Smart Hinges Using Shape Memory Alloys for Architectural Applications

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The objective of reducing energy usage in buildings has led to the development of adaptive and responsive systems that can respond to environmental changes in real time. Most responsive systems utilize rigid body mechanisms and electrically or pneumatically driven actuators. Actuation strategies are significant in designing adaptive facades since they are also in charge of energy consumption. Responsive systems can be integrated with smart materials capable of shape, color, and volume shifts in response to external stimuli change through material technology rather than relying on sensors, control systems, or active actuators. These smart materials, referred to as smart actuators, can be utilized to actuate systems. This study aims to present suggestions for a smart hinge for passive responsive shading structures using smart materials. The chosen smart material is nitinol wire, a shape memory alloy (SMA) with the ability to recall its preformed position. The methodology consists of two parts: an investigation of responsive systems composed of smart actuators and a proposal for a new smart hinge based on SMA utilizing Crane tool in Grasshopper. This paper shows the potential and constraints of smart actuators in architectural applications. The proposed smart hinge has the potential to contribute to the improvement of building envelopes through material technology.

Keywords: *biomimetic architecture, smart materials, smart actuator, shape memory alloy, nitinol wire*

INTRODUCTION

Architects have always sought ways to create adaptive buildings and parts that adapt to ever-changing requirements and environmental conditions. Nowadays, reducing energy consumption in architecture has become a significant challenge since 40% of total energy consumption and 76% of electricity usage are due to the building and construction industry (Baldwin et al., 2015). Reducing energy consumed by buildings has led to the development of adaptive systems that can respond to environmental changes in real time. Different strategies were investigated to improve adaptive systems.

In this context, the flow of the paper consisted of two parts; first is classifying the examining smart materials realized through shape memory alloys; presenting an experimental study based on smart hinge proposal, the discussion, and suggestions based on the literature review and experimental studies.

Smart Materials

All responsive aspects can be combined with smart materials based on material technology instead of using sensors, control systems, or active actuators. Smart materials are categorized as rigid materials, such as wood, metal types, thermochromic glass, thin glasses, and acrylic glasses; on the other hand, soft ones as shape memory alloys and shape memory polymers (Heidari Matin & Eydgahi, 2019). These materials are seen in the whole system or as a part of controlling systems. Khosromanesh & Asefi (2019) indicated that the usage of smart materials as sensors or automatic controls provides variability for responsive systems. Architectural and experimental projects are seen as the state of the art of smart materials. Moreover, Lelieveld (2013) presented architectural and experimental examples in the context of smart materials. On the other hand, smart materials can be classified based on the external stimuli that trigger their responses. These stimuli can be temperature, light, electrical, mechanical, magnetic, or chemical.

Firstly, materials that react to temperature changes play a crucial role in passive heating and cooling strategies. Shape Memory Alloys (SMAs) can be used in adaptive shading systems that adjust to temperature variations.

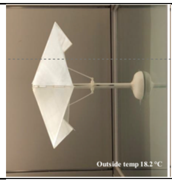
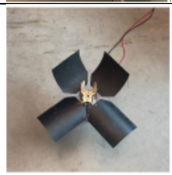
MATERIAL AND METHODS

Shape memory alloys (SMAs) have garnered significant attention for their unique properties, such as the shape memory effect and superelasticity, making them suitable for various applications, including architectural uses. SMAs like NiTi alloys can recover their original shape after deformation through an activation process involving heating and cooling (Yeon et al., 2022). These alloys can undergo large quasi-plastic strains and recover their shape at high temperatures, making them effective for structural shape control (Das & Kapuria, 2019).

In architectural applications, SMAs have been utilized for prototyping elastic building skins, where SMA springs and wires are employed to create self-shaping facades (Yi, 2021). Additionally, SMAs have been proposed for use in construction to achieve a balance between facade opening, pressure difference, and ventilation requirements by using strips of SMAs that expand or contract in response to environmental factors (Chang & Araki, 2016). These examples are investigated to understand the application strategies (see Table 1).

"The Air Flower," a lab-scale prototype abstracted from the behavior of opening and closing of flowers, is designed to ventilate the space. It began to open when the temperature increased from 15°C to 26 °C. Instead of using a sensor or servomotor, the passive system works through smart materials as an actuator. Shape memory alloy (SMA) is utilized due to its shape change capability, which is caused by temperature differences. When the heat increases, the SMA wires shrink; meanwhile, the wires can reverse back when the temperature decreases. Thanks to the advantage of a smart material, SMA, it does not need to be electric to initiate the movement. This prototype, designed by Lift Architect, has the potential to generate a double façade through computational design. According to their experiments, these wires can strain to 8% in response to temperature changes. In this context, projects triggered by temperature stimuli through SMA might be seen in practice due to the realization of prototypes. The investigation has shown that new approaches based on the combination of biasing springs and shape memory alloys might be more efficient solutions for applicability.

Table 1
Responsive architectural prototypes based on the usage of shape memory alloys

Actuation Methodology	Actuator Material	Prototype Image	Reference
The material is Aluminum for the panel and Nitinol (Ni-Ti) for the wire, providing the necessary force to open the panel.	SMA wire		(Formentini et al., 2018)
The aim is to develop textiles with integrated shape memory alloys for architectural applications.	SMA Wire		(Schneider et al., 2020)
The 3D-printed attachable kinetic shading device with alternative actuation is integrated with shape-memory alloy (SMA).	SMA wire		(Yi et al., 2020)
The linear actuator is designed to integrate the SMA and biasing spring.	Biasing Spring and SMA spring		(Vazquez et al., 2023)

A PROPOSAL FOR SMART HINGE

While most applications of shape memory alloys (SMA) focus on their use as actuators, their potential in hinge mechanisms remains largely unexplored in architecture. This study examines the integration of Nitinol wire within hinge zones to evaluate its impact on foldable structures. Using the Crane plugin for Grasshopper/Rhinoceros, various hinge configurations were analyzed to assess their influence on parametric folding dynamics.

Evaluation of Smart Hinge in Origami Patterns

Smart hinges in origami patterns integrate adaptive or programmable materials to enable controlled folding and unfolding, often responding to environmental stimuli such as heat, light, or electricity. These hinges enhance the efficiency of deployable structures, allowing for dynamic transformations with minimal mechanical input. Crane, facilitating the simulation of origami-based structures by enabling precise control over hinge constraints, allowing for the optimization of motion and stability in parametric folding systems, is a physics-based simulation plugin for Grasshopper/Rhinoceros. It is specifically designed for rigid origami simulation and kinematic motion analysis, making it a valuable tool for modeling deployable structures and foldable patterns. By using Crane, designers and engineers can simulate how folded surfaces behave under physical constraints, analyze their motion, and explore optimized folding pathways. This is particularly useful in architecture, product design, and engineering applications where foldable structures play a significant role.

The “Double Hinge” component in Crane is used to define two connected hinge constraints within a rigid origami structure. Hinges represent fold lines where panels rotate relative to each other, and the Double Hinge component allows for a more complex, coupled folding behavior. This means that two separate hinges can be controlled simultaneously, ensuring synchronized or dependent motion between them. This feature is particularly useful in advanced origami structures, such as Miura-ori patterns or other interdependent folding mechanisms, where multiple hinges must move in a coordinated manner.

Double Hinge Application as Smart Movements

In this study, the hinges are considered to be composed of nitinol, a shape memory alloy that responds to environmental changes such as temperature variations. This material choice enables the hinges to actively control the transformation of the structure, allowing for programmable motion and adaptive behavior. By integrating nitinol-based hinges, the system gains the ability to shift between folded and unfolded states with minimal mechanical input, making it suitable for deployable and responsive architectural applications.

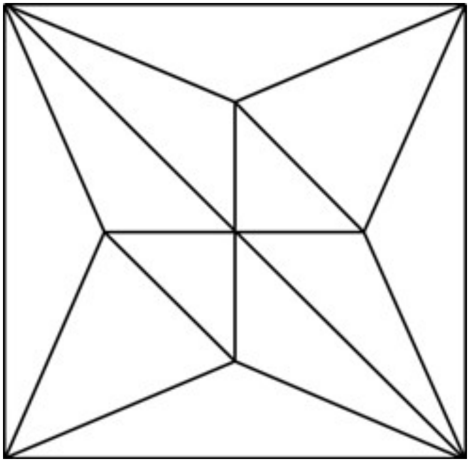


Figure 1
The Base
Geometry

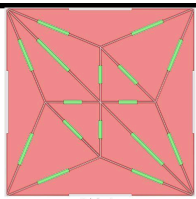
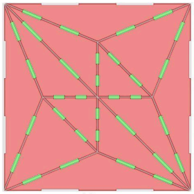
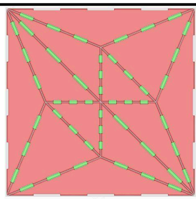
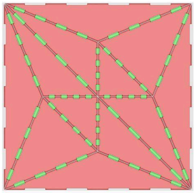
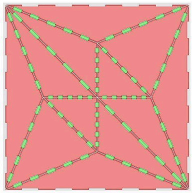
Geometric Modeling

The base geometry consists of a modular foldable unit, developed parametrically in Grasshopper. The model includes planar quadrilateral and triangular panels, ensuring geometric consistency across different hinge configurations (Figure 1). This parametric setup allows for systematic adjustments in hinge placement while maintaining the overall structural integrity of the foldable system.

Hinge Configuration

To evaluate the effect of hinge placement on motion efficiency, five distinct hinge configurations are developed using the Double Hinge component in the Crane plugin. These configurations include one, two, three, four, and five hinge connections between adjacent components (see Table 2). Each variation represents a different level of kinematic constraint, influencing the degrees of freedom and overall motion characteristics of the structure. By incrementally increasing the number of hinges, the study examines how structural dependency affects the range and fluidity of motion.

Table 2
Comparison of Hinge Configurations

Conf.	Kinematic Freedom	Structural Stability	Material Efficiency	Output
1	High (Unconstrained, may lead to instability)	Low (Panels may rotate undesirably)	Very High (Minimal hinges, but lacks control)	
2	Moderate-High (More control, but still flexible)	Moderate (Some constraints added)	High (Good balance of control and flexibility)	
3	Moderate (More structured motion, reduced freedom)	High (Better constraint, but may limit motion)	Moderate (Some redundant hinges possible)	
4	Low-Moderate (Constrained motion, predictable behavior)	High (Panels remain well-aligned)	Low (Additional hinges may not add much benefit)	
5	Very Low (Highly restricted motion)	Very High (Strong control, but may be over-constrai ned)	Very Low (Likely excessive hinge usage)	

Parametric Evaluation

Five hinge configurations are compared based on their ability to achieve the desired motion.

The optimization process focuses on identifying the minimal hinge configuration that maintains structural stability while allowing efficient transformation between folded and unfolded states.

To systematically compare the hinge configurations, evaluation criteria were defined and how each configuration performs was analyzed. Based on the optimization goal, the comparison were structured around three key performance metrics: Kinematic Freedom (Flexibility of Motion) to observe how freely the structure folds and unfolds; Structural Stability (Constraint Effectiveness) to observe whether additional hinges restrict undesired deformations; Material Efficiency (Minimization of Redundant Hinges) to observe the number of hinges required to achieve the desired motion without over-constraining the system.

Key Findings

- 1-Hinge Configuration allows maximum motion but lacks stability, leading to undesired deformations.
- 2-Hinge Configuration appears to offer a good balance between motion flexibility and stability.
- 3-Hinge Configuration introduces more constraints, limiting motion but ensuring better structural reliability.
- 4-Hinge and 5-Hinge Configurations over-constrain the system, reducing motion flexibility without significantly improving stability.

The optimal hinge configuration depends on the desired motion. If maximal flexibility is required, 2 hinges per component may be the most efficient solution. If higher stability is necessary, 3 hinges provide a more constrained but controlled motion. Configurations with 4 or 5 hinges tend to over-constrain the structure, making them less efficient unless precise positional control is a priority.

DISCUSSION

The integration of Shape Memory Alloys (SMAs), particularly Nitinol (Ni-Ti), in responsive architectural systems offers exciting possibilities for creating adaptive, sustainable designs. SMAs are unique materials capable of returning to their original shape when exposed to temperature changes, enabling passive actuation in architectural elements. This research demonstrates how SMA wires, used in prototypes such as the "Air Flower," mimic natural processes like plant movements, providing an innovative approach to environmental control without the need for traditional motorized systems. These systems, powered by the temperature-induced contraction and expansion of SMA wires, offer an energy-efficient alternative to conventional, complex mechanisms.

The focus on Nitinol wires for actuation in this study highlights the material’s potential in creating lightweight, cost-effective, and low-maintenance systems for architectural applications. These SMA-based systems can passively regulate ventilation, improve thermal comfort, and adapt to environmental changes without relying on electrical inputs. This is particularly beneficial in architectural design, where sustainability and energy efficiency are increasingly important considerations.

Since this research is part of an ongoing project, structural and strength tests with real wind loads and façade application details are not analyzed and presented within the scope of this research. Therefore, this study offers a conceptual experiment to explore the nitinol wires for smart hinges. The scalability also may affect the key findings.

The research also explores the optimization of hinge configurations for SMA-based systems. The evaluation of various hinge setups revealed that while more hinges provide

greater structural stability, they restrict the range of motion. On the other hand, fewer hinges offer increased flexibility but at the cost of stability. The optimal configuration depends on the design's specific goals, whether prioritizing flexibility or stability, and offers insights into how SMA-based systems can be tailored for different architectural applications.
The use of parametric design tools like Grasshopper and the Crane plugin has been crucial in modeling the foldable paper prototype at a 1:10 scale. Crane was selected over other Grasshopper-based simulation tools such as Kangaroo2 and FlexHopper due to its explicit focus on programmable kinetic behaviors and passive actuation logic, which were essential for accurately simulating the motion of the shading systems based on various materials. Unlike Kangaroo2, which is primarily optimized for structural form-finding, or FlexHopper, which prioritizes general-purpose physics with GPU acceleration, Crane offers a component-based framework tailored to simulate responsive material systems, enabling iterative design exploration with custom logic blocks, making it particularly suitable for early-stage prototyping of passive kinetic facades. These tools allowed for precise control over hinge placement and motion, enabling the exploration of different configurations and optimizing the system's performance. The ability to analyze how the structure behaves under various constraints and environmental conditions further enhances the design process, making it more efficient and adaptable.

It is important to acknowledge that the 1:10 model used in this study does not allow for a linear translation of material properties to full-scale (1:1) applications. These small-scale experiments enabled the identification of design-relevant parameters and behavioral thresholds, which form the foundation for subsequent full-scale validation. While not predictive of exact structural performance at 1:1, the models allowed for iterative prototyping and informed simulation workflows. Future work will include larger-scale prototypes or calibrated simulations to assess structural and environmental performance at architectural scale.

CONCLUSION

As the state-of-the-art in smart materials, a different strategy has been presented in this paper within the scope of passive responsive structures. The case study, which is a systematic part of a responsive envelope, proposes the use of nitinol wire as a smart hinge. Further research might focus on the durability of nitinol wires and the details of the prototype and physical model. Moreover, the integration of SMA may offer potential applications on a large scale since controlling wires as actuators can be much more efficient.

This research highlights the significant potential of SMA-driven systems in responsive architecture, showcasing how smart materials can transform the way buildings interact with their environment. The results suggest that SMA-based systems can offer sustainable, cost-effective, and adaptable solutions for future architectural designs. On the other hand, fatigue behavior tests should be investigated for the sustainability of architectural applications.

The findings contribute to the rationalization of hinge placement, ensuring that motion requirements are met with an optimized number of constraints. Further studies could explore the integration of SMAs with other responsive materials, other folding patterns, the scalability of SMA-based systems in full-scale architectural applications, and the long-term durability and performance of SMA-driven structures under varying environmental conditions. This approach provides a structured methodology for designing kinematically efficient origami structures, with potential applications in deployable architecture, robotic systems, and dynamic material systems.

REFERENCES

Baldwin, S., Bindewald, G., Brown, A., Chen, C., Cheung, K., Clark, C., Cresko, J., Crozat, M. et al. (2015) '*Quadrennial technology review: An assessment of energy technologies and research opportunities*'. USA: Department of Energy. Available at: https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf

Das, H. and Kapuria, S. (2019) 'Adaptive pitch control of full-scale ship composite propeller using shape memory alloy to enhance propulsive efficiency in off-design conditions', *Journal of Intelligent Material Systems and Structures*, 30(10), pp. 1493–1507. Available at: https://doi.org/10.1177/1045389X19835957

Formentini, M. and Lenci, S (2018) 'An innovative building envelope (kinetic façade) with shape memory alloys used as actuators and sensors', *Automation in Construction*, 85, pp. 220–231. Available at: https://doi.org/10.1016/j.autcon.2017.10.006

Guiducci, L., Razghandi, K., Bertinetti, L., Turcaud, S., Rüggeberg, M., Weaver, J.C., Fratzl, P., Burgert, I., et al. (2016) 'Honeycomb actuators inspired by the unfolding of ice plant seed capsules', *PLoS ONE*, 11(11). Available at: https://doi.org/10.1371/journal.pone.0163506

Heidari Matin, N. and Eydgahi, A. (2019) 'Technologies used in responsive facade systems: A comparative study', *Intelligent Buildings International*, 14(1), pp. 54-73. Available at: https://doi.org/10.1080/17508975.2019.1577213

Khosromanesh, R. and Asefi, M. (2019). Form-finding mechanism derived from plant movement in response to environmental conditions for building envelopes. *Sustainable Cities and Society*, 51(3). Available at: https://doi.org/10.1016/j.scs.2019.101782

Lelieveld, C.M.J.L. (2013). *Smart materials for the realization of an adaptive building component*. Unpublished PhD thesis. TU Delft. Available at: https://doi.org/10.4233/uuid:21ba183b-450e-45a1-bc89-24799586735c

Leung, C. and Gage, S.A. (2008) 'Dynamic building envelopes', *Middle East Art Design and Architecture Magazine (MEADA)* , 3(3), pp. 76-80. Available at: https://discovery.ucl.ac.uk/id/eprint/14607

Vazquez, E., Diarte, J. and Duarte, J. (2023) 'Kinetic Shades: Designing a shape-morphing device with bistable laminates and shape memory actuators', *Journal of Architectural Engineering*, 29(4). Available at: https://doi.org/10.1061/JAEIED.AEENG-1646

Schneider, M., Waldhör, E.F., Denz, P.R., Vongsingha, P., Suwannapruk, N. and Sauer, C. (2020) 'Adaptive textile façades through the integration of shape memory alloy', in *ACADIA 2020 Conference Proceedings*. Available at: https://doi.org/10.52842/conf.acadia.2020.1.360

Yi, H. (2021) '4D-printed parametric façade in architecture: Prototyping a self-shaping skin using programmable two-way shape memory composite (TWSMC)', *Engineering, Construction and Architectural Management*, 29(10), pp. 4132–4152. Available at: https://doi.org/10.1108/ECAM-05-2021-0428

Yi, H., Kim, D., Kim, Y., Kim, D., Koh, J.S. and Kim, M.J. (2020) '3D-printed attachable kinetic shading device with alternate actuation: Use of shape-memory alloy (SMA) for climate-adaptive responsive architecture', *Automation in Construction*, 114, p. 103151. Available at: https://doi.org/10.1016/j.autcon.2020.103151