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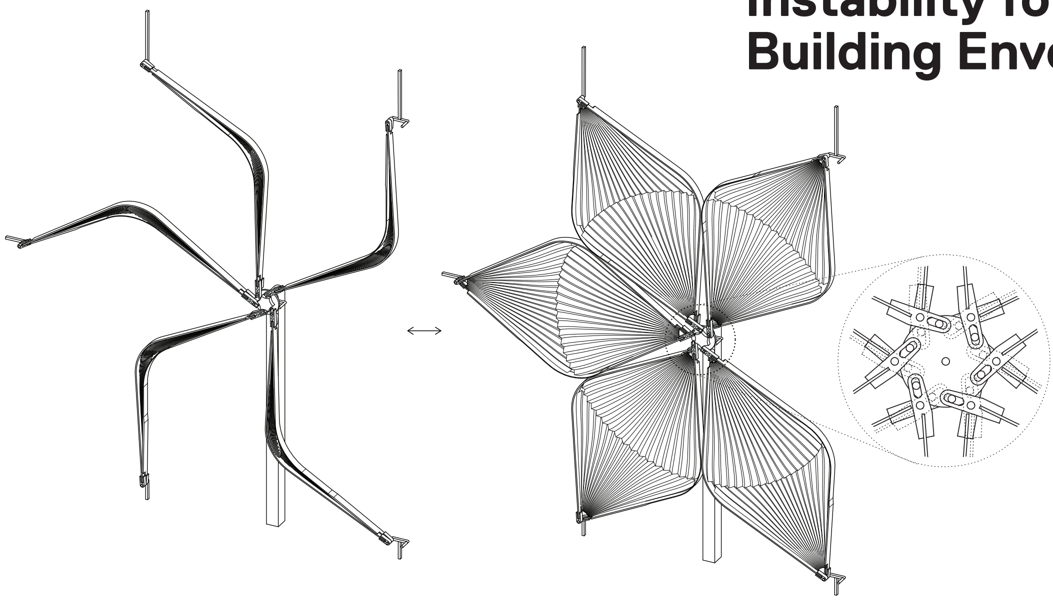
Snapping Facades: Exploring Elastic Instability for the Building Envelope



This article presents an alternative dynamic facade actuation mechanism utilizing the deformation of snapping instability without continuous force application. Based on analytical and numerical studies prior to fabrication, a prototype snapping facade is built and its proof of concept is demonstrated for the proposed snapping-induced motion. The snapping facade provides a novel way to exploit elastic instability in dynamic building-envelope applications. Further development of the system for practical applications will include the study of different materials for the snapping beams and shading membranes as well as the energy-performance benefits of the snapping facade system.

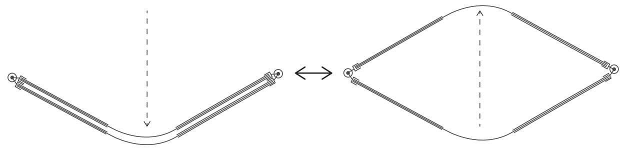
PEER REVIEW / OPEN

Introduction

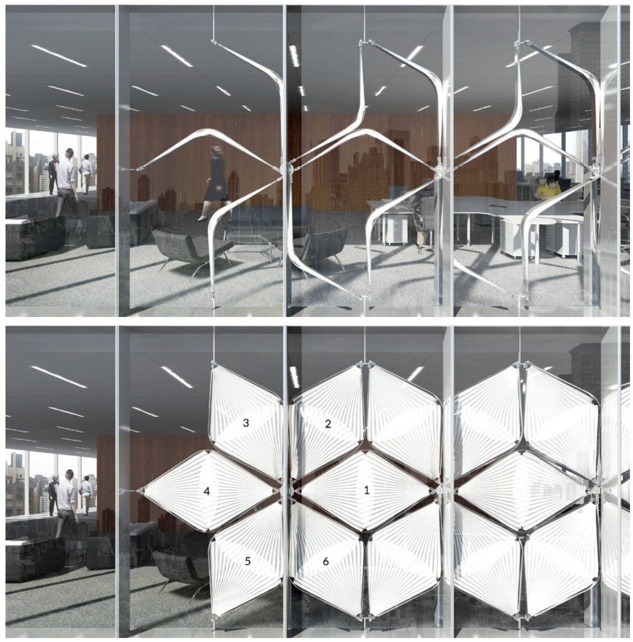
Snapping and buckling motions are physical phenomena associated with elastic instability, whereby a compressive force causes a transition from one state to the other via a rapid motion. Such motion has not been previously considered useful because, in most cases, the sudden release of elastic strain energy and shape change are difficult to predict and to control. More recently, there has been an increase in research that views elastic instabilities as favorable for "smart" applications such as dampers, isolators, sensors, energy harvesters, and actuators.[1] This shift in elastic instability research was captured in a special issue of *Soft Matter*[2] demonstrating the use of "buckling" across disciplines. Furthermore, the instability phenomena observed in daily life (i.e., rubber ball poppers, snap bracelets, foldable car window shades) have been adopted for energy-related applications (i.e., energy harvesting and energy dissipation)[3, 4] and motion-related applications (i.e., self-deploying or self-locking structures).[5] In architecture, however, the instability of structural components has traditionally been viewed negatively because it implies a reduction in capacity, large deformations, and the failure of structural members. This paper proposes that motion-related behavior can be beneficial in architecture and has potential as a form of dynamic shading in contemporary performative building-envelope design.

As newer energy codes require smaller window-to-wall ratios in facades, there is also significant interest in maximizing outdoor views and daylighting, as well as a simultaneous desire to insure convenient installation and maintenance through a conventional glass curtain-wall system. However, there are also tremendous technical challenges in fabricating efficient "transparent" curtain walls to counteract the often-limited thermal mass and heat gain consistent with such transparency. High cooling and heating loads and excessive brightness often result in a visually and thermally uncomfortable space for occupants.[6] A curtain wall may therefore require additional layers to improve the envelope's functionality. Venetian blinds are most commonly adopted due to their efficiency in blocking, reflecting, and transmitting light.[7] The shape and angle of the slats determine the performance,[8] and the efficiency of blinds can be measured.[9] Another option for window shading can be found in emerging glazing technologies and dynamic facade components. These systems utilize and test various actuation mechanisms in order to further investigate the dynamic and responsive control of shading and daylighting (the holy grail of facade technology)[10] for better visual/thermal comfort and efficient energy performance.

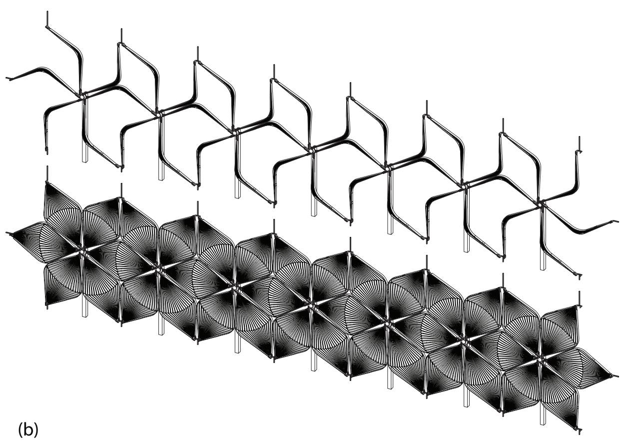
Contributing to this research, a dynamic facade has been conceived that adopts a "snapping motion" as an alternative mechanical actuation, exploiting the strain energy stored in structures via instability. In this article, the background and motivation of the current dynamic facade is reviewed and the various applications using elastic instability are also introduced. Then, the basic concept of snapping is illustrated by using a simple bistable spring model, and the results of finite element (FE) analysis of a key beam component of the proposed snapping facade are presented. As the validation of the proposed concept, a prototype using polystyrene beams with varying cross-sections and folding polyester membranes has been built.



△ Figure 1. Open and closed diagrams using snapping beams.



(a)



(b)

△ Figure 2. (a) Rendering of a group configuration using snapping beams. (b) Diagram of the same with membrane included.

Background and Motivation

Actuation Methods for Current Dynamic Facade Systems

In recent decades, the advancement of material science and manufacturing techniques has accelerated the development of dynamic glazing technology. Improvement in smart-glass engineering has enabled such systems to be commercially available and innovatively integrated. For example, photochromic glass changes transparency with light intensity, and thermochromic glass is affected by temperature. Polymer-dispersed liquid crystal (PDLC) and suspended particle devices (SPD) are actuated by electric current.[11] Gasochromic glass uses integrated gas-cycling systems with an electrolyser to change the transmittance. Electrochromic glass, which uses low voltage to change light transmission properties, has been evaluated as one of the most efficient commercially-available tintable smart glasses.[12] Field testing of electrochromic windows at the Lawrence Berkeley National Laboratory has also demonstrated the lowest energy use and best peak-demand performance.[13] Additionally, the research and development of electropolymetric displays (EPD) demonstrate this technology's promising future for use in dynamic shading, as its geometry can be changed and it has the capacity to be programmed for various displays. Krietemeyer et al. also focus on energy performance and architectural effect through the design of shutter placement (i.e., dynamic filters).[14] In a dynamic window using an electropolymetric display, which is close to being available for purchase, a thin resilient layer (i.e., a shrinkable polymer) located inside of an insulating glass unit can be wrapped or unwound by applying an electric current.[15] Electroactive polymer (EAP) actuators have been investigated as artifical muscles due to their large deformation capacity.[16] Recently, the kinetics of flexible electroactive polymer surfaces have been explored at an architectural scale.[17]

Most of these dynamic shading technologies are based on insulating glass units actuated by electricity (i.e., glass enhancement). Since the actuation mechanism of the insulating glass unit is located within the glass thickness, its enhancement of human comfort and energy savings do not constitute an architectural intervention at the scale of the building. As an alternative, some recent projects have utilized state-of-the-art manufacturing techniques to incorporate building-scale mechanical movement as a kinetic mechanism for building shades. The Abu Dhabi Investment Council Headquarters (Aedas and Arup) and the Kiefer Technic Showroom (Ernst Giselbrecht + Partner) exhibit unique folding patterns responding to occupants' needs and the external climate. In addition, the mechanical shifting and overlapping of panels provides shade at the World Trade Center Souk (Foster + Partners). Unlike glass enhancement, the mechanical shading controls adopted in these examples are an integral and defining part of the facade design, often embodying sociocultural references such as historical motifs. However, such kinetic systems usually employ mechanical hinges, resulting in a high installation cost, additional energy consumption, complex maintenance over time, and periodic replacement.

Motion-Related Applications Using Elastic Instability

The snapping motion from an initial shape to a buckled shape usually allows large deformation of a material without the continuous application of force, while simultaneously releasing a significant amount of elastic strain energy. Self-deploying structures which use snap-through instabilities are an example of such motion-related applications. Typically, elastic bars are tied to rigid plates to shift between deployed and packed configurations.[18] In addition, the idea behind a collapsible steel tape measure has been applied to the Storable Tubular Extendible Member™ (STEM) and the Collapsible Tubular Mast (CTM)[19] to provide a rigid compression post deployed from an initial collapsible (i.e., rolled and packed) state. A bistable geometry using elastic instability is also proposed to control the shape of trailing edge devices in flights.[20] The trailing edge composed of two outer skins and two inner skins achieves different configurations by pulling and pushing the inner skins, which give pitch control, or air braking.

Due to its length-scale independent characteristics, elastic instability can be applicable at both a micro- and building-scale. Using an array of micro-lens shells as a surface geometry, a snap-through transition was designed to produce biomimetic responsive surfaces for the application of switchable optical devices.[21] Flectofin is an example of a building-scale bistable application for a shading prototype, motivated by morphological analysis of plant movements.[22] Deformation of the shading surface (i.e., the wing surface) is actuated by bending in the backbone. Besides the size of the application, the type of materials used in elastic instabilities can include conventional metals, fiber-reinforced composites, polymers, and piezoelectric materials. Instability is also utilized as a self-assembly mechanism that changes the surface morphology in polymeric materials and structures.[23] Fiber-reinforced polymers (FRP) have been explored to combine high tensile strength with low bending stiffness.[24] By applying a prestress to selected fibers in laminates prior to curing, a buckling mechanism can create two bistable bowing geometries.[25]

Given the range of applications, alternative actuation mechanisms in dynamic facade systems can be developed by using the benefits of elastic instability such as large deformations without continuous force application, scale-independent characteristics, and emerging materials.

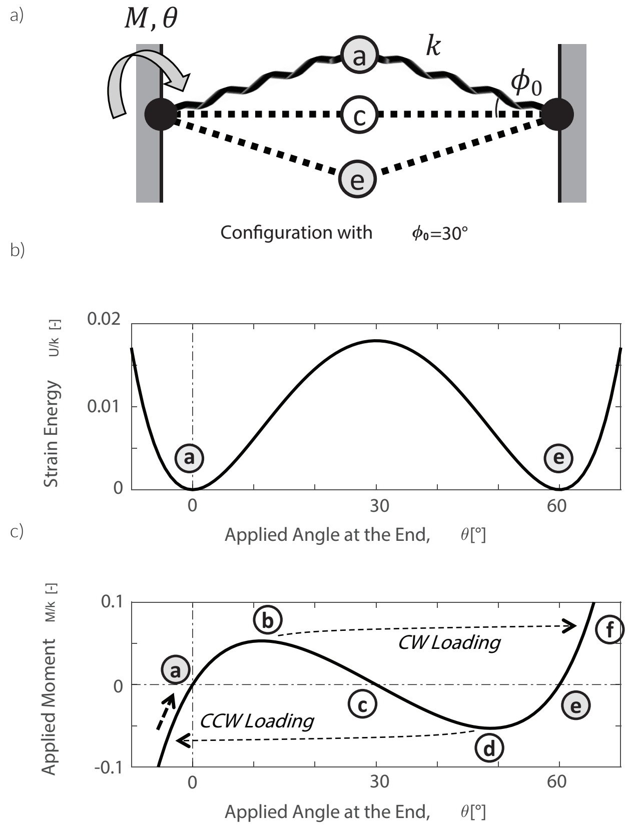
Exploring Elastic Instability for Dynamic Facade Systems

The snapping mechanism proposed in this study exploits strain energy (the energy stored by a structure undergoing deformation) via elastic instability. Typically, a force must be applied continuously to a structure in order for it to reach a prescribed level of deformation. However, the proposed snapping facade exploits the strain energy stored in a bistable structure that deforms quickly, without this type of force. To explore this principle further, a simple bistable beam structure, which provides an open and closed position, was designed and evaluated (Figure 1). The shape of the basic snapping module, a set of two bent beams, governed the shape of the resulting facade. The angle of the two beams was found by maximizing the area being shaded and was determined to be 60 degrees. A radial array of the basic snapping module becomes one group, and multiple groups form the proposed facade system in Figure 2.

The Basic Principle of Snapping Motion: Analytical Study and Numerical Simulation

Analytical Study of a Simple Bistable Spring Structure

The concept of snapping-induced motion is illustrated in Figure 3a using a simple bistable structure, where two elastic springs characterized by the stiffness *k* are connected at an initial angle of Φ_0=30°. As the applied rotation angle θ increases, the strain energy *U* stored in the structure evolves. Figure 3b shows the analytically obtained evolution of the strain energy *U* with respect to the applied angle θ, and its two stable configurations are denoted by (a) and (e) in Figure 3b. The first zero strain energy (a) corresponds to the initial configuration of the structure (i.e., the applied angle of θ=0°), and the second zero strain energy (e) is observed at the applied angle of θ=60°. The equilibrium path of the applied moment, *M*, with respect to the applied angle θ was obtained through analysis (see Figure 3c). At the beginning of its structural motion (i.e., near the configuration (a), the applied clockwise moment *M* increases as the angle θ increases. However, once the angle θ reaches a threshold at the configuration (b) having θ≈10°, the structure abruptly jumps to the configuration (f) and stabilizes at the configuration (e) having θ≈60°. Consequently, this drastic snapping motion of Δθ≈50° can be achieved by applying deformation only up to θ≈10°. This motion amplification can be optimized through proper structural analysis and design. By applying a counterclockwise moment in the configuration (e), the structure can re-evolve from the configuration (e) to (a) without any permanent deformation. Due to the assumed elastic nature of the system, this kind of motion can be repeated.

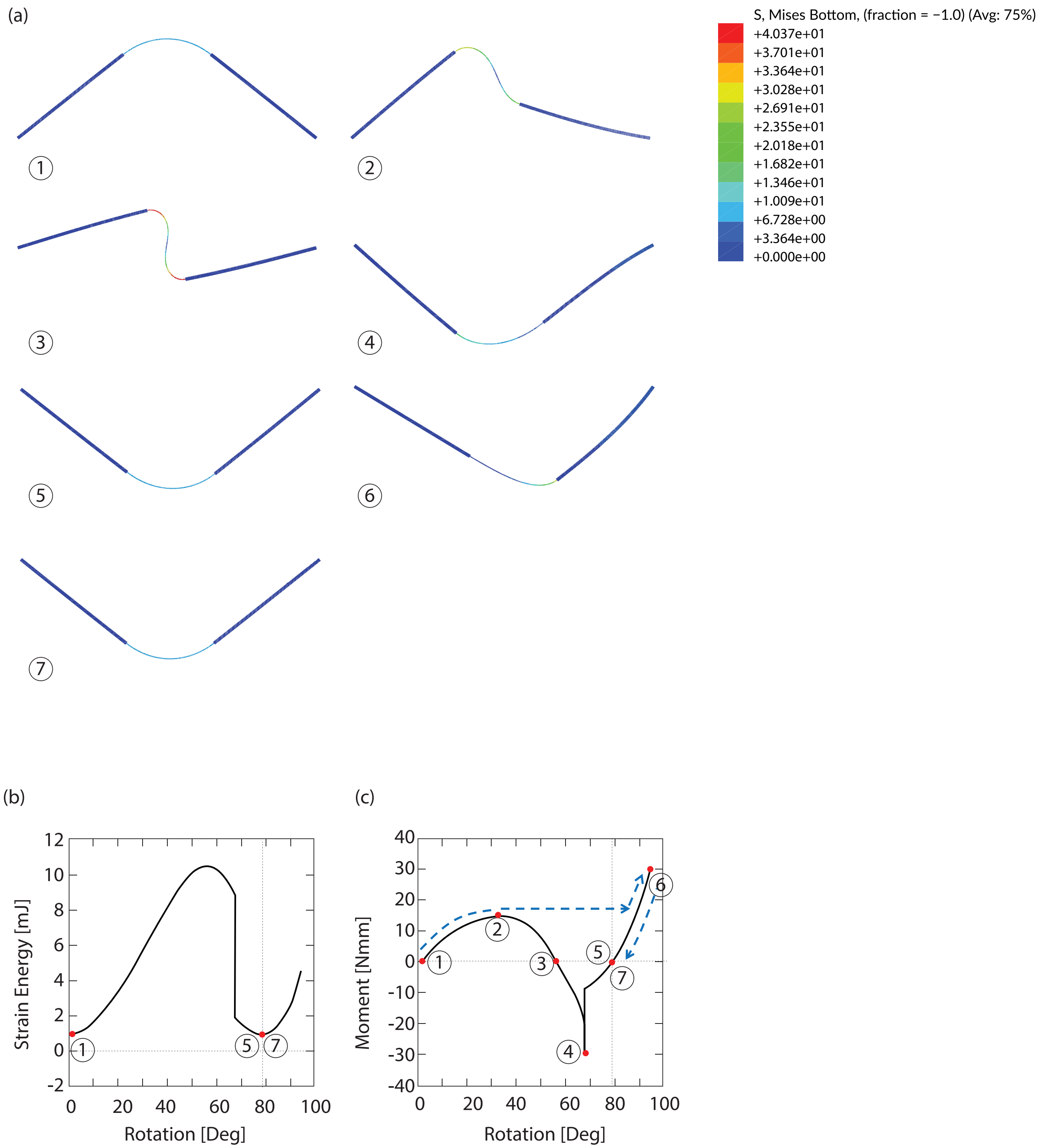


△ Figure 3. (a) Schematic of a simple bistable structure. (b) Relationship between the rotation angle and the corresponding strain energy stored in the structure. (c) Relationship between the rotation angle and the applied moment.

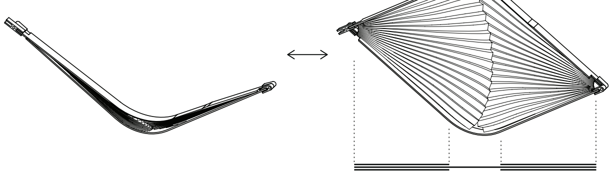
Numerical Simulation of Bistable Beam Component for Snapping Facade

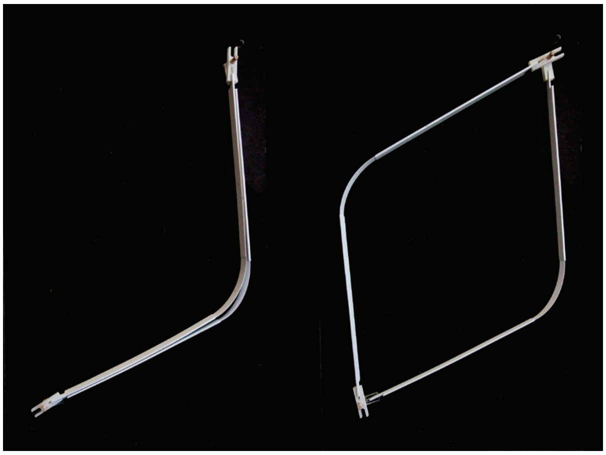
Based on the above analytical model of the proposed bistable structure, a component or beam with a varying cross-sectional area was considered. The snapping motion of the bistable spring structures can also be achieved in a beam with this detailing or shaping. To test this idea in a physical form and to create a proof-of-concept model for a snapping facade, polystyrene was selected as the material of the prototype (shown in section Design of Snapping Facade). Polystyrene is one of the most widely used plastics, is known to be nonbiodegradable, and allowed for a simpler fabrication than metal. The considered polystyrene is an isotropic material, hard but rather brittle, and it can be easily fabricated with a laser cutter. It is naturally transparent and can be colored with pigments. As a thermoplastic polymer, polystyrene is in a glassy state at room temperature, but becomes rubbery if heated above the glass transition temperature *Tg*≈90°C.[26] Prior to the construction of the prototype structure, a set of numerical simulations were performed using the finite element (FE) method (Figure 4). The outcome of the structural simulations is incorporated into the design and fabrication of the prototype structure, as discussed in section Design of Snapping Facade.

The material properties of polystyrene employed in the structural analysis were: Young's modulus of *E*=3.30 *GPa*, Poisson's ratio of *v*=0.38, and yield strength of σ_y=55*MPa*.[27, 28] The total length of the considered beam component is *L*=1000*mm*. In order to model the middle hinge of the simple bistable structure shown in Figure 3, a thin middle cross-sectional (L_{mid}=260mm with t_{mid}=1mm) was introduced between the two thick end parts (L_{end}=370mm with t_{end}=3mm). Note that the beam component is curved with the initial angle of Φ_0=40° at the supports. The FE analysis was conducted using ABAQUS/Standard software.[29] Figure 4a illustrates the FE results showing the progressive deformed shapes upon the rotation-control setting, which allows one to numerically evaluate the complete equilibrium path of the considered structure. In addition, Figure 4b depicts the evolution of the strain energy stored in the beam component, illustrating two structurally stable points from the two concave-up shapes in (1) and (5)/(7). Note that the critical points in the deformed process are denoted by circled numbers in Figure 4. Similarly, Figure 4c shows the relationship between the applied rotational angle and the corresponding moment acting on the beam component. It is clear that the critical points (1) and (5)/(7) represent the stable deformed shape of the beam component. Under the moment-controlled setting, a snapping motion can be observed in the deformed process as shown in Figure 4c. In this considered beam structure, once the rotation angle reaches a threshold at the configuration (2) having θ≈40°, the structure jumps to the configuration (6) and stabilizes at the configuration (5)/(7) having θ≈80°. Consequently, this drastic snapping motion



△ Figure 4. (a) progressive deformed shapes of the FE analysis; (b) relationship between rotation angle and the corresponding strain energy stored in the structure; (c) relationship between rotation angle and the applied moment.





△ Figure 5. Base module of the snap deformation: (a) drawing; (b) developed prototype structure.

of $\Delta\theta \approx 40°$ can be achieved by applying $\theta \approx 40°$. The FE analysis reveals that the maximum von Mises stress[30] (σ_{max}=40MPa) during the deformed process is below the yield strength of the considered polystyrene.

In summary, the FE simulations show that the snapping motion of the considered cross-section-varying beam component undergoes linear elastic deformation only, without any plastic deformation. Note that the maximum stress can be further reduced by performing a series of FE analyses with a different set of component dimensions. The snapping motion for the facade design can be structurally modeled, as in this study, prior to facade fabrication, and FE simulations can help architects determine the dimensions of the snapping beams.

Design of Snapping Facade

Based on the analytical and numerical study of the snapping-induced motion shown in Figures 3 and 4, a prototype snapping module was designed to serve as a building block of the proposed snapping facade. The basic snapping module is composed of the snapping frames, which dictate the motion, and the folding membrane that covers the area between the snapping frames when in an open position.

Design of Snapping Frames

The basic snapping frame consists of one rotating beam and one fixed (i.e., stationary) beam, which are connected at the opening junctions (Figure 5). These connection points are pin-jointed to supporting frames (i.e., mullions) through a hinge. As there is no structural moment acting on these pin joints, conventional mullions are expected to have the capacity to support snapping modules made of polystyrene beams. The horizontal dimension of one module in the prototype is 635 mm, which can be scaled to fit any window. The dimensions of the polystyrene beam are similar to the one used for the FE simulations. While three polystyrene layers are bonded together near the junction, only one layer is employed to introduce a thin cross-section in the middle of the beam (Figure 5a).

Figure 6 illustrates the configuration of one operational group consisting of five snapping modules, all of which can be actuated at a single junction by rotating a wheel. The concept of a Geneva drive was used to efficiently actuate the multiple modules. Note that the actuating junction containing the wheel can be viewed as a combined unit of six Geneva drives (see Figure 6b). Because the modified Geneva drive uses the concept of a lever, the actuating torque (i.e., moment) can be controlled by the detailed design of the actuation junction. The larger the actuation junction arm, the smaller the force/moment necessary to operate it. In this study, the dimension of the actuation junction was such that the motion of six snapping modules could be easily actuated by hand without a mechanically powered aid (Figure 6c).

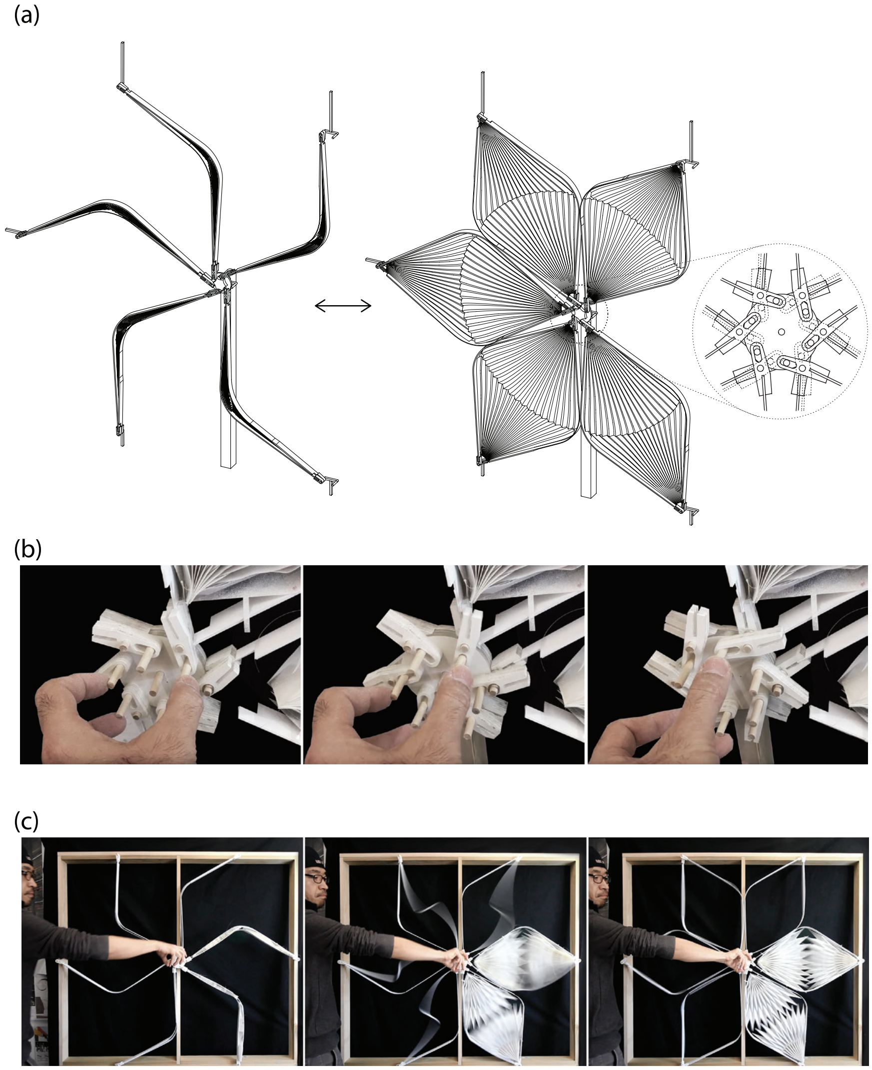
Design of Folding Membranes

After constructing the snapping module, polyester membranes were designed to be placed between two beams. Various designs were explored that would efficiently cover the area between two beams when opened and be neatly folded when the beams close the gap (see Figure 7). For example, the use of elastic fabric bands, which turn and overlap when the rotating beams fold (Figures 7a–7b), was attempted, but the snapping motion was not consistent due to separation in the central area of the gap. In order to fix this issue, fabric bands tied in the central area were also considered, as shown in Figures 7c–7d. However, that snapping motion was not completed due to the kinematic discrepancy between the two beams resulting from shear deformation, preventing a complete closure. Additionally, origami using papers and clear films (Figures 7e–7h) were tested to find specific folding patterns that would produce stable transformations between the open and closed states of the basic snapping module. Eventually, a folding pattern based on Miura-ori,[31] depicted in Figures 7g–7h and Figure 8, was developed. This proposed folding pattern for the membrane covers the middle area without kinematic discrepancy. Further testing found that the proposed radial folding pattern is more efficient when operating in a coplanar configuration, as compared to the simple linear folding in the original Miura-ori pattern. Inserting these folding patterns within the snapping modules (see Figure 9) completed the assembly of the prototype and confirmed that the snapping facade as developed can be operated by hand (Figure 6c and Figure 10).

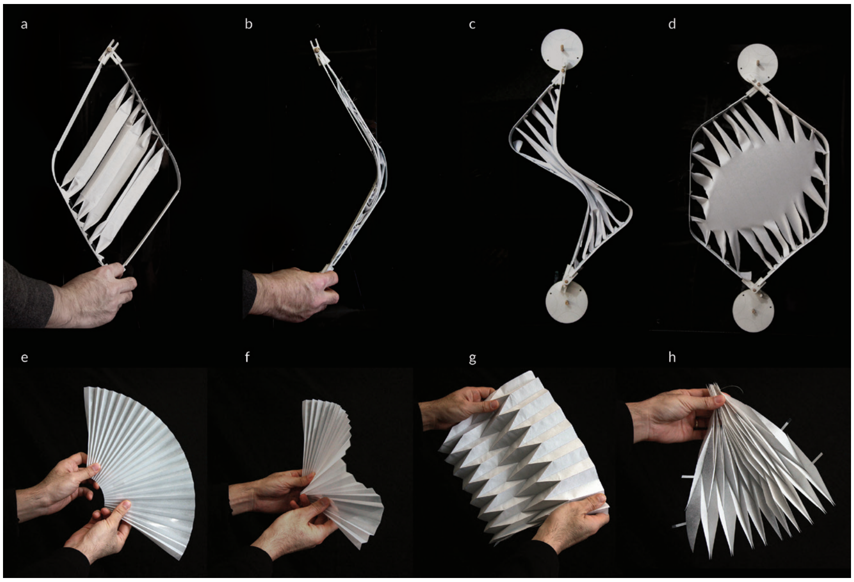
Limitation, Discussion, and Future Studies

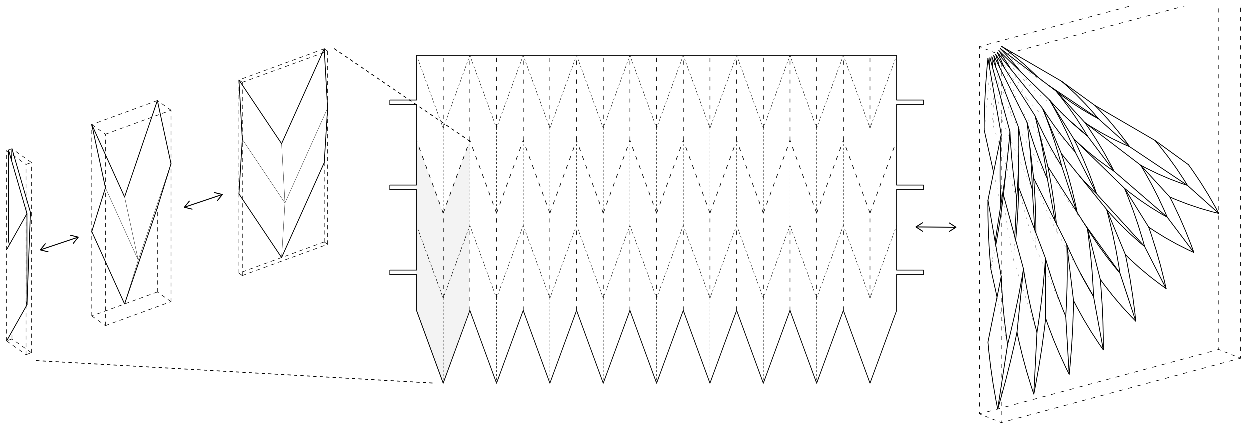
This study demonstrates a proof of concept for a dynamic facade based on snapping-induced motion, where continuous force application is not needed for the desired level of deformation. In this prototype, polystyrene beam components were selected in order to avoid a complex fabrication procedure and to dispense

▷ Figure 6. (a) Design of base module and detail of the modified Geneva drive. (b) Hand operation test model using modified Geneva stop mechanism. Counterclockwise rotation from left to right. (c) Snapshots of hand operation: counterclockwise rotation by hand will actuate clockwise opening.



▷ Figure 7. Various membrane designs.





△ Figure 8. Diagram of a folding mechanism.

with the use of mechanical actuation motors. In practical applications, however, other materials (e.g., steel, wood veneer) can also be adopted for the beam components, and the dimensions of the snapping beams would need to change accordingly to meet practical design requirements, including the strength of the existing mullions, the level of applied forces, and the effect of temperature. For example, if steel is selected for the beam components in a practical building envelope, it will cause a higher level of applied force/moment compared to the polystyrene beams. In this case, an additional assembly design for the steel snapping module will be needed to enable its desired motion. If hand operation is required, the resulting higher level of applied force must be properly addressed. The dimension of steel snapping modules would need to be reduced, or a cascade motion of the snapping actuation should be implemented to sequentially distribute the total amount of force/moment for the snapping actuation. Alternatively, if mechanical actuation motors are allowed, architects may have more flexibility in determining the overall dimension of the snapping modules, which will be achieved at the expense of periodic motor maintenance. Regardless of the types of materials used in the beam components, the actuation junction can be further investigated to provide an easy, efficient operation of the proposed snapping facade.

Furthermore, the membrane folding pattern needs to be improved for the application of the proposed snapping facade to develop it into a functional building envelope. The proposed membrane folding pattern covers much of the area between two beam components without kinematic discrepancy. However, it does not completely fill the gaps between two radial folding patterns, allowing light to pass through the gaps. Thus, there is more room to improve the design of the membrane folding patterns in order to completely fill the area between the two beams.

Learning from the prototype in this study, the work can continue to explore different materials and/or geometries for the snapping module. The success of the prototype, including the operation of one group (here, 6 snapping modules), demonstrates that numerical simulation can successfully estimate the force/moment required to operate multiple groups of snapping modules. In addition, the structural FE simulations utilized prior to the actual fabrication will help architects design the beam components so that they only undergo linear elastic deformation without any plastic deformation. In the future, an entire wall consisting of multiple uncoupled individually-operated snapping facade modules could be built to compare and test operation by hand versus a simple mechanical gear. Work is also planned to develop new shading surface materials and patterns for exterior applications. The holistic energy performance of the applied system will also need to be analyzed in comparison with other conventional shading systems.

Conclusion

In this study, snapping-induced motion is adopted as an alternative actuation mechanism for designing a dynamic facade system. First, the fundamental snapping concept using a bistable spring structure was reviewed, and then a structural analysis was conducted to evaluate the snapping motion of a beam, to be adapted into a snapping facade. Based on this study, a basic facade module was designed and built. In addition, a folding pattern is also presented for the potential design of the window covering within the snapping facade. In a proposed structure, this prototype of a snapping facade validated the hand-operated snapping motion.

This proof-of-concept model demonstrates that there is an opportunity to explore the benefit of elastic instability in buildings, and, in particular, to improve the performance of shading devices using a low-energy actuation mechanism. The factors of climate, orientation, and geographic location will be considered in future studies. Scientists and engineers have only begun to understand the potential benefits of elastic instability,[32] and the proposed snapping facade provides a novel way to exploit the strain energy stored in structures via elastic instability, underlining designers' role in this emerging field.

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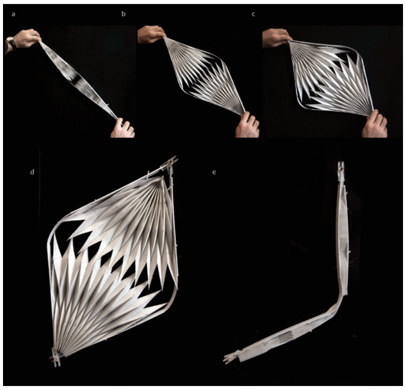
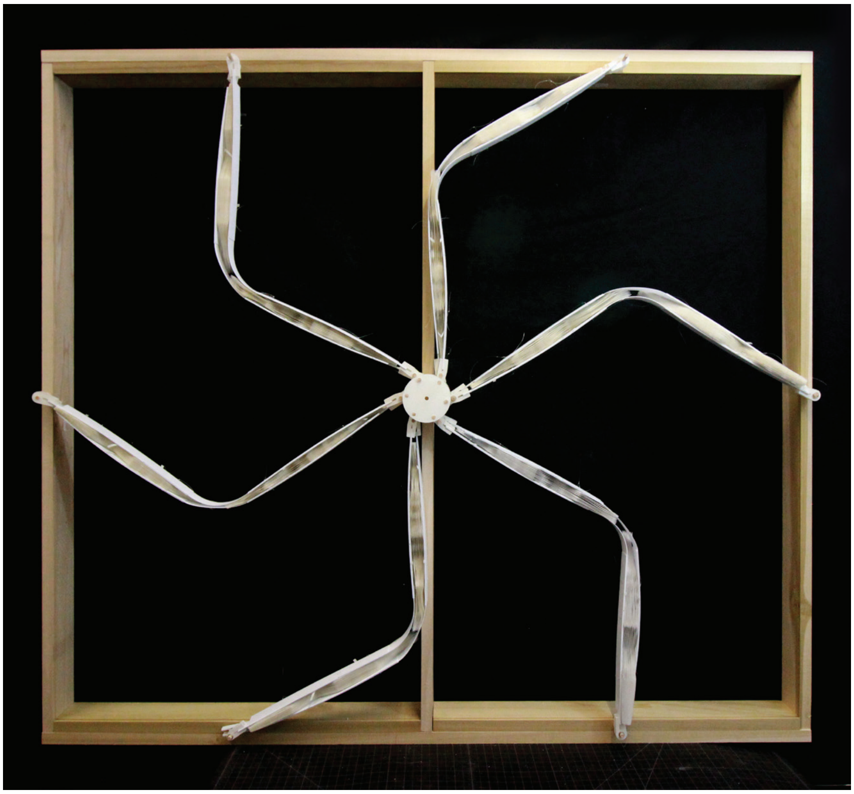
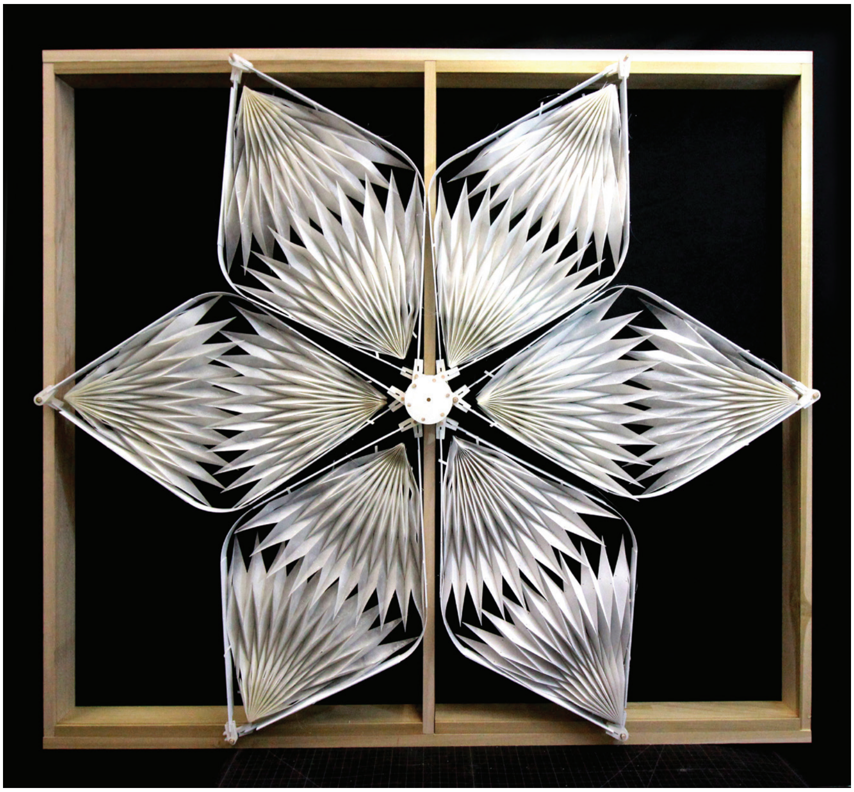


△ Figure 9. Membrane in a snapping facade base module.





△ Figure 10. Prototype of snapping facade.

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