Fatigue Behavior of Compliant, Pneumatically Actuated Glass Fiber-Reinforced Shading Modules: A Case Study of the FlectoLine Façade

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1 Abstract

Responsive façades provide an effective strategy for improving a building's energy efficiency while maintaining occupant comfort. Due to worldwide climate targets, the development of such adaptive systems is becoming increasingly relevant. FlectoLine addresses this issue: An adaptive façade shading system consisting of a glass fiber-reinforced polymer (GFRP)/elastomer hybrid laminate with integrated pneumatic actuation. The laminate architecture consists of thermoset GFRP layers with elastomeric interlayers and weather-resistant thermoplastic polyurethane (TPU) surface films. An intentionally asymmetric stiffness distribution around an internal pneumatic chamber enables reversible angular deflections of up to 90° at moderate actuation pressures of approximately 0.45 bar.

In 2023/24, a full-scale FlectoLine façade demonstrator with 101 modules, was installed in the Botanical Garden at the University of Freiburg in Germany. This demonstrator proves the feasibility of transferring compliant mechanisms to large-scale outdoor applications. Previous fatigue testing (35,000 cycles) and fire testing demonstrated mechanical durability and compliance with fire class B2/E. However, a gradual reduction in the required air pressure for actuation was observed in all installed modules during the first year of operation [2]. While full functionality was maintained, this behavior suggested potential aging effects related to the material or structure, for which no experimental evidence was available at that time.

The present study provides a systematic investigation of FlectoLine after three years of outdoor exposure. One representative façade element was dismantled from the installation and examined for wear and aging phenomena. Non-destructive ultrasonic testing was performed on the hinge and transition zone to detect internal damage, delamination, or changes in laminate integrity. These

investigations were complemented by mechanical testing to quantify alterations in bending stiffness and tensile strength.

The combined results allow for a systematic interpretation of the reduced actuation pressure observed during operation and distinguish between reversible material adaptation and critical degradation processes. Overall, this study provides insights into the long-term, real-world performance of pneumatically actuated GFRP/elastomer hybrid laminates, supporting their use in durable, low-maintenance, scalable, responsive façade applications.

2 Introduction

Adaptive façade shading systems have emerged as a key strategy in contemporary building design to reconcile energy performance with occupant comfort [14]. Unlike static envelope systems, these façades dynamically respond to changing environmental conditions such as solar radiation, temperature, and daylight availability [10, 13]. By modulating solar gains in real time, adaptive systems can significantly reduce cooling loads, mitigate glare, and enhance indoor environmental quality without compromising the visual connection to the outdoors [5]. In the context of increasingly stringent global climate targets, such responsive building technologies are gaining importance as, they offer a pathway to reducing operational energy consumption while supporting sustainable architectural design [8, 12].

Within this field, FlectoLine, see Figure 1a, represents a notable case study that explores the integration of material innovation and adaptive functionality on a façade at a scale suitable for real-world applications.

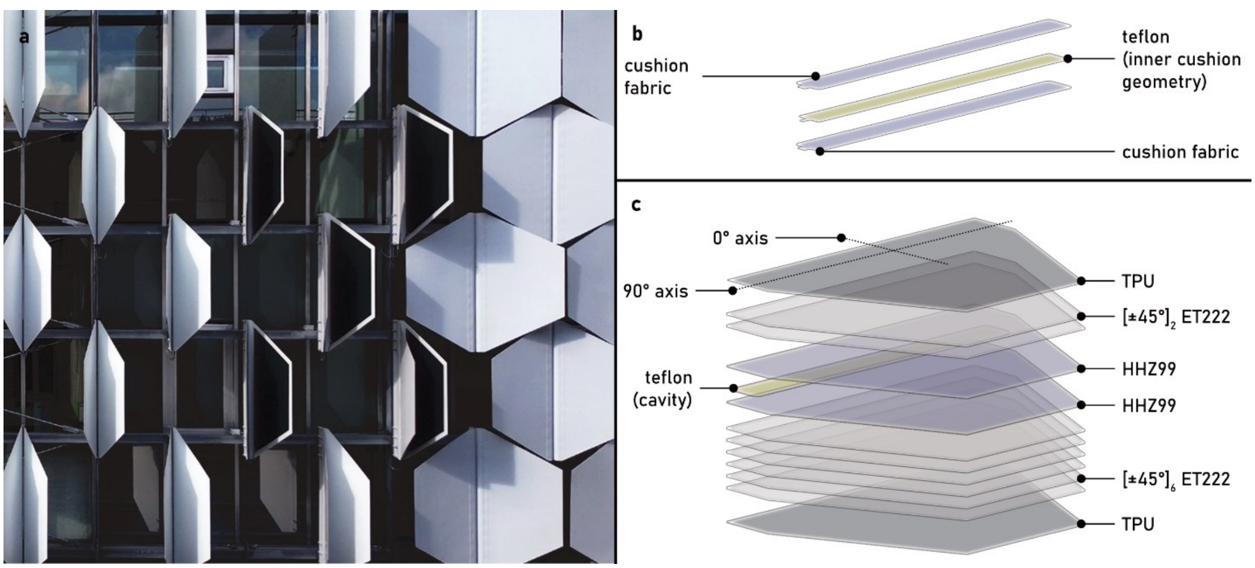

Figure 1 a) FlectoLine façade at the Botanical Garden (Freiburg/Germany), b) laminate setup of the actuator cushion, c) laminate setup of the thermoset FlectoLine element.

The system is based on a GFRP/elastomer hybrid laminate which enables a reversible change in shape through embedded pneumatic actuation. A pneumatic actuator in the form of a cushion is asymmetrically embedded in a premanufactured cavity within the laminate (cushion and laminate setup, see Figure 1b and c), resulting in bending deformation under inflation due to larger deformation of the top hinge part [9]. This approach, inspired by insect wings, allows the façade modules to adapt in response to environmental inputs, creating a lightweight, energy-efficient shading system. By combining material performance with environmental and user responsiveness, FlectoLine demonstrates how advanced composite materials and adaptive design principles can be synthesized into a scalable façade system, contributing to the broader development of intelligent and resource-efficient building envelopes.

2.1 Degradation Mechanisms in Fiber-Reinforced Polymers

Fiber-reinforced components with an epoxy-based matrix are susceptible to various environmental degradation mechanisms throughout their service life. Moisture ingress significantly compromises the epoxy matrix's structural integrity, often causing plasticization and measurable loss of mechanical properties. This moisture acts synergistically with ultraviolet (UV) radiation, resulting in extensive matrix erosion, micro-tears, fiber debonding, fiber loss, and void formation. [7]

Beyond environmental factors, these components undergo ongoing mechanical degradation due to the inherent viscoelastic behavior of the epoxy matrix. When subjected to continuous mechanical stress, the material undergoes time-dependent responses, specifically stress relaxation and creep processes. Over time, these processes manifest as sustained macroscopic deformations. [11]

Ultimately, these long-term environmental and mechanical behaviors significantly accelerate the fatigue damage process. Under cyclic loading, fatigue damage usually begins with the initiation of a crack, followed by its propagation. This progressive failure manifests as a complex combination of damage modes, including fiber breakage, matrix tears, fiber-matrix interfacial debonding, and delamination. [6]

3 Material and Methods

3.1 Materials

The FlectoLine module is made of a GFRP-elastomer hybrid material with a TPU surface film. The materials are listed in Table 1 and the laminate setup is shown in Figure 1c. Each material is assigned a specific task within the locally compliant FlectoLine module. The GFRP component determines the stiffness of the laminate, defining the bending direction and necessary actuation force. The TPU film provides weather resistance, both visually and mechanically. It also gives the laminate a pure white color, which is an important aesthetic criterion for its application in an architectural context as a façade module. The elastomer provides interlaminar strength in the actuation plane and prevents delamination. It is also assumed that the elastomer can compensate for stress peaks within the material.

3.2 Façade Actuation Monitoring

The motion of the adaptive façade modules is monitored using an automated control and sensing system designed to capture their real-time kinematic behavior. The angular displacement of the modules is continuously measured to track their opening and closing states. In addition to the kinematic response, the system records the actuation input in the form of pneumatic pressure, enabling the relationship between input (pressure) and output (angular displacement) to be evaluated.

Table 1 Materials used for the FlectoLine module and their mechanical properties [2].

ID	description	thickness	density	modulus	shear modulus	elongation at break	tensile strength
		h	ρ	$E_{\parallel,\perp}$	G	ε	$R_{\parallel,\perp}$
		[mm]	[g/cm³]	[MPa]	[MPa]	[%]	[MPa]
ET222	glass fiber-epoxy prepreg (twill weave 2/2; 165 g/m²)	0.13	2.02	16,600	6,900	2.4	546.5
HHZ82	elastomer film (EVA-based)	0.39	1.37	5.60	-	463.0	12.5
TPU	thermoplastic elastomer film (urethane-based)	0.25	1.10	126.40	-	56.8	7.2

[a] Manufacturer: Toray Group Composite Materials (Italy) S.r.l; Trade name: ET222
[b] Manufacturer: Gummiwerk KRAIBURG GmbH & Co. KG; Trade name: HHZ9628/82
[c] Manufacturer: Gerlinger Industries GmbH; Trade name: 4980

The acquired data are integrated into a central control system, where measurements are recorded at regular intervals (minute-level logging). The resulting dataset consists of timestamped records of angular position and actuation pressure over an extended monitoring period. This enables multi-scale analysis of façade behavior, including daily actuation profiles and seasonal variability. The high-resolution data further support the identification of oscillatory behavior, operational regimes, and anomalous events.

3.3 Non-Destructive Testing

3.3.1 Ultrasonic Testing

Ultrasonic testing (UT) was conducted to assess possible internal damage within the laminate, with particular focus on the flange and hinge-related regions of the dismantled FlectoLine module. Three specimens of each tested area (1: flap [reference], 2: flap [FlectoLine module], 3: top hinge, 4: bottom hinge, and 5: transition area hinge-to-flap left side/6: transition area hinge-to-flap right side) were inspected using an OmniScan MX2 unit equipped with a 5 MHz, 64-element phased-array probe (Olympus). Due to the different ultrasonic wave velocities in the TPU, HHZ82 and GFRP layers, conventional layer-specific calibration was not feasible for the present hybrid laminate. Therefore, the inspection setup was calibrated using the total measured thickness of the specimen as an effective through-thickness reference. Although this approach does not resolve the individual material layers separately, it enabled a practical assessment of the laminate interior and allowed screening for possible subsurface discontinuities such as tears, delaminations, or other internal flaws.

3.4 Mechanical Testing

3.4.1 Tensile Testing

Residual tensile strength was evaluated according to DIN EN ISO 527-4 standard [3] (testing setup, see Figure 2a), with a testing speed of 2 mm/min, specimen dimensions 25 x 250 mm, and a sample size of n = 5. For tensile testing, a Z100 materials testing machine from ZwickRoell with a 100 kN load cell was used. The specimens were tested in the direction of the hinge axis of the FlectoLine module (90° axis in Figure 1c).

3.4.2 Roller Peel Testing

To quantify the interfacial adhesion and investigate the failure mechanism observed in the FlectoLine modules, roller peel tests were conducted according to the DIN EN 1464 standard [4] (testing setup, see Figure 2b). This methodology was specifically selected to recreate the delamination occurring within the flexible top part of the hinge, located between the two GFRP layers. The hinge of the FlectoLine module and a reference, non-weathered virgin laminate were cut to a standard width of 25 mm. The experiments were executed utilizing a Servo-Hydraulic Zwick RetroLine testing machine with a 100 kN load cell, equipped with a roller peel fixture. A displacement rate of 100 mm/min was used to test the specimens. For each experimental configuration, at least three specimens were tested to ensure statistical repeatability.

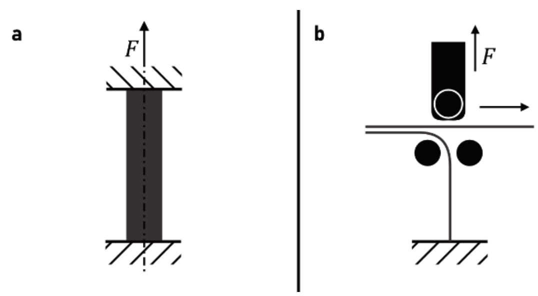

Figure 2 Schematic drawings of the conducted tests;
a) tensile test acc. to ISO 527-4, b) roller peel test acc. to DIN EN 1464 with roller diameter 25 mm.

4 Results

4.1 Operational Patterns of the Façade System

The system can operate under two control approaches: either by directly applying pressure and inflating the cushion, resulting in a corresponding angular displacement, or by specifying a target angle, with the control system adjusting the pressure accordingly. During the initial phase of operation, the system was controlled primarily through pressure input. Over time, however, a conditioning effect was observed, where progressively lower pressure was required to achieve the same angular displacement. This behavior is attributed to material settling and cyclic softening within the hinge mechanism. As a consequence, the modules occasionally exceeded the intended maximum angular deformation of 90°, which may have contributed to increased material fatigue.

A clear temporal pattern can be identified in the actuation behavior of the adaptive façade system at both daily and seasonal scales. The modules are primarily activated during weekdays, corresponding to the building's occupancy schedule, indicating that system operation is aligned with periods of active use. At the same time, the façade remains largely inactive during winter months and extended periods of spring and autumn, when maximizing solar gains is beneficial for thermal performance. Increased actuation is therefore concentrated in periods with higher solar exposure, where dynamic shading becomes necessary.

4.2 Fatigue examination of FlectoLine module

4.2.1 Visual Examination

As part of the development of FlectoLine, it has already been revealed that the actuation pressure of the modules has been reduced by nearly 50 %, from the initial approx. 0.45 bar to approximately 0.19 bar [2]. To analyze the cause, one FlectoLine module from the bottom row of the façade was dismantled and first subjected to a detailed visual inspection, see Figure 1.

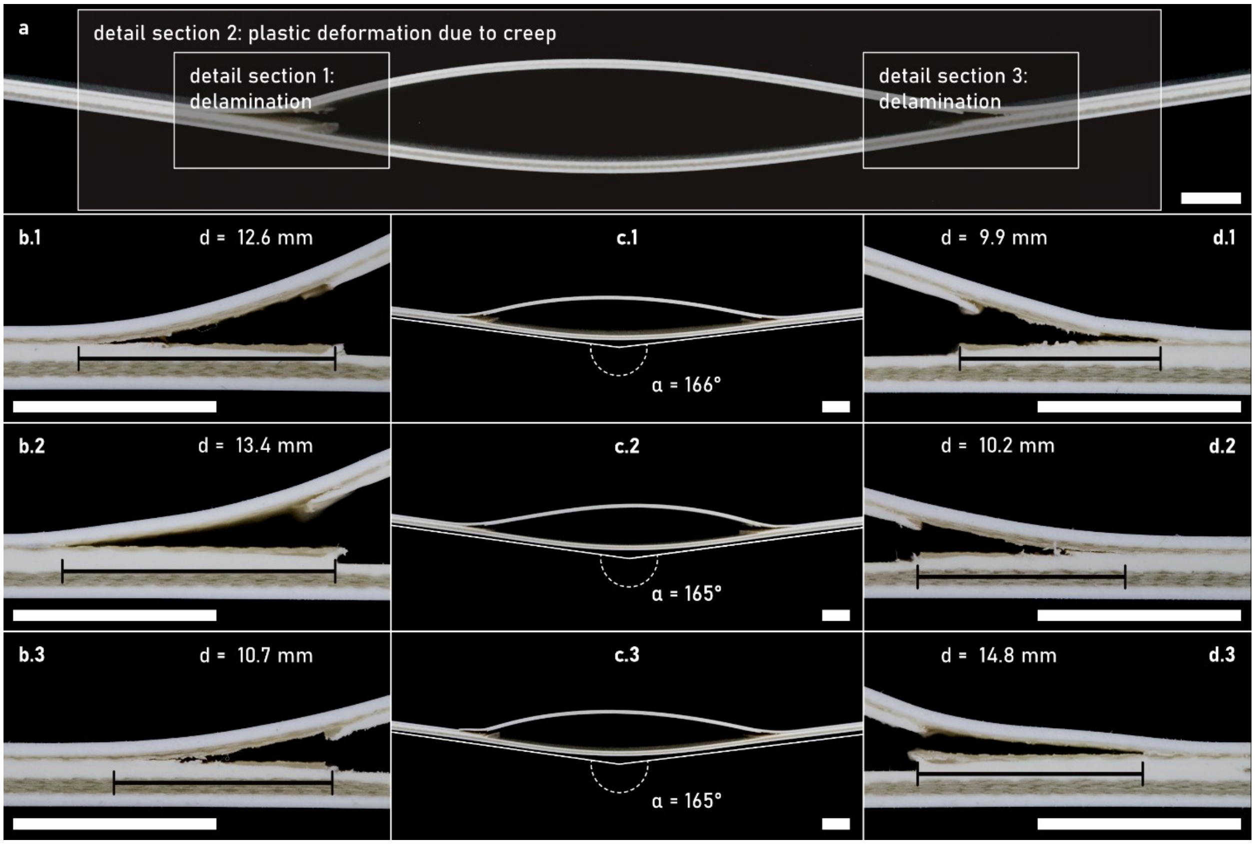

Figure 1 Visual examination of three representative specimens (25 × 250 mm) from the hinge zone of a FlectoLine module, scale bars: 10 mm; a) overview of one specimen with markings indicating the sections for detailed views b–d, b) detailed view of the delamination with dimensioning on the left hinge-to-flap transition, c) plastic deformation measured by angle over the full width of the hinge, d) detailed view of the delamination with dimensioning on the right hinge-to-flap transition.

It can be seen that delamination has occurred starting from the actuation cavity. The delamination to the right and left of the actuation cavity is shown in detail in Figure 1b and Figure 1d for three specimens. The delamination length is 11.9 ± 2.0 mm. At the same time, plastic deformation due to creep is visible, see Figure 1b–d.2. Starting from an initial flat state with an angle of 180°, plastic deformation of approximately 15° has occurred after three years of service.

4.2.1 Ultrasonic Testing

An ultrasound inspection was conducted to identify potential internal defects that were not visible on the specimens' surfaces. However, no indications of internal tears, delaminations, or other discontinuities were observed in regions without visible damage. Thus, while visible damage was noted, no evidence of further flaw propagation within the laminate thickness was found within the detection capability of the ultrasonic testing approach. Figure 3 shows representative scan results.

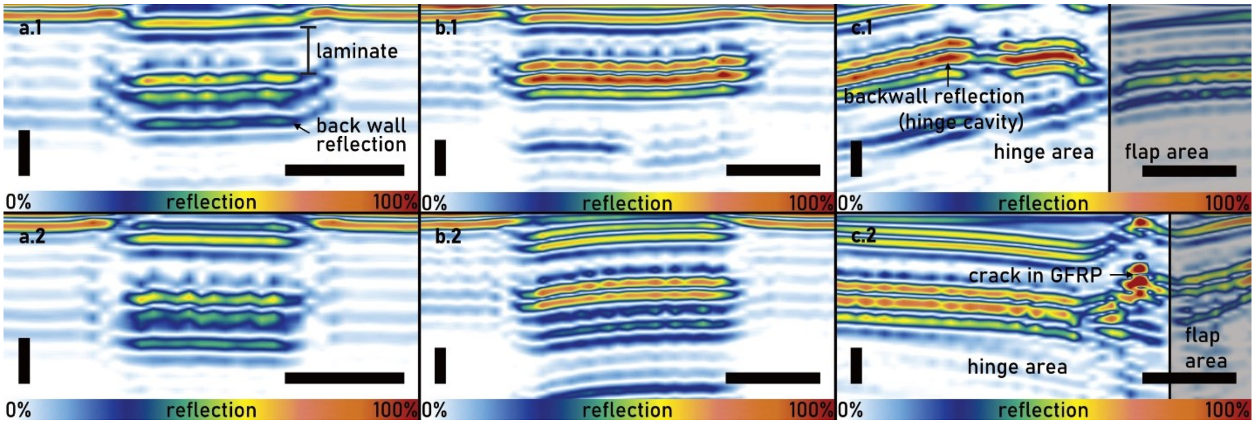

Figure 3 Representative scan results of Ultrasonic Testing, scale bar x-direction: 1 mm, scale bar y-direction: 10 mm; laminate setups: a.1) flap non-weathered, a.2) flap weathered, b.1) top (flexible) hinge part, b.2) bottom (stiff) hinge part, c.1) transition hinge and flap without crack in GFRP layers, c.2) transition hinge and flap with crack in GFRP layer.

4.2.2 Tensile Testing

The results of the tensile tests are presented in Table 2. As can be seen, there is no significant difference in performance between the reference flap area and the flap area from the dismantled FlectoLine module. These results align with those of the laboratory weathering tests from [1].

Table 2 Results of the tensile tests (according to DIN EN ISO 527-4 [3]) with a theoretical tensile strength calculated from the non-weathered reference for the three tested sections of the FlectoLine module.

class	material setup	tensile modulus $E_{\parallel,\perp}$ [MPa]	tensile strength $F_{\parallel,\perp}$ [N]	theoretical tensile strength $F^*_{\parallel,\perp}$ [N]	difference in load bearing capacity [%]
reference	flap – reference [TPU/(ET222 ±45°)$_2$/HHZ99$_2$/(ET222 ±45°)$_6$/TPU]	3,035 ±64	4,887 ±200		
FlectoLine module	flap [TPU/(ET222 ±45°)$_2$/HHZ99$_2$/(ET222 ±45°)$_6$/TPU]	2,927 ±149	5,314 ±537	4,887	+9
	top hinge [TPU/(ET222 ±45°)$_2$/HHZ99]	1,555 ±98	1,011 ±115	1,220	-17
	bottom hinge [TPU/(ET222 ±45°)$_6$/HHZ99]	4,105 ±72	3,210 ±456	3,665	-12

Regarding material strength, the weathered and non-weathered flap areas demonstrate comparable performance. Although the weathered samples exhibited a higher mean tensile strength (+9 %), this difference is not statistically significant due to the high standard deviation of the test results (σ = 10 %). Furthermore, calculations for the top and bottom hinge areas reveal that the top hinge possesses a significantly lower tensile strength compared to the calculated baseline of the non-weathered hinge (17 % reduction, σ = 11 %). Conversely, the 14 % reduction in tensile strength observed in the bottom hinge with hinger rigidity is not statistically significant (σ = 14 %).

4.2.3 Roller Peel Testing

The experimental methodology successfully reproduced the delamination mechanism observed on the outdoor façade. The reference, non-weathered specimens were manually pre-damaged via localized bending (>90° with a small bending radius) to initiate a critical fracture within the flexible FRP layer. Testing these pre-damaged specimens yielded a load-displacement response directly comparable to that of the weathered samples. The peel force profile revealed a prominent initial peak within the first 10 mm of displacement. This localized load spike corresponds to the structural resistance of the unbroken HHZ99 layer, which effectively holds the composite layup together prior to failure. Once the ultimate strength of the HHZ99 layer was exceeded and tearing occurred, the initial GFRP fracture propagated into a continuous delamination of the flexible layer, plateauing at a steady-state peel force of 1 N mm^{-1}.

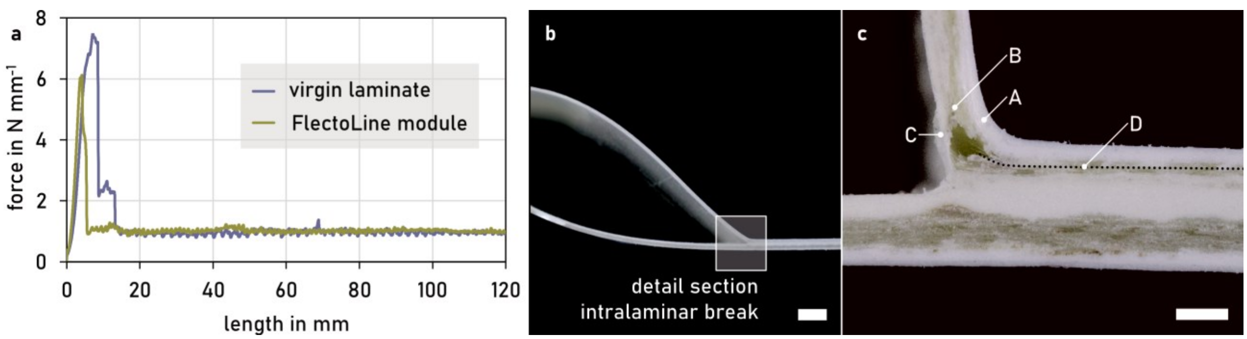

Figure 2 Results of roller peel test; a) diagram of the peel force of a specimen made from virgin laminate and a specimen made from a three-year-old FlectoLine module, b) image of the cross-section of a specimen from the FlectoLine module and markup of the hinge-to-flap transition (scale bar: 5 mm), c) detail view of the cross-section of the transition area marked in Figure 2b) (scale bar: 1 mm) with A) TPU surface film, B) GFRP part of flexible (top) hinge part with crack at transition point, C) HHZ99 layer of the flexible (top) hinge part and D) visualization of delamination progression in GFRP part of flexible (top) hinge under peel force load with dotted line.

5 Discussion

After three years of operation, analysis of the FlectoLine modules proves that weathering itself has generally no effect on the mechanical performance of the GFRP/elastomer hybrid composite. However, the dynamical load due to the bending motion causes defects in the overall structure at the macro level in the transition zone from hinge to flap and within the material itself at the micro level in the hinge area. At the macro level, delamination is observed, likely caused by the over-actuation of the FlectoLine modules when controlling the elements based on pressure values during initial operation. If the bending angle is too large, a bending radius that is too small develops at the hinge-to-flap transition. This can result in a fracture of the GFRP layer in the top hinge. Consequently, during cushion inflation, the elastomer layer cracks and, due to the lower adhesion between two GFRP layers compared to the adhesion between GFRP and the elastomer layer [1], progressive delamination occurs between the two GFRP layers in the top hinge part. These effects are not expected if the top hinge part is reinforced with textile-based reinforcement rather than brittle, fiber-reinforced plastic to limit elastomer deformation.

Ultrasonic inspection further indicated that the observed damage was limited to the regions that were visibly affected. No internal tears or delaminations were detected in areas of the laminate that were not visibly damaged.

Furthermore, creep was observed in the hinge zone at the macro level. Mechanical testing demonstrates that both the modulus of elasticity of the flexurally stressed hinged area and the force-absorption capacity are reduced. This confirms the hypothesis already proposed in [1, 2] that, on the micro level, the epoxy resin in the GFRP layer fails due to brittle fracture caused by alternating bending stress. As a result, force transmission between the fibers is reduced and the load-bearing capacity is decreased.

6 Conclusion and Outlook

The study demonstrated that FlectoLine modules exhibit significant damage after just three years, as evidenced by a reduction of approximately 50 % in the actuation force required to achieve the same bending angle. This damage manifests as delamination and micro-tears in the GFRP layer. In summary, it can be said that the change in the mechanical properties of the FlectoLine modules is caused, on the one hand, by the alternating bending load itself and, on the other hand, by the over-actuation of the modules. However, even with perfect control, over-actuation cannot be completely avoided due to wind loads [2]. In such cases, the control system would need to take into account the deflection caused by the wind load.

Future research must investigate which alternative materials can be used for the flexible side of the hinge, and which design guidelines regarding stiffness in relation to maximum deformation should be taken into account for pneumatically actuated hinges. In addition, the flexible (top) part of the hinge could be replaced by a flexible yet geometrically constraining structure.

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