

Fiber-Reinforced Compliant Hinges with Shape Memory Alloy Actuation for Responsive Façades

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Abstract

Responsive façade systems require lightweight and robust actuation strategies capable of adapting building envelopes to changing environmental conditions while minimizing mechanical complexity. This paper presents the development of shape memory alloy (SMA)-actuated glass fiber-reinforced polymer (GFRP) compliant hinges for adaptive shading applications. Building upon previous research on pneumatically actuated compliant façade systems, the study investigates an actuation approach in which SMA wires are embedded within composite compliant mechanisms to generate controlled bending through thermally induced contraction. A systematic design and development framework is proposed, covering the entire process from target deformation to experimental validation. The mechanical behaviour of the compliant hinges was characterized through Force–Rotation–Stroke experiments to establish the relationship between hinge geometry, stiffness, required actuation force, and achievable deformation. Based on these results, SMA wires were integrated into the laminate using Bowden tubes to enable reliable actuation while protecting the actuator within the composite structure. Experimental results achieved the target bending deformations of 145°. SMA activation produced smooth and progressive shape transformations, confirming the feasibility of the proposed actuation strategy. The research demonstrates the potential of SMA-integrated GFRP compliant hinges as compact, lightweight, and mechanically simplified alternatives to conventional adaptive façade actuation systems and establishes a foundation for the future development of multifunctional responsive composite material systems capable of more complex and multidirectional deformation behaviours.

Keywords: shape memory alloys (SMA), glass fiber-reinforced polymer (GFRP), compliant mechanisms, façade shading, design methodology, Nitinol (NiTi), Bowden tube.

1. Introduction

Responsive façade shadings have become increasingly important in contemporary architecture as buildings are required to address both environmental performance and occupant comfort under rapidly changing climatic conditions [1]. As solar radiation is one of the primary drivers of indoor heat gain and glare, adaptive façade systems capable of dynamically regulating solar exposure offer significant potential for reducing operational energy demand while improving indoor environmental quality [2]. Unlike static shading systems, responsive façades can continuously adapt to variations in weather and user requirements, enabling optimized daylight admission, thermal regulation, and visual comfort

throughout the day [3]. In addition to lowering the dependence on mechanical heating, cooling, and lighting systems, responsive shading façades also create opportunities for integrating renewable energy harvesting technologies by building integrated photovoltaics (BIPV) [4].

Research on bio-inspired compliant mechanisms demonstrated that the elastic deformation of fiber-reinforced polymer (FRP) composite materials can replace conventional hinges and rigid-body mechanisms in responsive façades [5]. Recent research projects demonstrated the potential of integrated pneumatic actuators within GFRP structures, enabling large-scale responsive shading modules with reduced mechanical complexity and high geometric flexibility [6-9]. Building up on these developments, this research investigates new possibilities of actuation systems aiming for a more compact embedded actuation strategy. Instead of relying on high volume pneumatic actuators integrated within laminate hinge zones, this research explores the use of SMA as compact, lightweight, and highly efficient embedded actuators for compliant façade components representing a shift toward materially integrated responsiveness, where material and actuation can achieve higher integration.

1.2. Embedded SMA actuation in GFRP compliant hinges

SMA are materials with excellent actuation and sensing capabilities that are increasingly used in medical, aerospace, and automotive applications due to their lightweight design, silent operation, and high performance [10]. SMA are particularly promising for responsive architectural systems due to their high volumetric work density, reaching up to 107 J/m³, which is among the highest of all known actuators [11]. Their ability to generate large forces and significant reversible deformation within extremely compact dimensions enables a substantial reduction in actuator size and system complexity compared to other systems such as electromagnetic or pneumatic actuators [12].

Current research increasingly focuses on the integration of SMAs into FRP composites to create responsive systems. Embedding SMA actuators within FRP systems enables lightweight structures to achieve active deformation, sensing, and actuation capabilities [13]. FRP composites with integrated SMA actuators offer several advantages, including high energy density, smooth and controllable deformations [14], and straightforward integration into textiles, elastomers, and 3D-printed components [15]. Furthermore, deformation behavior can be tailored through fiber orientation, stiffness distribution, and SMA placement, enabling localized and complex three-dimensional shape transformations [16].

The paper therefore investigates the design, fabrication, and mechanical behavior of GFRP compliant hinges with embedded SMA actuation for potential responsive shading applications. In the present research, the actuation strategy exploits the shape memory effect of SMA wires, where thermally induced contraction is used to generate controlled motion via the embedded material compliance. Particular focus is placed on the relationship between hinge geometry, and deformation. To expand the potential application range, the developed actuation concept targets angular deformations of up to 145°. Such capabilities are particularly relevant for responsive shading systems where increased angular deformation can improve energy harvesting performance with BIPV. The developed hinge concept relies on compliant zones within the composite laminate that allow elastic bending without the use of conventional mechanical joints. Embedded SMA wires are positioned along the longitudinal side of the composite element and anchored at both ends, where their thermally activated contraction generates tensile forces across the laminate. As the SMA elements shrink during activation, they induce asymmetric stresses within the compliant hinge zone, causing the element to bend (Figure 1). This embedded actuation strategy enables compact and lightweight responsive elements capable of achieving larger angular deformations than previously reported pneumatic actuation systems, which targeted angular deformations of 90°. Through this work, the research aims to contribute to the development of a new generation of sustainable responsive façade systems in which material, compliant behavior, and actuation are fully integrated into a unified responsive shading element.

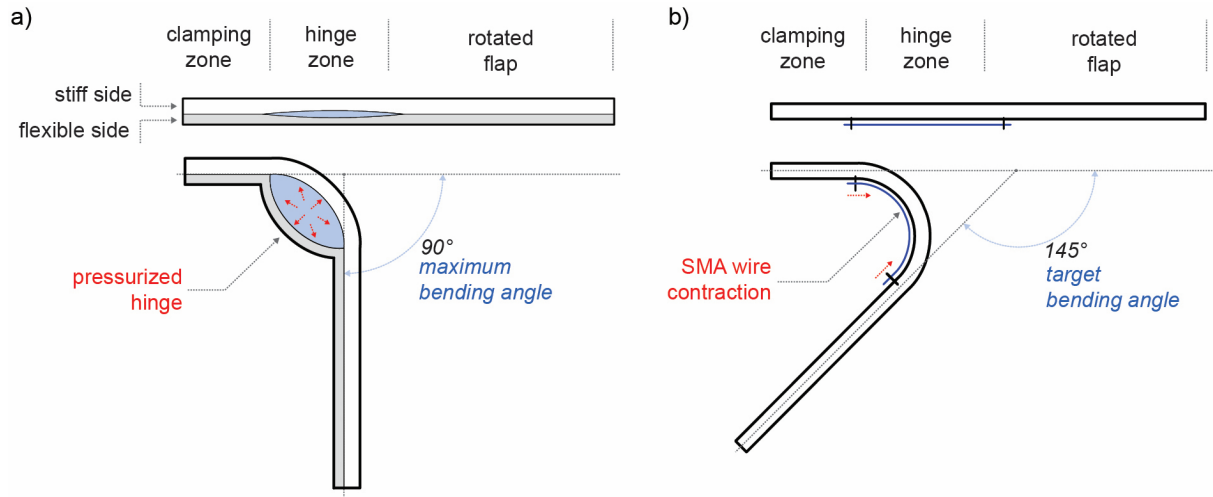


Figure 1: a) Actuation force and bending behavior of FlecoLine module based on chamber pressurization; b) Actuation and force and bending behavior of GFRP hinge with integrated SMA.

2. Hinge development methodology

The process begins by defining the target deformation and designing the hinge geometry through parameters such as gradient distribution, hinge dimensions, and laminate thickness. The mechanical behavior of the hinge is then characterized through bending tests to determine the required actuation force and deformation capacity by developing Force-Rotation-Stroke curves. Based on these results, an appropriate SMA actuator is selected according to its thermomechanical properties and integrated into the hinge region through different placement and attachment strategies. A control system based on Joule heating is subsequently developed to activate the shape memory effect. Finally, test specimens are fabricated and experimentally validated through thermal cycling, stiffness, and deformation tests. The results are iteratively evaluated against the design requirements until the desired adaptive performance is achieved.

2.1. Definition of target deformation

The deformation strategy for the proposed compliant hinge system is structured as a progressive development process that transitions from simple one-dimensional deformations toward increasingly complex multi-directional kinematic behaviours. This research focuses on the initial investigation phase on simple deformation modes characterized by single-axis kinematics. By limiting the deformation behaviour to elementary angular deformations, the relationships between hinge geometry, and SMA actuation can be more effectively analysed and optimized.

2.2. Hinge geometry and design

Based on the target deformations, the geometric configuration of the hinges is developed through parameters such as gradient design, hinge width, hinge length, and hinge thickness. By systematically varying and experimentally evaluating these parameters, the relationship between hinge geometry, stiffness, and the required actuation forces can be identified. This characterization provides the first basis for understanding the mechanical behavior of the compliant hinge.

2.3. Hinge performance characterization via Force–Rotation–Stroke curves

Hinge performance characterization is conducted through curvature-controlled bending experiments designed to establish the relationship between applied force, actuator stroke, and resulting rotational deformation of the compliant hinge. In the present study, stroke is defined as the linear displacement applied to the specimen through the tensioning cable, corresponding to the shortening distance required

to induce bending within the hinge region. For this purpose, two complementary testing approaches were developed: a manual and a digital setup for mechanically induced deformation experiments. In both configurations, the specimens were subjected to axial tension in order to induce controlled bending within the compliant hinge regions. The experimental setups enabled the extraction of force, stroke, and bending angle data, allowing the generation of Force–Rotation–Stroke curves for the evaluation of deformation behaviour. The manual testing rig provided an initial characterization of the mechanical response of the hinge system; in this method axial tension is applied through a pulley system using stackable weights to generate controlled loading conditions. In the digital setup the manual weight system is replaced by a servo motor with a cable spool whose rotation angle process the stroke, enabling automated and programmable displacement control. A load cell continuously measures the applied tensile force. In both cases an integrated optical angle detection records the corresponding bending angle.

2.4. SMA actuator selection

SMA are commercially available in several forms, including wires, springs, tubes, foils, and plates [17]. Among these, the selected form for this research is wires since they are particularly suitable for GFRP materials systems due to their ease of integration into composite structures.

SMA can further be classified according to their functional behavior into one-way shape memory effect, two-way shape memory effect, and superelasticity, [18]. The present work utilizes the one-way shape memory effect because of its reliability, and commercial applicability. The experimental investigations employ a 0.38 mm diameter Nitinol (NiTi) wire supplied by Ingpus GmbH. This has an austenite finish temperature of approximately 90 °C was selected to ensure that phase transformation occurred only through controlled Joule heating and not through passive environmental heating. Typical NiTi SMA wires provide about 4–8% contraction, however, this contraction is often limited to 4–5% to ensure high fatigue resistance. Since the recoverable contraction or stroke is assumed to be 5% of the total SMA wire length, the required wire length (L) can be calculated as:

$$L = \frac{\text{Stroke}}{5\%} \quad (1)$$

For the calculation of the wire diameter, equation (2) is used. F represents the maximum force obtained from the Force–Stroke–Angle curves and d denotes the diameter of the circular SMA wire cross-section. For σ typical design stress of NiTi SMA wires in the range of 300–500 MPa [19] is assumed.

$$\sigma = \frac{F}{A} \text{ and } A = \pi \frac{d^2}{4} \rightarrow \sigma = \frac{4F}{\pi d^2} \rightarrow d = \sqrt{\frac{4F}{\pi \sigma}} \quad (2)$$

2.5. SMA placement into hinges

Once the SMA type and specifications have been identified, the actuator placement within the hinge system is defined. This includes the configuration of the SMA path, such as linear or zigzag arrangements, based on actuator length and spacing relative to the hinge geometry. The positioning strategy directly influences the resulting deformation mode, amplitude, and actuation efficiency. Based on the required wire length and the hinge dimensions, a decision is made whether to implement a meander wire configuration. This approach also allows the electrical connections to remain on the same side of the hinge system, thereby simplifying installation and integration.

2.6. SMA integration process

Locating the SMA further away from the neutral axis increases the stress during bending [20]. In order to reach a high bending deformation, the wire should be placed with a high distance to the neutral axis [21][22]. However, in outside applications, this is not functional. Aesthetic reasons aside, thin wires left exposed on a façade might lead to animals and debris getting trapped and potentially causing wear and

tear over time. In the use case on a façade, the insulation and, consequently, the slower cooling and motion of the SMA can be disregarded.

Thus, the concept of a Bowden tube was adapted for the use case on a façade. In previous work tube guided SMA actuators exhibited high stroke compared to non-tube guided wires [23]. It has been found, that with increasing sheath length, the deformation of SMA-GFRP soft actuators could be increased [24]. In previous research, separating agents were also used to allow free motion of the wire inside the matrix [25]. However, the heat of the manufacturing process can change the learned properties of the SMA, which means an insertion after pressing is required and thus PTFE tubes were chosen as a low friction sheath material.

2.7. Design of Control System

The previously described digital testing rig also provides the capability for digital control of SMA electrical activation. The shape memory effect is thermally induced through Joule heating using a programmable power supply combined with a microcontroller-based control system. During SMA actuation experiments, the bending angle of the hinge specimens was recorded as a function of the applied voltage under a constant current corresponding to the maximum operating conditions specified by the SMA manufacturer. Optical camera-based tracking systems integrated into the testing rig enabled continuous monitoring of the deformation process and precise measurement of angular displacement throughout the experiments. Deactivation of the hinge actuation occurs through passive cooling via heat dissipation to the surrounding ambient environment.

2.8. Hinge prototype development and experimental validation

The experimental results are evaluated against predefined design and performance constraints. If the required criteria are fulfilled, the process leads to the final hinge design. Otherwise, the workflow loops back iteratively to earlier development stages, enabling further refinement of geometry, actuator configuration, material selection, or control parameters until the desired adaptive performance is achieved, see Figure 2.

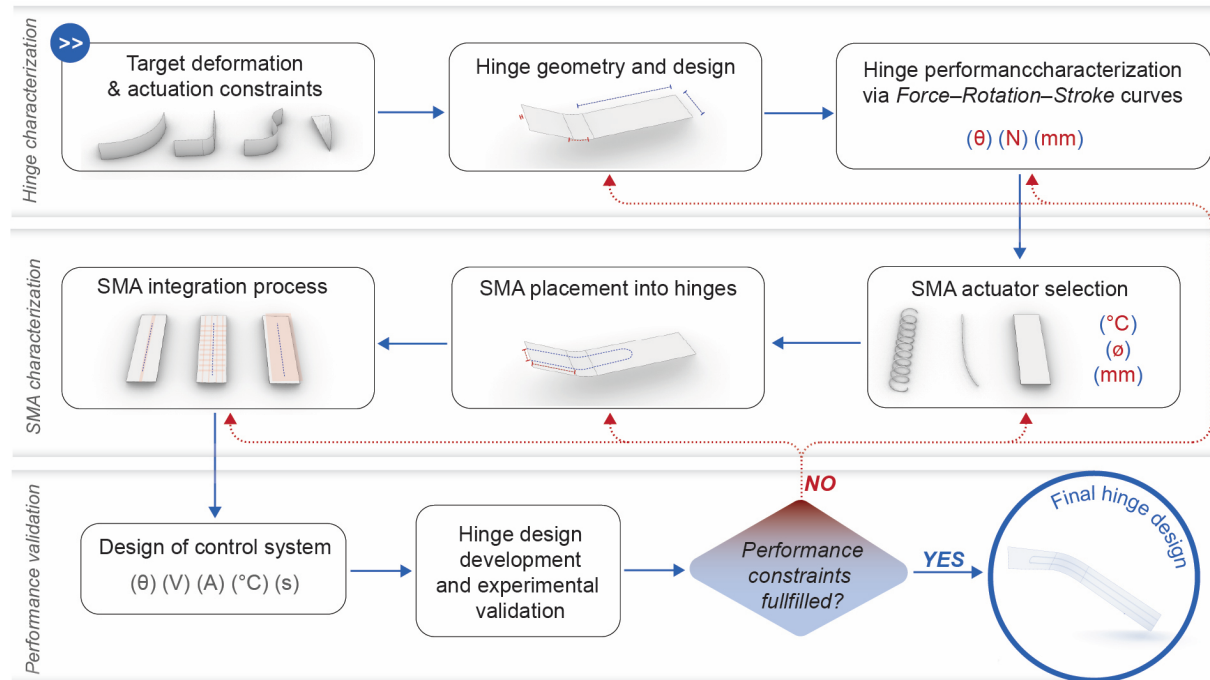


Figure 2: Methodology use for the development of the GFRP compliant hinges with embedded SMA actuation.

3. Results

3.1. Materials System

The material used in this study has been validated in various previous research studies for use in fiber-reinforced compliant mechanisms and as adaptive façade elements [6, 8, 9, 26]. It is composed of a glass fiber fabric prepreg pre-impregnated with epoxy resin and elastomer. The GFRP provides the stiffness and the load bearing capacity within the laminate, while the elastomeric film is assumed to distribute stress peaks in the material during bending motion. The materials and their mechanical properties are listed in Table 1.

In the context of this study, PTFE tubes are integrated into the layered structure to sheath the SMA. The PTFE tubes are encased between two layers of an elastomer and one layer of fabric mesh to reduce the risk of the elastomeric layers tearing.

Table 1 Materials used for the sample preparation and their properties.

ID	description	thickness	density	modulus	shear modulus	elongation at break	tensile strength
		h	ρ	$E_{\parallel,\perp}$	G	ε	$R_{\parallel,\perp}$
		[mm]	[g/cm ³]	[MPa]	[MPa]	[%]	[MPa]
ET222	glass fiber-epoxy prepreg (twill weave 2/2; 165 g/m ²)	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
fabric mesh	inherently flame retardant fabric mesh (Trevira fibers; 75g/m ²)	-	-	-	-	-	-
PTFE tube	(inner diameter 1 mm; outer diameter 2 mm)	-	2.1-2.3	-	-	-	18

^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: Gerriets GmbH; Trade name: Gittertüll CS

^d Manufacturer: SourcingMap Ltd.

A schematic sketch of the laminate setup is shown in Figure 3. The basic laminate setup for all sample configurations consists of three continuous layers of ET222 at a fiber orientation of $\pm 45^\circ$. A single layer of elastomer (HHZ82) is added to one side of these three layers, followed by a PTFE tube fixed in a U-shape with small pieces of paper tape. The PTFE tube is covered by an additional HHZ82 layer. To prevent tearing of this layer during actuation, a fabric mesh is added beneath the top layer of HHZ82. This mesh and the top HHZ82 layer are shorter than the other layers of the sample, leaving the ends of the tubes uncovered for SMA insertion.

This study involves fabricating and testing two sample configurations with this basic laminate setup. As illustrated in Figure 3a), the difference between the configurations lies in the width of the curve in the PTFE tubing.

The samples are stacked by hand and pre-compressed with a hand roller to reduce air voids. Hot pressing is performed using a steel mold. A release film is added between the mold and the samples to prevent them from sticking to the mold. Additionally, a 1.8 mm thick cardboard cutout in the shape of the PTFE tubes is placed on top of the stack to enable even pressure around the tubes without squishing them.

Pressing is performed using a VCP 500/1 OK hot press from Lauffer GmbH & Co. KG at a pressure of 60 bar with a vacuum of 100 mbar in the press chamber. The temperature increases from 60 °C to 125 °C at a rate of 7.5 °C/min, and then remains at 125 °C for 30 minutes. Finally, the temperature is decreased to 30 °C at a rate of 10 °C/min. After pressing, the individual samples are cut from the plate with a bandsaw.

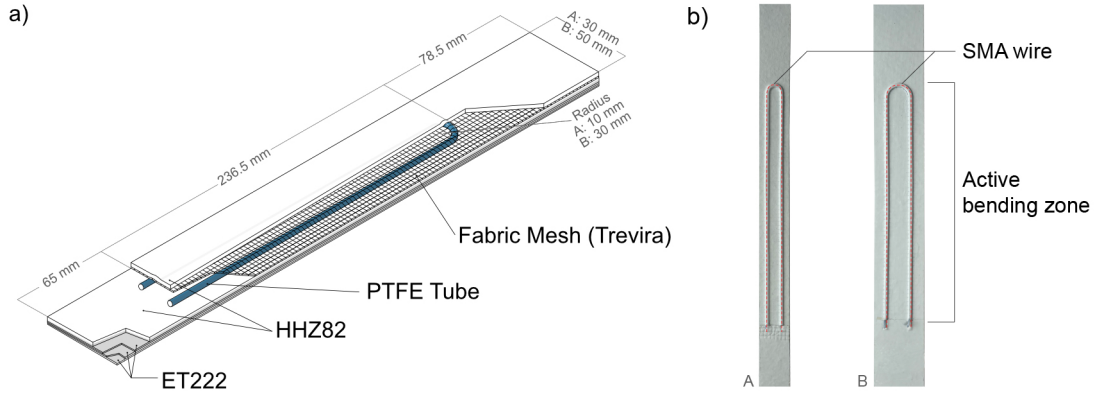


Figure 3: a) Schematic sketch of laminate setup with A: dimensions of narrow samples; B: dimensions of wide samples; b) Pictures of samples indicating SMA integration and actuation zone

3.2. Actuation

Actuation tests were conducted with the described specimens to evaluate the influence of the fabrication approach on the material and structural behaviour. The Force–Rotation–Stroke curves shown in Figure 4a) and 5a) show similar overall deformation targets for both specimens. In both cases, the required stroke increased rapidly at lower rotation angles and gradually approached a plateau at higher rotations, reaching approximately 43 mm at the maximum bending angle. This behaviour indicates that the required actuator displacement is primarily governed by the geometric kinematics of the bending geometry rather than by the specimen width-to-length ratio. In contrast, the generated force exhibited a strong dependence on specimen geometry. While the narrow specimen (A) required approximately 58 N to reach the maximum rotation angle, the wide specimen (B) generated forces of approximately 68 N under comparable deformation conditions. The higher force demand of specimen B can be attributed to its increased structural stiffness resulting from the larger hinge width.

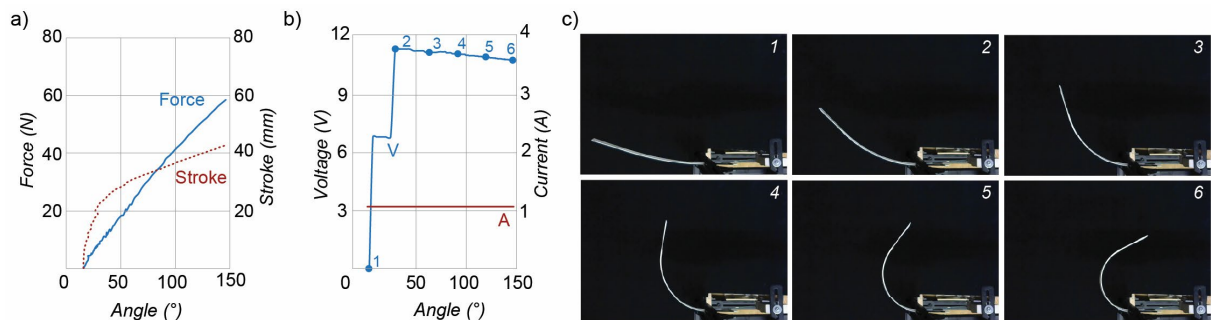


Figure 4: Actuation results of sample A. a) Force-Rotation-Stroke curves; b) Applied actuator voltage as a function of rotation angle; c) Sequential images of the deformation corresponding to the numbered stages in b)

The SMA transition phase was achieved through a stepwise voltage-controlled actuation strategy as seen in Figure 4b) and 5b), in which the voltage was increased incrementally under a constant current of 1.2 A to ensure controlled bending and prevent overheating. Although the actuation was driven under a constant current, the measured voltage varied during activation because the power supply adjusted the voltage in response to changes in the electrical resistance of the SMA circuit.

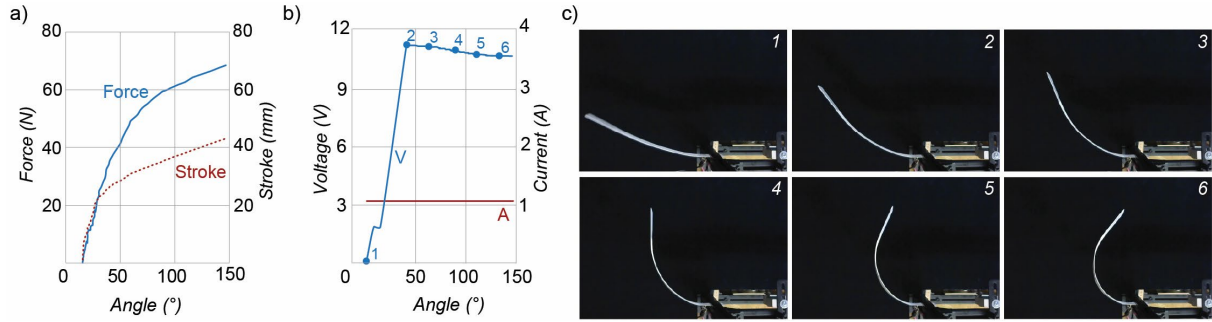


Figure 5: Actuation results of sample B. a) Force-Rotation-Stroke curves; b) Applied actuator voltage as a function of rotation angle; c) Sequential images of the deformation corresponding to the numbered stages in b)

4. Discussion

The PTFE Bowden tube-guided actuator integration strategy proved beneficial for combining performance with actuator protection. By separating the SMA wire from the surrounding composite matrix, the actuator can contract freely while remaining protected from environmental exposure and mechanical damage. The concept also facilitates replacement or maintenance of the actuator, supporting practical implementation within modular façade systems. At the same time, friction within the PTFE channel and potential wear of the wire–tube interface may influence long-term performance and should therefore be investigated through extended cyclic and environmental durability studies.

The Force–Rotation–Stroke characterization demonstrated that increasing the hinge width-to-length ratio leads to higher force transmission and increased stiffness. This behaviour can be attributed to the larger effective cross-sectional area resisting deformation, resulting in a greater force requirement for achieving comparable rotations. In contrast, the achievable stroke remained relatively constant across the investigated configurations, indicating that the deformation capacity is primarily governed by the geometric kinematics. This distinction is important, as it suggests that stiffness and actuation force can be adjusted independently from the achievable deformation range.

5. Conclusion

This study presented a systematic methodology for the development of SMA-integrated GFRP compliant hinges for responsive façade systems. The developed hinge system achieved bending deformations of up to approximately 145° through embedded SMA actuation. This study represents the first implementation of the presented methodology and establishes a framework for the future development of compliant mechanisms capable of more complex deformations. While the presented experiments demonstrate the feasibility of SMA-actuated compliant hinges, challenges remain before implementation in building-scale façade systems particularly regarding long-term cyclic performance, actuation range, environmental durability, maintenance requirements, and passive cooling SMA deactivation. Future research will further expand the materials system towards bio-based FRP composites fabricated through different textile and manufacturing approaches for scalable applications.

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