STRUKTUR PODATNYCH SIŁĄ ŚCINAJĄCĄ BEZ ZGINANIA

Obecnie zaawansowane technologicznie aplikacje w budowie maszyn i pojazdów w coraz większym stopniu muszą spełniać wysokie wymagania dotyczące komfortu i ochrony zasobów naturalnych. W związku z tym konstrukcje lekkie z kompozytów włóknistych dzięki zdolności do integracji funkcji oraz dużej swobody projektowania posiadają znaczny potencjał aplikacyjny. Dodatkowo, zastosowanie tzw. „compliant elements" - elastycznych elementów ze specjalnie regulowaną podatnością oferuje możliwość generowania ruchu tylko przez odkształcenie strukturalne. Do badania zachowania odkształcenia tych elastycznych, kompozytowych zawiasów złączowych, a także do analizy anizotropii związanych z efektami sprzężenia wielowarstwowych kompozytów może być z powodzeniem stosowane zginanie bez sił ścinających. Przedstawiona praca wnosi wkład w rozwój badań zmęczeniowych elastycznych struktur kompozytowych wzmocnionych włóknami. W celu przeprowadzenia statycznych i dynamicznch badań zginania kompozytowych próbek płaskich opracowano nowe kinematyczne stanowisko badawcze. Jednostka główna jest wielofunkcyjnym, sześcioczłonowym mechanizmem, który zapewnia czyste zginanie bez występowania sił pochodzących od ścinania. Przedstawione prace projektowe koncentrują się głównie na mechanicznym dostosowaniu opisu matematycznego mechanizmu w odniesienu do trajektorii ruchomego punktu utwierdzenia. Ponadto, wyniki pierwszych badań z uwzględnieniem momentu, siły oraz odkształcenia wzmocnionych włóknami elastycznych zawiasów złączowych zostały zaprezentowane i zweryfikowane za pomocą tomografii komputerowej.

Słowa kluczowe: kompozyty włókniste wzmacniane tkaninami, mechanizmy podatne, badania zmęczeniowe

INTRODUCTION

Compliant mechanisms consist of special elements that have, according to their functional purpose, higher rigidity (rigid elements) or higher elasticity (compliant elements). Thus, specific linkages such as transmission and guiding mechanisms can be realized. Movement capability heavily depends on both the material used and the geometry of the rigid and elastic elements. Beyond that, the type, placement, and value of the loads influence the transmission function and the trajectories [1-6].

The analysis of existing standardized testing techniques for the determination of the bending properties of compliant mechanism links shows that these methods do not allow for a bending moment transmission free of shear and longitudinal force in general. Anyway, even in the investigation of composite materials this is mandatory because of the overlying stress conditions induced by longitudinal and shear stress, which lead to considerably modified failure mechanisms.

In the frame of the accomplished research work, novel concepts for testing arrangements free of shear force were developed and successfully verified by textile-reinforced compliant specimens. The presented studies in detail make a contribution to the design and development of an appropriate kinematic that realizes the precalculated trajectory of the restraint to apply pure bending. In this manner, an almost shear-force-free moment transmission can be assured without resigning from a rotatory drive, which is advantageous for endurance testing [7].

During the bending tests of thin plain structures, structural deflections will be realized onto the range of the elastic limit of the coating material, which necessarily requires proper tracking of the rotation points. These points result in the form of a circular arc due to the constant bending moment transmission, close to the ideal case. Thus, the aim of the special testing device development considered here is to realize the most possible accurate reproduction of the circular trajectory while simultaneously tracking the force input.

SELECTION OF MATERIALS

A key objective in the design of compliant hinge mechanisms is to obtain the most compact size. Moreover, the elastic potential of the hinge material can be advantageously used to achieve minimal energy consumption when opening or closing. Suitable materials must allow high, geometrically nonlinear elastic deformation of the compliant hinge members and endure the resulting high effort without injury.

The usefulness of metals as a compliant hinge element is rather limited due to its high stiffness. In comparison, non-reinforced polymers such as EP or PP systems can bear much higher elastic strains. Thermoplastics seem to be the best choice for compliant links. Using PP as a thermoplastic matrix system, a further increase of deformability can be achieved by textile reinforcements, since woven or knitted fabrics provide higher values as unidirectional reinforcements.

Textile reinforcement allows not only for the adjustment of structural hinge parameters but also for the adaptation of textile-specific parameters such as bond type and thread architecture for the purposeful design of compliant joints. These additional design options are directly provided by means of the specific manufacturing processes of the textile; thus, no further processing steps are necessary [8].

EXPERIMENTAL ANALYSIS OF PURE BENDING

For the experimental determination of the deformation behaviour of compliant mechanism links, pure bending can be used. Compliant mechanism links realised by symmetric multi-layered fibre composites will be approximated by thin (strip-shaped) beam specimens. Therefore a kinematic test stand was developed, which can be used for static and dynamic bending tests. The centrepiece is a six-bar mechanism that injects a pure moment or torque, devoid of any shear force. By means of this multiple actuated linkage, specimen loading under pure bending is guaranteed. The emphasis in the mechanism synthesis was on the adaptation of a suitable mechanism to the trajectory of the moving restraint point. A negligible difference between the exact mathematical description and the mechanically possible trajectory ensures a nearly pure (shear-force-free) bending moment installation.

Kinematic test stand

The technical task for the mechanism to be realized in a testing device is shown in Figure 1.

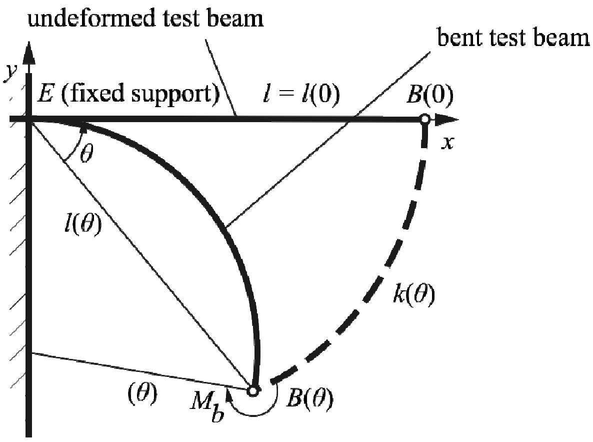

Fig. 1. Schematic exposition of projected bending test

Rys. 1. Schematyczne przedstawienie planowanej próby zginania

With l as the beam length, θ as the bending angle, and constant curvature radius ρ over the beam length for pure bending, according to Figure 1, result in the correlations

$$l(\theta) = l\frac{\sin\theta}{\cos\theta},\ \rho(\theta) = \frac{l(\theta)}{2\sin\theta} = \frac{l}{2\theta}$$

and for moving restraint point B, the trajectory is in parametric form:

$$x_B(\theta) = l(\theta)\cos\theta,\ y_B(\theta) = -l(\theta)\sin\theta$$

For a specimen beam length l = 300 mm and $\theta_{max} = 50°$, trajectory k reaches in interval $0 \le \theta \le \theta_{max}$ a maximum of 0.4% deviation with respect to a circular trajectory, i.e. point B moves in a circular arc with an adequate approximation.

With crank-rocker mechanism A_0ABB_0 that realizes an oscillation, bend angle θ_{max} can be generated [9]. A centric crank-rocker with a rotational drive (electric motor) is an inexpensive solution. The design layout of the test stand mechanism is shown in the initial and final position in Figure 2.

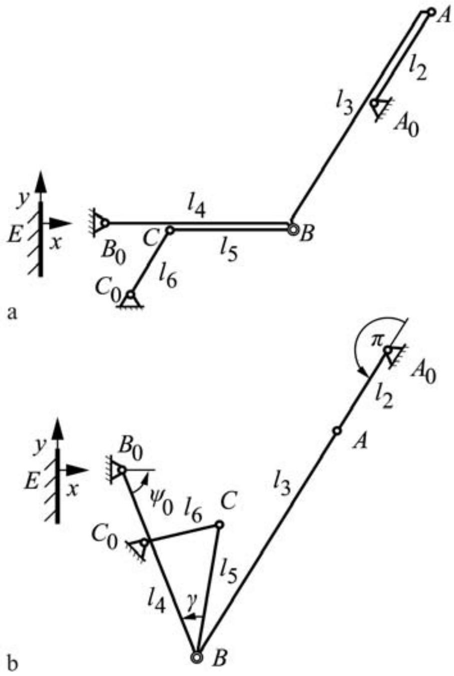

Fig. 2. Test stand mechanism design in initial position (a) and final position (b)

Rys. 2. Stanowisko badawcze, konstrukcja mechanizmu w pozycji wyjściowej (a) i w pozycji końcowej (b)

For a pure (shear-force-free) bending moment transmission in the movable restraint of the test beam at point B, it is necessary that bending moment M_b is held in the same direction in the testing structure at any time. The function can be done with sufficient approximation by the so-called ASSUR group C_0CB.

Figure 3 illustrates the final test stand design. The mechanism is driven by a step motor with specially adapted control technology.

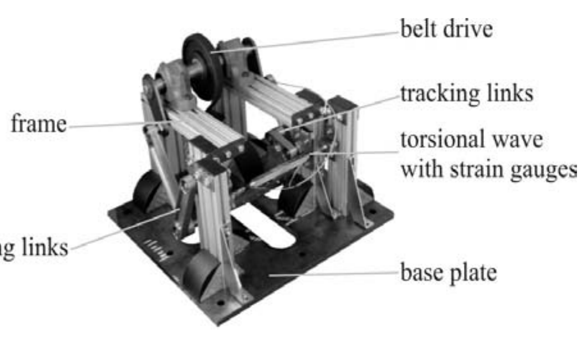

Fig. 3. Kinematic test stand for determining flexural properties of composite hinges

Rys. 3. Stanowisko badawcze pozwalające na określenie właściwości elastycznych kompozytowych zawiasów złączowych

Bending tests

For the function evaluation of the kinematic test stand and the characterization of appropriate hinge materials, textile-reinforced thermoplastic beam (strip shaped) specimens (GF/PP) were tested under long-term loading. The occurring moments and forces can be reliably detected by means of highly-sensitive strain gauges, whereas the hinge surface strains are calculated by the cognition of the trajectory and specimen geometry. In conclusion, the totality of the collected measurements allows the deduction of the bending stiffness. Figure 4 shows the results of an exemplary endurance test carried out with a speed of 83 rotations per minute (1.383 Hz). After more than 3 million load cycles, still no significant drop of the resultant bending moment can be monitored. Hence, the capability of glass fibre fabric reinforced polypropylene for hinges in compliant mechanisms is confirmed.

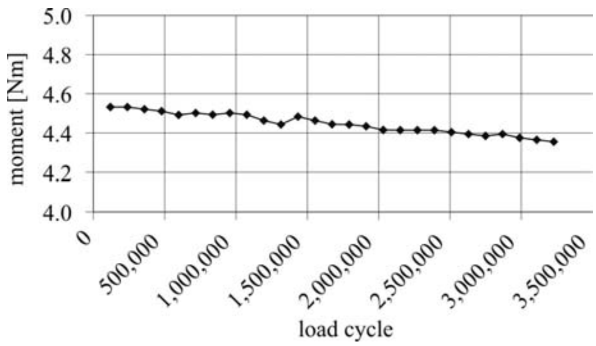

Fig. 4. Endurance testing of textile-reinforced polypropylene specimen with 1.383 Hz

Rys. 4. Badania zmęczeniowe o częstotliwości 1,383 Hz, próbki z polipropylenu wzmocnionego tkaniną

After endurance testing, a noticeable change of the specimen surface topology could be seen by visual inspection (Fig. 5).

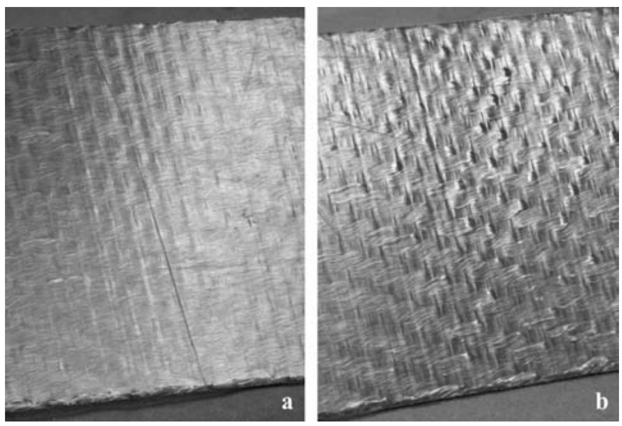

Fig. 5. Surface topology of GF/PP specimen before (a) and after (b) endurance testing

Rys. 5. Topologia powierzchni próbki GF/PP przed (a) i po (b) badaniach wytrzymałościowych

In detail, areas of fibre concentration seem to have dissolved away from the specimen surface as they are no longer supported by the circumfluent thermoplastic matrix system. It can be assumed that these effects are related to the marginal decrease of the resulting moment during long-term testing. Furthermore, a residual curvature of the formerly plain specimen can be monitored, which is caused by creep mechanisms occurring in the polypropylene in consequence of the permanent bending load.

To identify the reasons for the characteristic behaviour, an X-ray analysis was accomplished by use of a micro computer tomograph with a 180 kV micro focus tube and a 12 bit flat detector with a 50 μm x 50 μm pixel size. Figure 6 shows the magnified CT scans of an exemplary top view section and cross-section achieved by a voltage of 80 kV, a current of 400 μA, and a resolution of 5.5 μm/voxel. Hence, cracks in the thermoplastic matrix and inter-fibre cracks along the interface of glass fibres and polypropylene could be detected. The hinge surface is damaged by these cracks which start from the specimen surface and run through the thickness direction until they are stopped by a perpendicular glass fibre roving, in a manner that the matrix sections close to the surface are not able to support the embedded fibres any longer. This is the reason for the fractional dissolving of single fibre rovings located in the surface layers.

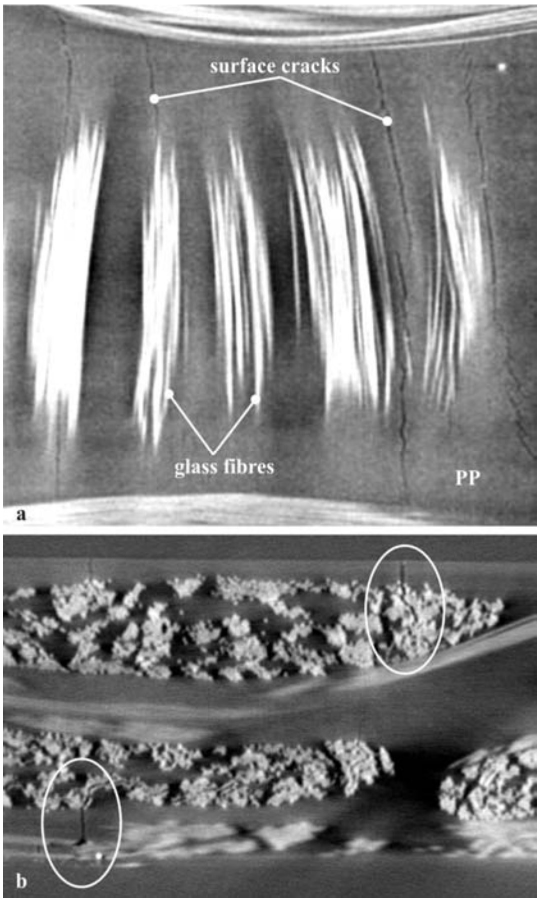

Fig. 6. CT through-thickness scan (a) and cross section scan (b) of GF/PP specimen after endurance testing

Rys. 6. Tomografia komputerowa struktury (a) oraz przekrój poprzeczny (b) próbki GF/PP po badaniach wytrzymałościowych

CONCLUSIONS

The developed bending test stand offers the possibility of static and dynamic analysis of compliant hinges by the transmission of shear-force-free bending. The presented work deals with the specific design and implementation of an appropriate kinematic, which realizes the pre-calculated trajectory of the restraint point. In this way, the input of nearly shear-force-free bending moments can be assured, without resigning from the rotary drive, which is very advantageous for endurance tests. Compared to conventional methods, the designed concept based on a crank-rocker mechanism allows for long-term testing under pure bending with high deflections and absolutely free of wear in the restraint zones.

The first endurance tests on selected compliant mechanism hinges made of glass-fibre-reinforced polypropylene were carried out successfully. The results show an almost constant resulting bending moment after more than three million load cycles even under the appearance of visible changes in the surface topology. By means of computer tomography analysis, identification of these changes such as matrix and inter-fibre cracks as well as a detailed evaluation have been accomplished.

Acknowledgement

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