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Shape-morphing materials and structures for energy-efficient building envelopes

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A B S T R A C T

Buildings account for 30% of global energy consumption. Improving the energy efficiency of buildings becomes essential to reducing energy consumption for alleviating their deteriorating impacts on the environment. As one of the key elements, the building envelope is essential to reducing the building energy consumption. Recent researches have demonstrated the promise of environmentally adaptive shape-morphing building envelopes in enhancing energy efficiency over the conventional stationary ones. In this review, we briefly discuss the recent advances in energy-efficient shape-morphing building envelopes from both structural designs and engineering materials viewpoints for energy saving and energy harvesting. For structural designs, we discuss the designs and performances of four representative categories of shape-morphing building envelopes, including conventional dynamic façades with simple rigid motions, biomimic adaptive structures, reconfigurable kirigami/origami-based structures, and morphable wrinkling surface–based smart windows. For materials design, we discuss the typical materials and design strategies used for actuating the shape-morphing building envelopes and smart windows. We expect that this brief review will be insightful for developing future shape-morphing building envelopes to make buildings more energetically efficient, comfortable, and environmentally friendly.

1. Introduction

Currently, energy consumption for buildings accounts for 30% of global energy consumption [1–3], which is beyond transportation and industry sectors, and will keep growing in the future because of worldwide urbanizations [2]. In the United States, commercial and residential buildings account for over 76% of nationwide electricity use and 40% of all primary energy usage and associated greenhouse gas emission. Thus, reducing energy consumption in buildings is essential to alleviating deteriorating impacts on the environment. Improving the energy efficiency of buildings is becoming a priority by converting buildings from energy consumers to energy-neutral or even energy-positive entities, which produce more energy from renewable sources than they consume [4–7]. To improve the building performances, building efficiency requires the integration of superior architecture and engineering designs, energy-efficient building materials, quality construction practices, and intelligent operation of the structures. Among the energy use in buildings, heating, ventilation, and air conditioning (HVAC) consume the most energy, with 35% of total building energy, followed by lighting with 11% in the United States. In each area of the energy use, there are many opportunities to improve their performance in building energy consumption.

Here, we focus on the energy-efficient building envelope that is essential to reducing building energy consumption. Building envelope, generally referring to the artificial structures on the skin of building walls, roofs, and windows, is responsible for the energy transfer, such as daylight, heat, and air between the external (climate-control) and internal (resident-driven) environments [8]. Thus, as one of the essential elements, the building envelope accounts for the majority of building operational energy consumptions, including heating, cooling, ventilation, and lighting for comfortable living/working spaces [9]. It is highly demanding to scale up technical efforts and economical investments for enhancing the building envelope's performances [10,11].

Current research on energy-efficient building envelopes mainly focuses on optimizing the structural and materials designs of façades and smart windows. Building envelopes use the control of

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solar radiations to balance interior lighting and thermal conditions or harness reusable onsite sunlight to generate electrical/thermal energy [12,13]. To date, a variety of structural systems and technologies have been developed for designing energy-efficient building envelopes, including integrated solar shades [14], manually controlled roller blinds [15], and other systems [16,17]. However, the building envelopes in these traditional designs are often bulky and stationary, which prevent them from adaptively responding to daily or seasonally external environmental changes. Thus, a static building envelope could cause potential performance issues (e.g. overheating) and deteriorate indoor comfort, which ultimately shortens the service life of buildings [18]. An ideal building envelope should be capable of maintaining stable and comfortable indoor climate while tolerating external environmental variations. A shape-morphing building envelope equipped with enhanced environmental adaptability is becoming a potential promising solution [19]. Compared with traditional stationary designs, the shape-morphing building envelope can adjust its structural form and shape to adapt to time-changing external environments, as well as the psychological and living needs of inside occupants at acceptable spatiotemporal scales.

There are various types of shape-morphing building envelope designs. Readers can refer to previous reviews [19,20] on their deformation, control, and performances of some special designs. In this review, we will conclude previous designs of shape-morphing building envelopes from a more basic and more comprehensive aspect ranging from the representative yet very basic structural forms, construction materials, actuation mechanisms, the overall energy efficiency and performances, to their limitations. Generally, we will classify all the designs into two main different categories: passive solar shading envelope structures and active envelope structures integrating with energy-generating materials. Moreover, given their special structural forms, commonly used materials that are potentially applicable to fabricate and actuate are also summarized accordingly. The aim of this review is hoping to from the bottom design level to inspire designers or researchers to further revolutionize future novel shape-morphing building envelopes that can optimally satisfy practical needs.

In this article, we briefly review recent advances in the energy-efficient shape-morphing building envelopes with a focus on the dynamic shape-changing façades and smart windows from the viewpoint of structural and material designs. The review is organized as follows. In Section 2, we summarize the main structural design principles for energy-efficient shape-morphing building envelope, including conventional kinetic façades and bio-inspired façades, shape-morphing kirigami/origami structure–based building envelopes, and shape-morphing surfaces and materials based smart windows. For building envelopes, both the passive designs for solar shading and the active structures integrated with energy-generating materials are discussed. In Section 3, from the materials design side, we discuss different actuation mechanisms for building envelopes made of representative actuating materials, including shape memory alloys (SMAs), shape memory polymers (SMPs), liquid crystal elastomer (LCE), and hydrogels. Finally, in the last section, we conclude with the summary of current designs of energy-efficient building envelopes and outlooks for potential future developments.

2. Structural designs of energy-efficient shape-morphing building envelopes

Generally, the shape-morphing building envelopes can be classified into two main categories in terms of energy saving and energy harvesting. One is using the dynamic shape changes of building envelopes for sole solar shading to save energy as discussed in Section 2.1. The other is integrating dynamic shape-changing building envelopes with photovoltaic materials or devices for both energy saving and energy harvesting as discussed in Section 2.2. In Section 2.1, we further classify the building envelopes into four categories in terms of structural designs, including conventional dynamic façades via rigid rotations as discussed in Section 2.1.1, bio-inspired adaptive façades in Section 2.1.2, novel shape-morphing kirigami and origami structures in Section 2.1.3, and morphable surface structure–based smart windows in Section 2.1.4.

2.1. Structural design of shape-morphing building envelopes without energy conversion

2.1.1. Conventional structural designs of dynamic façades

Conventional façades usually perform shape changes through simple mechanisms, such as rigid rotations, sliding, translation, inflation, extrusion, and swing [12,13,19–21]. These façades are composed of simple rigid structural components in the triangular (Fig. 1a, [22]) or quadrilateral shape (Fig. 1b–d; [23–25]). Under actuations driven by electrical motors, these structures can quickly adjust their shapes via rigid rotation (Fig. 1a–b) or combined rotation and sliding (Fig. 1c–d). These adaptive building façades are often built into an individual system to adjust indoor thermal climate and visual effect by blocking and letting light through [25]. The individual façade can change its structural forms by opening and closing the pores locally and independently, as seen in the examples of the façade cells on the SDU Campus Kolding (Fig. 1a), the climate adaptive façade system (Fig. 1c), and the kinetic sliding/rotatable window of the Helio Trace Centre (Fig. 1d). These individual façade systems can meet various needs of occupants to achieve enhanced environmental adaptability. Moreover, they are also programmable to form desired shapes. As demonstrated in Fig. 1b, for better indoor working conditions, the interactive kinetic façade can change its pattern from a fully open state (Fig. 1b, left) to a gradient open state (Fig. 1b, right). Simulation results show that such a kinetic façade can keep indoor visual conditions in a satisfactory level, as well as enhance the internal daylight metrics with an average daylight illuminance in the ranges of 54–82% [23]. In addition to rigid rotation and sliding, one can also use the kinetic translation and scaling shape-morphing mechanisms to design dynamic façades. Fig. 1e shows that the kinetic façades with hexagonal-shaped units can translate to different locations or rotate with different angles to change their shapes. Thus, it renders different structural permeability to block and let light through, as well as tune indoor visual conditions [26]. Simulation results show that such a rotational kinetic façade could improve the daylight by approximately 50% in summer and spring, whereas 30% in fall and winter, which renders almost 100% enhancement for daily indoor illuminance [26]. Their simple geometries and 2D kinetic motions facilitate the systematic designs with optimized performances through efficient simulation tools, as opposed to conventional long-term experiments-guided design strategies.

In addition to rigid motions, other deformation mechanisms such as pneumatic inflation (Fig. 1f), extended extrusion (Fig. 1g), closed-loop self-rolling (Fig. 1h), and bending (Fig. 1i) have been proposed to build dynamic façades with solar shading effects. The air cushion structure made of ethylene tetrafluoroethylene (ETFE) sheets is one of the representative façades actuated by pneumatic air. Fig. 1f shows two such examples of Detalle del ETFE building (left) and Water Cube (right). The façade units can expand into curvature-tunable surfaces after pneumatic air pressurization to filter the solar ultraviolet (UV) rays dramatically and tune the indoor thermal conditions to desired states [27,28]. Thus, it can reduce more buildings energy consumption on air conditioning.

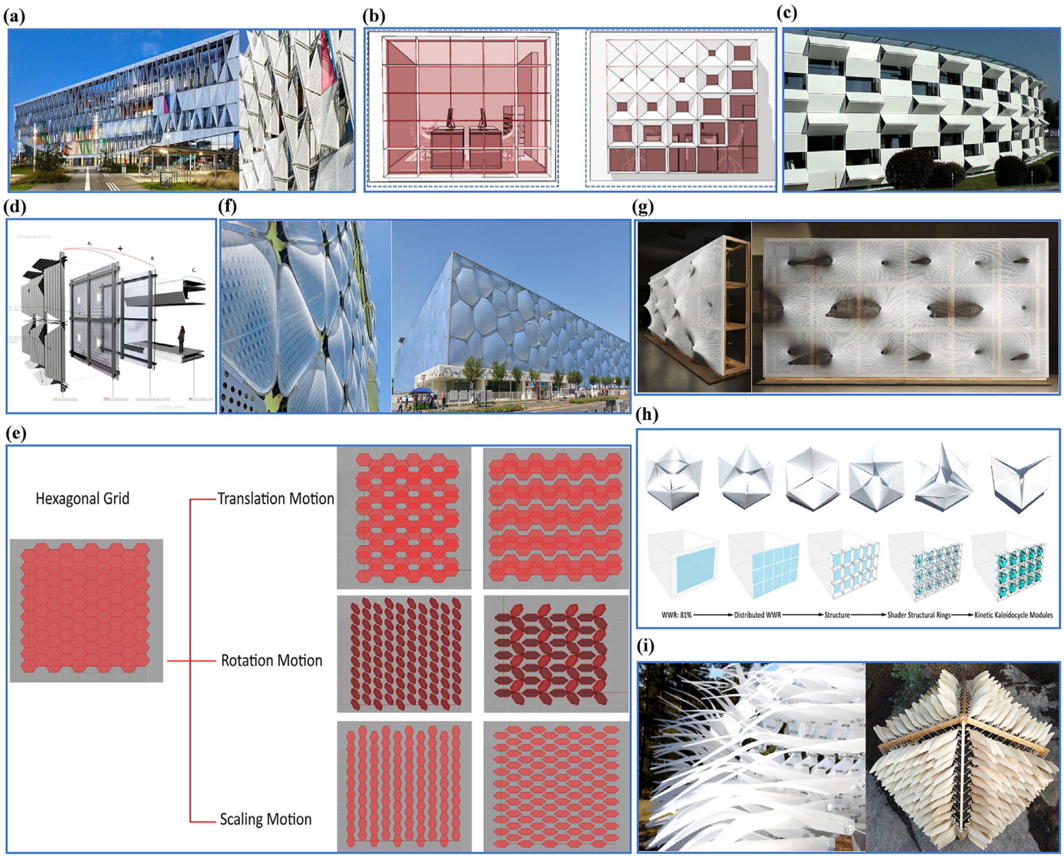

Fig. 1. Structural designs of conventional kinetic shape-morphing building envelopes. (**a**) SDU Campus Kolding with kinetic rigid façades (Copyright to ArcDog, the Social Network for Architects) [22]; (**b**) Interactive kinetic façades [23]; (**c**) Climate adaptive building shells: the dynamic façade of Kiefer Technic Showroom (Copyright by Inhabitat - Sustainable Design Innovation, Eco Architecture, Green Building and image by Sarah Lawley) [24]; (**d**) 3D section for Helio Trace Centre window (Copyright to SOM and image from dwell.com) [25]. (**e**) Kinetic façades with shape changes tuned by translation, rotation, and scaling [26]. (**f**) Pneumatically tunable ETFE façades (Left: MEDIA-TIC, Copyright and Image by Barcelona (SP), 2007; Right: Water Cube in Beijing, Copyright by 2021 Slyar Home) [27,28]. (**g**) Elastic fabric net-like kinetic wall with shape change by mechanical extrusion (Copyright to Barkow Leibinger and Photo by Johannes Foerster) [29]. (**h**) Kaleidocycle façade changing shape by closed-loop rotation [30]. (**i**) Shiver house with wind actuated rooftops (Copyright to and images from NEON.UK) [31].

Furthermore, combining with the inflation mechanism, additional surface coatings can be integrated on these façades to alter their surface micromorphologies for sunlight modulation upon air inflation [10], which has been applied to design shape-morphing smart window as discussed later. The similar concept of shape-morphing building envelope can also apply to other materials, for example, elastic synthetic fabric shown in Fig. 1g of Kinematic Wall [29]. By extending/retracting a series of motorized rods, the elastic fabric would transform into sectional peaks and valleys to mimic the inflatable façades for achieving tunable curved surfaces. Given the generated non-uniform pore sizes, the peak region will become more transparent than the valley area. Thus, it can realize different local visual conditions [29]. Compared with the pneumatic façades, this elastic fabric design is more dynamically shape-programmable considering its unlimited extrusion/retraction points on the surface.

Remarkably, the rigid mechanism structures have also been used to construct individual façade systems, for example, the Kaleidocycle ring–based façade units shown in Fig. 1h. The Kaleidocycle ring is a closed-loop mechanism with its internal structural permeability changing periodically with the continuous rigid rotation [30]. Thus, similar to the façade designs in Fig. 1a–d, to achieve comfortable visual and thermal conditions, one can manipulate the desired patterns with appropriate structural porosity by actively motorizing different Kaleidocycle rings with intended angles. Building energy simulation shows that such a dynamically tunable façade can achieve over 85% of hourly daylight enhancement [30]. For small-scale architecture such as residential houses, the shape changes in their façades can be driven passively by natural forces, such as wind, rain, and snow [20], to save energy. For example, the façades of the Shiver house are composed of lightweight feather-like individuals (Fig. 1i, left) and closed-loop kinetic mechanisms (Fig. 1i, right). They can bend or move by the wind to realize different shading effects [31].

2.1.2. Bio-inspired design of dynamic façade

In nature, some plants are well known for the extraordinary capability of morphing their shapes to adapt to the environmental changes, which inspires the designs of biomimic adaptive façades [12,32]. Fig. 2a shows one example of bio-inspired dynamic façade design, that is, an elastic hingeless façade with flapping mechanism. The design is inspired by the valvular pollination mechanism from the kinematics of the bird-of-paradise flower. The natural prototypes are petals of *Strelitzia reginae* flowers. Upon birds landing or leaving, the flower petals are opened or closed to transfer their pollen [33]. To mimic the elastic flapping deformation, Schleicher et al. [33] created a simple physical model that is composed of rigid and stiffer backbones and soft elastic thin fin-sheet (Fig. 2b, bottom-left). By bending the rigid backbones, the thin fin-sheet can bend or/and even buckle with a large deflection angle. Lienhard et al. [34] showed that integrating this physical model with the building skin can generate a hingeless façade

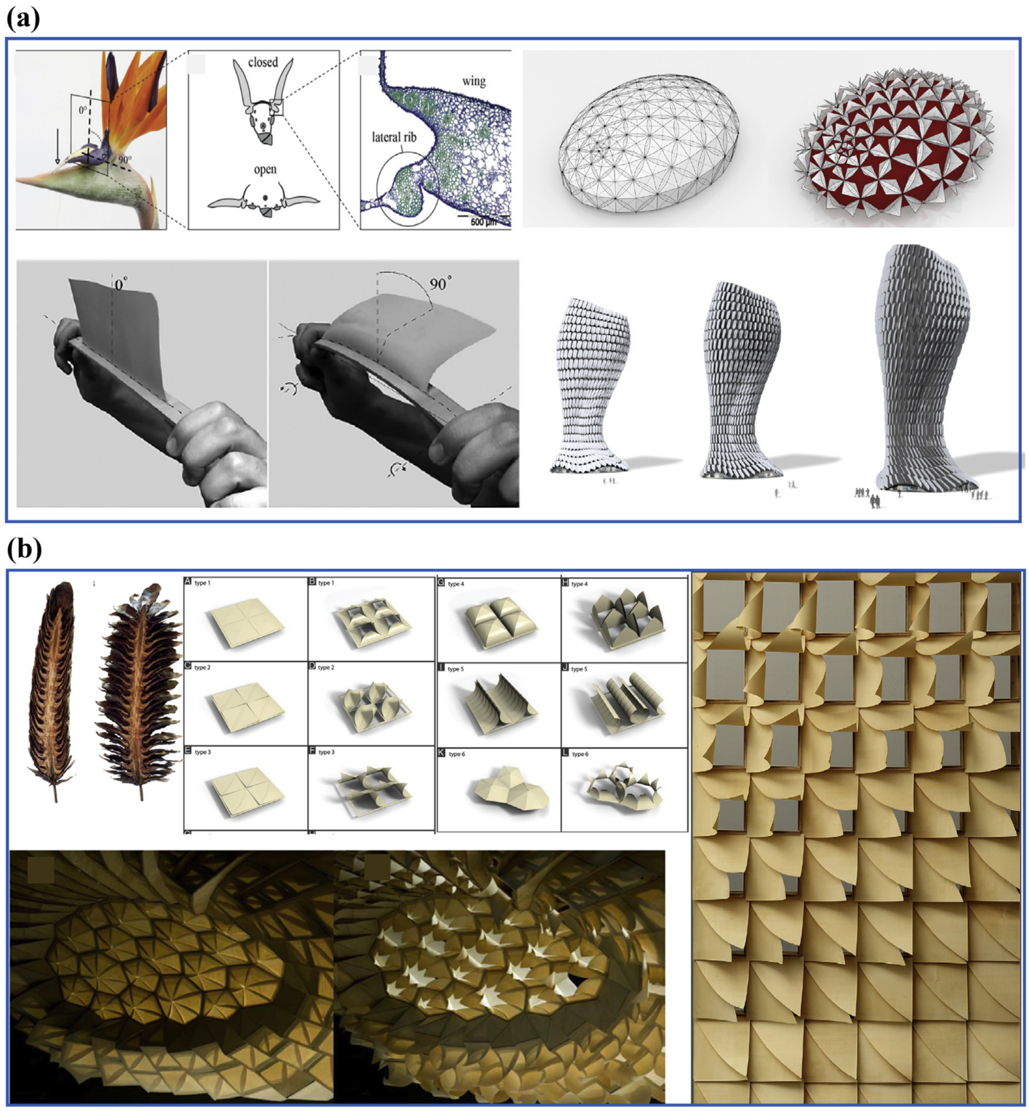

Fig. 2. Structural designs of biomimic shape-morphing building envelopes. (**a**) Flectofin with hingeless flapping mechanism [33]; (**b**) Humidity actuated façades made of wood sheets with structural anisotropy [36].

system, where each individual cell acts as a solar shading system (Fig. 2a, right). The benefits of this design are its lightweight structural feature because of the thin fin-sheets and no need of traditional cumbersome mechanical hinge systems for actuation. Similar biomimic façades with tunable porosity are also proposed by imitating anisotropic leaves or mimicking stomata function in leaves [36], which can be passively opened or closed under different humidity of air moisture (Fig. 2b, [35]).

2.1.3. *Kirigami- and origami-inspired novel structural designs of dynamic façades*

Recent advances on kirigami and origami structures have demonstrated their promise for broad applications in the phononic, photonic, electronic, and robotic fields [37–39]. Kirigami (paper cutting) and origami (paper folding) are the ancient paper art, where "kiri" means cut and "ori" means folding. Introducing cutting slits and/or folding creases to thin sheets of materials can achieve varieties of reconfigurable 2D and 3D structures via out-of-plane buckling or folding [40–44]. The pore opening and closing in kirigami structures [40–42] and folding of origami structures [39,43] can be harnessed to block and let light through, making them promising candidates as new-generation shape-morphing building envelopes. For kirigami structures, buckling of sectional cut strips opens the patterned cut slits, generating periodic arrays of pores. The pore size and shape can be dynamically tuned as needed by simple stretching strain. Unlike the kirigami approach, origami structures harness the folding of prescribed crease patterns to transform from a compact folded state to a fully expanded state to achieve dynamically tunable shading effect.

The kirigami façades can be either implemented as an individual (Fig. 3a) or integrated system (Fig. 3b–c). Zhang et al. [45] proposed the first proof-of-concept demonstration of kirigami structures for solar shading. Arrays of rectangular shutter-like individual kirigami reflective membrane with non-penetrating cuts are bonded to a transparent soft elastomer (Fig. 3a, top). This design relies on different stretching strain to make kirigami membrane structural elements dynamically and timely reflect the solar radiation to reduce the optical transmissions. Specifically, stretching the elastomer with different strains will tilt the kirigami elements out of plane with different tilting angles (Fig. 3a, middle). As the kirigami array rotates upward, it will gradually block the normally incident light to tune the optical transmittance. Given the dependence of

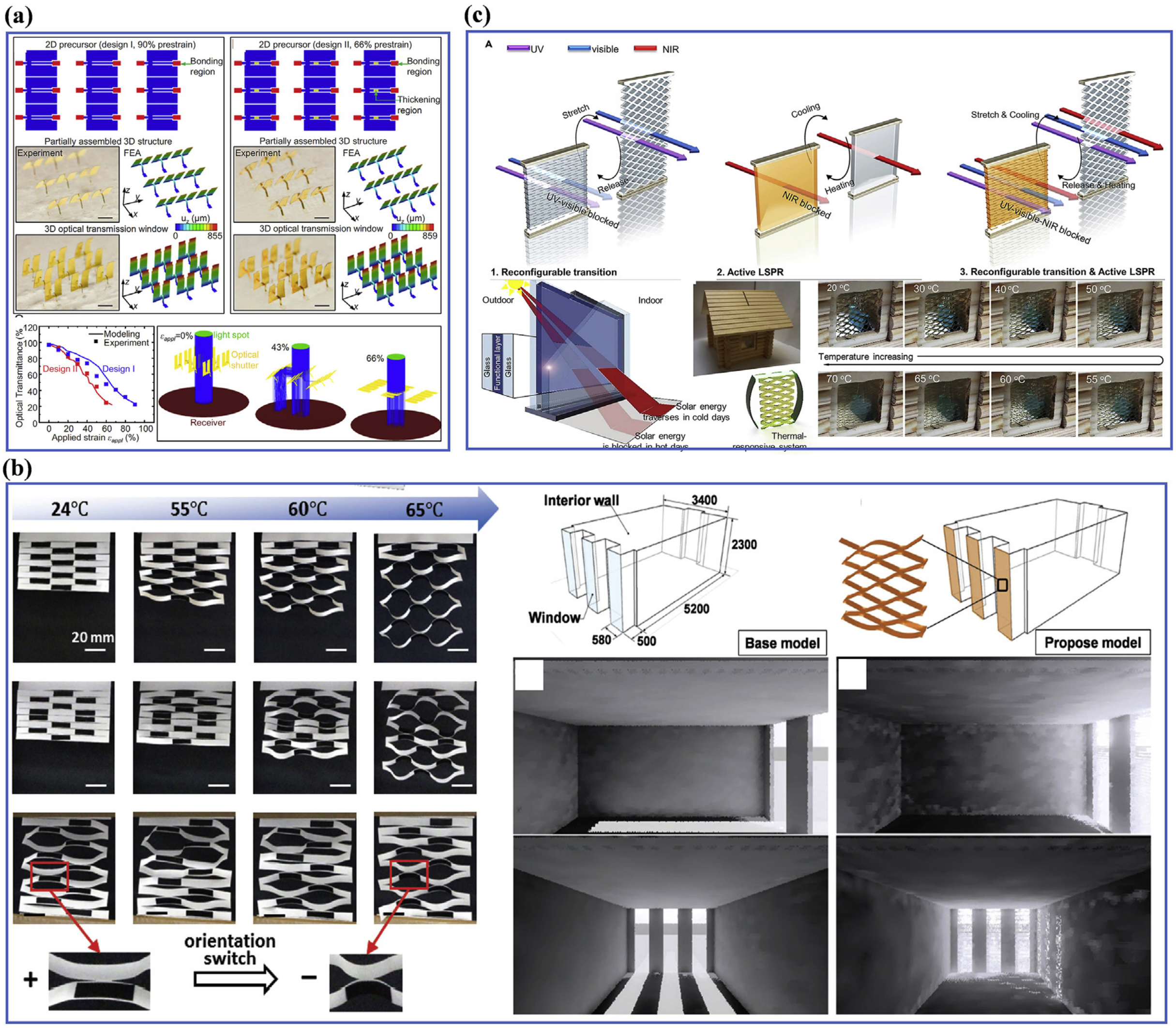

Fig. 3. Structural designs of kirigami-based shape-morphing building envelopes. (**a**) Mechanically tunable optical transmission window with tunable solar irradiation by optical reflection [45]; (**b**) Kirigami façades with parallel cuts blocking light by thermally actuated pore opening and closing [46,47]; (**c**) Adaptive thermochromic kirigami windows modulating both ultraviolet–visible and near-infrared solar rays [48].

their optical transmittance on the uni-axial tensile strain, it can realize a large range of shading effect (Fig. 3a, bottom-left). For example, the optical transmittance can decrease significantly from approximately 97% at zero applied strain to around 22% at an applied strain of approximately 90% [45]. Tang et al. [46] further used the reflective kirigami structure with periodically distributed parallel cuts as an integrated system for designing environmental adaptive building envelopes (Fig. 3b). When constructing the kirigami structure with temperature-responsive materials, the integrated kirigami design could actively open or close its pores in response to environmental temperature changes. The surface could be coated with reflective coatings to reflect and redirect the sunlight for building energy saving. This kirigami envelope could diffuse the sunlight around the window area and reduce the penetration of direct solar light into room that causes glare. The generated arrays of pores and adaptively tilted ribbons could collectively diffuse the sunlight more evenly for electricity saving. Therefore, the indoor light level can be appropriately adjusted by controlling the penetration of sunlight. In summer, this kirigami envelope could reduce cooling load and electricity consumption by blocking or diffusing sunlight, while in winter, it could help to reduce the heating electricity usage by actively tilting its struts to allow more solar light into the building. Based on the same structure, through building energy simulation, Yi et al. [47] showed that the kirigami façade could effectively reduce the energy consumption by reducing electricity use over 26% on the tested building, reducing air-cooling load over 47.4% in summer when compared with buildings without any façades. Very recently, researchers have tried to achieve multifunctional performances of the kirigami façades by integrating with functional materials. Ke et al. [48] proposed a bi-functional kirigami building envelope made of composite elastomer. Such a kirigami composite envelope is constructed by embedding the elastomer with plasmonic vanadium dioxide (VO_2) nanoparticles (NPs; Fig. 3c). It can actively tune the indoor solar irradiation. The working mechanism relies on the structural geometrical structure transition and the temperature-dependent localized surface plasmon resonance (LSPR) in ultraviolet–visible and near-infrared regions. Specifically, upon stretching, the kirigami composite with local cut slits can transform to a non-compact configuration with cuts open up and thus control the transmittance of ultra-violet-visible solar rays. In fact, this stretching induced kirigami envelope can as well achieve a dynamically optical transmittance control under different mechanical strains. Moreover, the thermal-dependent LSPR can tune the near-infrared region [48] because of the metallic state phase transition of VO_2, resulting in the releasing of free electrons to distinguish the near-infrared light absorption. In response to the increasing environmental temperature, they showed that this kirigami composite envelope provides gradually tunable indoor temperature through the combination of its strain-controlled shape morphing to block visible light and material phase transition to diffuse infrared (IR) light. Correspondingly, it is found the transmittance in the UV—vis—NIR regions can changes from 75% (open state) to 0% (closed state). This work opens a new avenue of integrating both structural and materials designs for shape-morphing building envelopes to facilitate enhanced solar energy modulation.

Based on the origami structures, Pesenti et al. [49] systematically explored the crease patterns to construct the origami-inspired façades in an integrated structural form (Fig. 4a). In general, the integrated origami façades rely on the crease folding to change their surface areas to block and let light through in different levels of light intensity. As shown in right of Fig. 4a, different creases folding angles of local origami structural elements can change shape with out-of-plane deformation; thus, it engenders void structural sections that are uniformly distributed throughout the whole structure. Benefiting from these size-tunable void sections, this origami envelope could timely block or allow the solar light into room to tune indoor thermal and illuminant conditions. Moreover, the element of this origami envelope can be designed with various structural patterns for practical environmental consideration. With the optimized design, they showed that the motion time for the origami façades could be as low as 7 h during the winter weeks and 14 h during the summer time to achieve comfortable indoor thermal conditions. All the studied crease patterns show excellent performances in tuning the indoor illuminance, all of which meet over 74% daily lighting requirement. They also showed that when considering internal cooling, heating, and lighting, the optimized façade pattern could save over 10% energy [49]. Compared with the integrated system, individual origami façades are more convenient for transportation, installation, and manipulation. The individual origami façade design has been implemented on the Al-Bahr-Towers [50]. As shown in Fig. 4b, the design is inspired by the "marshrabiya" flower that uses origami folding to change its shapes. The individual façade is constructed from a simple origami model composed of six foldable

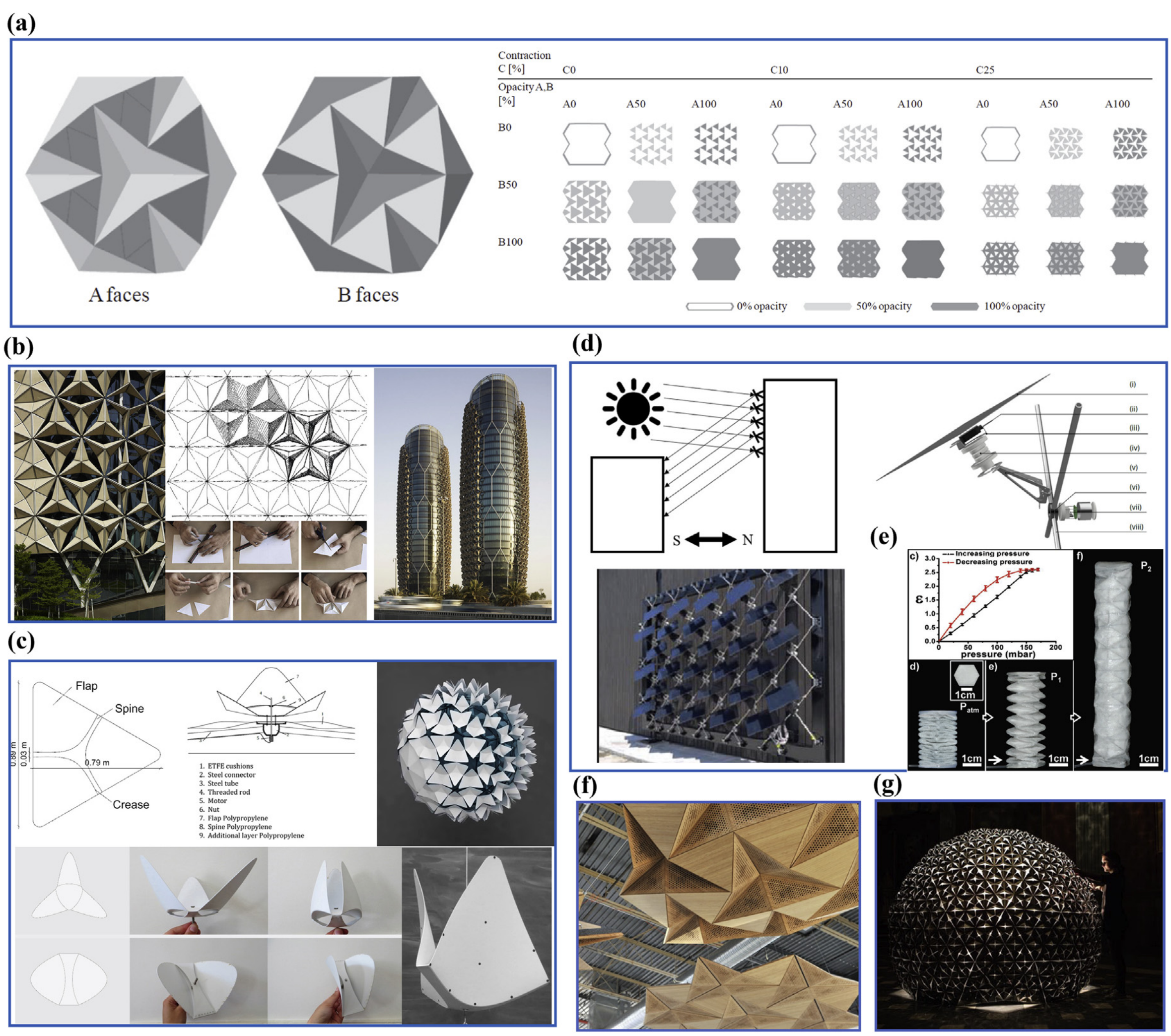

Fig. 4. Structural designs of origami-based shape-morphing building envelopes. (**a**) Integrated adaptive origami shading systems with different patterns [49]. (**b**) Dynamic origami façades with individual systems (Copyright to AHR Group; Photo: Al-Bahr-Towers) [50]. (**c**) Shape-morphing origami individual façades based on origami patterns with curve fold lines [51]. (**d**) Adaptive façades actuated by soft pneumatic origami actuators [52]. (**e**) Soft origami actuators with multiple directional control [54]. (**f**) Indoor origami resonant chamber sound control (Copyright to and image from the Regents of the University of Michigan) [55]. (**g**) Interactive origami skin (Copyright to and image from Screencity LAB) [56].

triangular facets. After folding actuated by electrical motors, the triangular facets can retract inward and generate pores in different sizes with tunable structural permeability. Thus, these size-tunable structural pores can be used to control the transmission of sunlight and adjust internal thermal and optical conditions in the buildings and finally to save electrical energy for illumination and cooling/heating uses. Moreover, through distributing the individual units discretely onto the building skin, occupants can freely and independently adjust the shading façade in the vicinity of their workspace for customized needs. Moreover, different individual façades can be intelligently programmed to achieve the optimized solar reducing/gaining performance both timely and spatially [50]. The origami façade system provides a sustainable construction solution because of its potential in significantly reducing buildings' energy needs for artificial lighting and air conditioning. Furthermore, Fig. 4c (top) shows that origami structures with curved folding creases can also be used to build individual façade systems. After applying a bending moment to the central area of the curved origami structure (Fig. 4c, top), its neighboring facets bounded by the curved folds will buckle inward with a larger bending angle [51], resulting in a 3D pore-opening structure in different pore sizes. Fig. 4c shows the design by arraying them onto buildings as a façade. It is noted that this design exhibits similar solar shading effect through the structural pore sections generated by the folding of local curved origami structural elements. Compared with the straight-fold based origami façades, the curved origami façade is more energy efficient because it requires less actuation energy to trigger the buckling deformation of the shading parts.

In addition to its application as a dynamic façade for energy saving, the origami design can also act as an actuator to drive the motion of façades. Svetozarevic et al. [69] proposed a combined modular façade system (Fig. 4d, left) with flat sheet as a façade to tune the indoor shading and thermal conditions. The soft pneumatic actuator that controls the facing directions of upper façade structures is composed of a three-channeled origami structure. Upon air inflation into the channels of this soft origami actuator under a controllable way, the facing direction of the upper façade structural element can be timely and continuously adjusted to block/allow sunlight into buildings during daylight hours. Correspondingly, the internal visual and temperature conditions will be appropriately tuned to reduce electricity uses. They further demonstrated that photovoltaic materials can be additionally integrated onto the upper structural elements to build active shape-morphing facades that can produce energy. Compared with traditional rigid actuation methods with cumbersome metal-based mechanical parts, this origami-based soft actuator is lightweight and more flexible to achieve a large tunable space with higher durability for a longer service life [52,53]. Fig. 4e shows that more channeled soft origami actuator is feasible to achieve more degrees of freedom in enhancing the tunable tilting range of façades [54]. For indoor use, the origami façades also showed multifunctionality of sound control (Fig. 4f, [55]) and informative interactions with humans (Fig. 4g, [56]).

Considering buildings with varieties of complex exterior surface shapes, kirigami and origami designs [57–59] that can achieve rich 2D and 3D shape shifting (Fig. 5a) provide a large design space for potential façades purposes. Moreover, additive kirigami and origami designs by combining cuts and folds (Fig. 5b–d, [60–62]) open new potential opportunities for designing environmental adaptive shape-morphing façades. For example, by replacing the point hinges in the classical square kirigami structure with foldable hinges (Fig. 5b, top), Tang et al. [60] demonstrated a new class of active foldable kirigami structures with a large range of tunable permeability (Fig. 5b, middle and bottom) in response to environmental temperature changes. Together with the central rigid plates, the pop-up hinges could potentially provide an enhanced shading effect [60].

2.1.4. Dynamically tunable surface morphology–based smart window

Smart windows are composed of optical materials with tunable optical transmittance. They can switch from transparent to opaque to block or let light through for energy saving under actuation. Unlike the movable and shape-changing building envelopes or façades discussed above, smart windows are stationary without involving any movable components. The dynamic glazing materials are mainly chromogenic materials, such as electrochromic, photochromic, and thermochromic materials, in response to electrical field, light, or temperature [63]. Such chromogenic optical materials rely on the internal structural changes on the small scale to achieve tunable optical transmittance. Recently, there has been increasing research interest in a new class of wrinkling surface–based smart windows. Different from the smart chromogenic materials, it uses the dynamically tunable surface morphology on the microscale to scatter or diffuse light to achieve switchable transparency and opacity. Similar to the shape-changing characteristics in dynamic façades, the microscale wrinkled surface morphology is shape morphable and dynamically tunable under applied mechanical strains, which can switch from a wrinkled (opaque or translucent) to a flattened state (transparent) instantaneously and reversibly. In this section, we will limit our discussions to such shape-morphing wrinkled surface–based smart windows from structural viewpoints.

The wrinkled surface–based smart windows often use a bilayer composite structure with a stiff coating resting on top of a compliant substrate. Fig. 6a shows the typical substrate prestrain approach to generate small-scale wrinkling patterns on elastomeric substrates [64]. The optically transparent elastomeric substrate is first prestretched to a certain strain, followed by either surface treatment or film deposition to generate a stiff coating on its top. Releasing the substrate prestrain generates the periodic wrinkling pattern on the microscale (Fig. 6b, right; [65]), which renders an opaque bilayer composite because of surface scattering. Repeating the process of mechanical stretching and releasing flattens and reforms the wrinkles, leading to a reversible switch between transparent and translucent states (Fig. 6a, bottom; Fig. 6b, right). Lin et al. [66] showed that combining sequential prestrain release and surface treatment could further generate more complex wrinkling patterns such as self-similar hierarchical wrinkles with both micro- and nano-scale features (Fig. 6c, top). Such a hierarchical wrinkling-based smart window displays both opaqueness and iridescent structural color (Fig. 6c, bottom).

For the substrate prestrain approach, generally wrinkling and cracking will co-exist in the wrinkled films because of the Poisson's effect. The combined wrinkles and cracks could strengthen surface roughness and consequently enhance the optical scattering effect, which could even lower its optical transmittance dramatically [67]. Referring to this method, Tomholt et al. [68] proposed a novel pneumatically tunable light-modulating façade based on the ETFE façade system [27,28]. The individual unit is composed of three major parts: soft and inflatable circular-shaped transparent PDMS (polydimethylsiloxane) on top, stiffer ETFE sealed with metal O-ring, and air tube for inflation (Fig. 6d, left-top). Upon air inflation, the mounted wrinkled PDMS with gold coating is non-uniformly stretched along the radial direction, generating a complex cracking pattern (Fig. 6d, left-middle). Upon deflating, the individual façade returns to the flat state with cracks closed. Thus, this façade can achieve two functionalities: the coated gold layer can tune near-infrared transmission to change indoor thermal environment, whereas the combined wrinkles and cracks can tune the

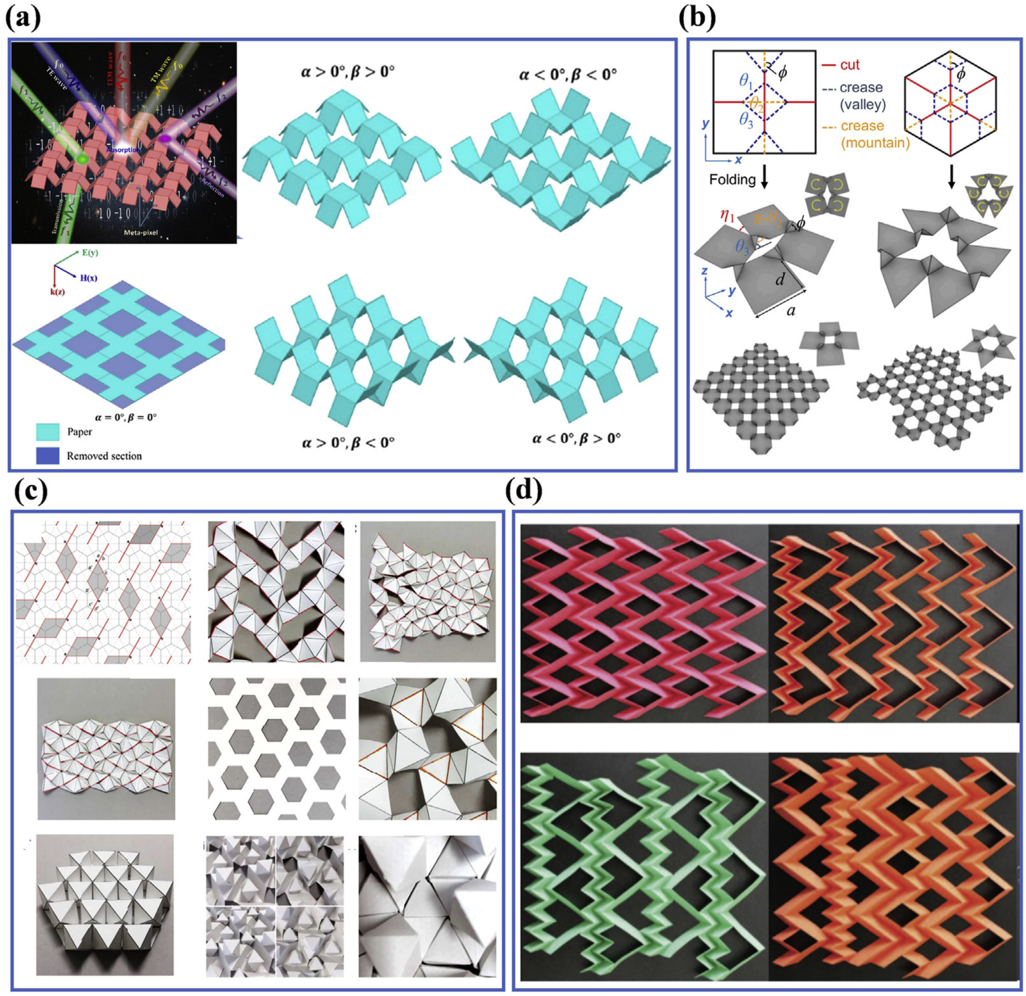

Fig. 5. Selected novel kirigami and origami structural designs. (**a**) Kirigami cut design to morph into desired 2D and 3D shapes [57]; (**b**) Kirigami structure design with foldable hinges [60]; (**c**) Additive origami structures with cutouts [61]; (**d**) Zigzag origami structures with cutouts [62].

visual effect by adjusting air pressure (Fig. 6d, top-right). Setting this individual façade onto the building skins such as windows and rooftop (Fig. 6d, middle-right) can save up to 70% energy than that without façades (Fig. 6d, bottom). Moreover, this new system shows promising robustness without sacrificing its optical performance after thousands of cycles [68].

We note that the wrinkle-based façade design method is promising to create more types of dynamically tunable envelope systems, which could be integrated with other façade designs to enable multifunctionalities for modulating solar light.

2.2. Structural design of shape-morphing building envelopes with energy harvesting

So far, the shape-morphing façade designs discussed above are for energy saving purpose. To further increase the building's energy efficiency, it would be preferable to combine both energy saving and solar energy harvesting in the shape-morphing building envelope. The development of solar cell technologies provides another dimension to design active façades with energy generation functionality, which could potentially render more energy saving and even energetically positive buildings. The simplest way of constructing energy harvesting building envelope is to integrate the façades with solar cells. Considering the direction changing of the sunlight, dynamic solar trackers can be embedded in the shape-morphing building envelope to obtain the maximum instantaneous incident power. In this section, we focus on discussing recent work on the structural designs of smart shape-morphing façades as solar trackers with additional energy generation capability.

In contrast to static solar panels, shape-morphing façade-based solar trackers can tune their facing directions to adapt to the changing incidental solar light for enhancing energy generation efficiency. For conventional kinetic individual façade systems, researchers have explored the method of direct adding of photovoltaic devices onto the flat shading sheets (Fig. 7a, top left) for energy harvesting [53]. By pneumatically actuating these façade solar trackers (Fig. 4d, right) in accordance with the incidental sunlight spatially and hourly, this façade system can actively and efficiently modulate the solar radiation for energy generation without losing its passive heating and shading functionalities [69]. The onsite experimental verification shows that this active façade can generate a yearly energy surplus over 146 kWh, making the tested building energy positive. Compared with static and stationary façades, the energy harvesting efficiency of this dynamic active building envelope can improve more than 20–50% on the generation of net electric energy, arising from its pneumatic actuators to timely adjust the upper facades facing direction with right angles. For office room in temperate climates, it can cover up to 115% of the net energy demand. However, the electric energy consumed for the

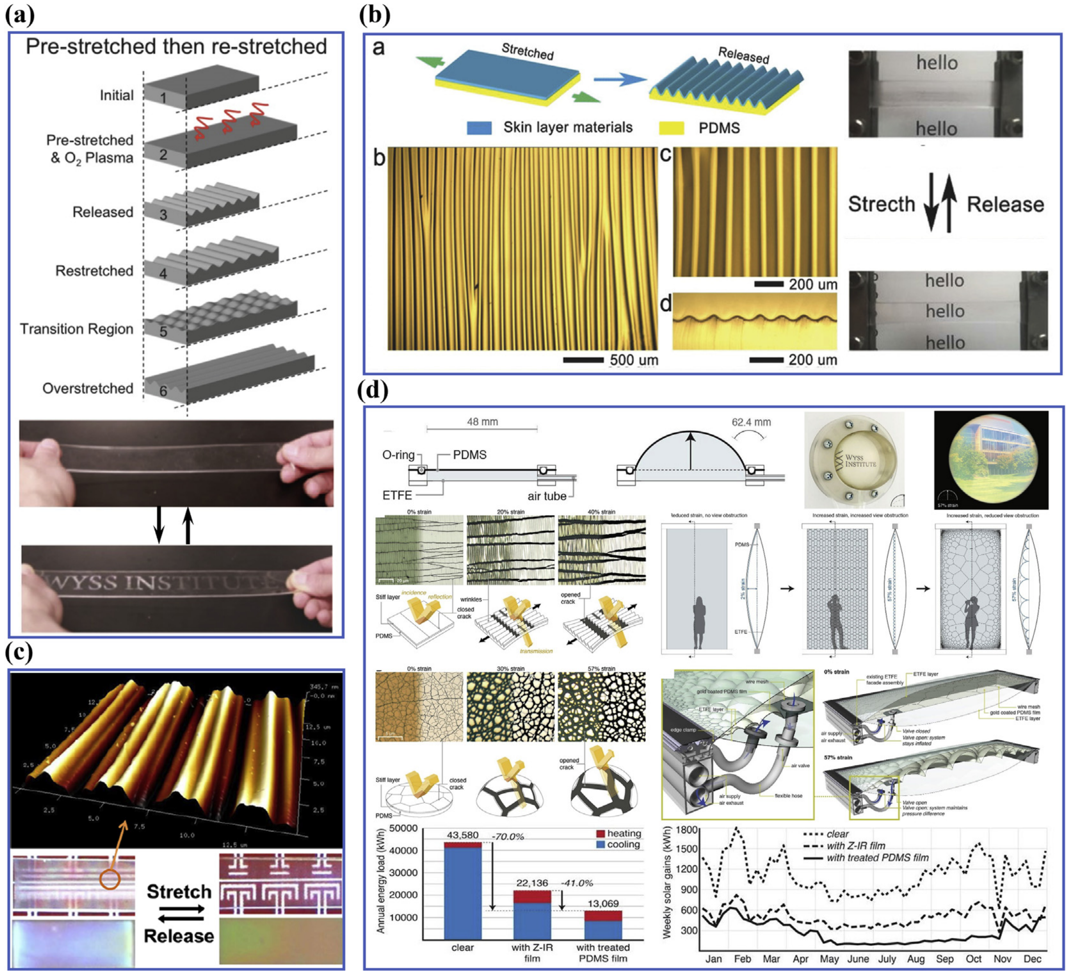

Fig. 6. Structural designs of wrinkle-based shape-morphing building envelopes. (**a, b**) Smart window design with surface wrinkling fabricated by mechano-responsive optical materials. Dynamical optical transmittance is tuned by the mechanical stretching/releasing process. (a) PDMS with surface treated with oxygen plasma [64]; (b) Bilayer PVA/PDMS film-based smart window [65]. (**c**) Self-similar hierarchical wrinkle-based smart window with tunable optical transmittance and structural color [66]. (**d**) Pneumatic ETFE/PDMS façades with solar modulation: infrared rays reflected by coated Au film and optical transmittance tuned by inflation-controlled surface wrinkles and cracks [68].

system operation only accounts for approximately 3% of its generated energy. Despite the promise, drawbacks remain including the complicated setting ups of the actuator systems and the bulky devices.

To overcome these drawbacks, a dynamic kirigami façade (Fig. 7b) could be a promising solution because of its lightweight structure feature. Lamoureux et al. [70] proposed one type of kirigami solar tracker by attaching flexible solar cells to the kirigami strips shown in Fig. 7b (top).

Under different stretching strains, the buckled kirigami strips tilt accordingly to track the changing incidental sunlight. Compared with the stationary solar panels, this dynamically tunable kirigami solar tracker can improve the energy generation density by over 40% for a whole day (Fig. 7b, bottom; [70]). The energy conversion efficiency will increase with the length of cut slits and the width of discretized strip structural elements in a certain range. Despite the promise, the performance of such a kirigami solar tracker is tested in the centimeter scale. When applying it to the building scale as a potential shape-morphing building envelope, it needs further exploration to test its scalability and energy conversion efficiency. Similarly, origami structures (Fig. 7c) are often used as shape-morphing solar panels for deployable energy harvester in outer space [71]. However, there are few works on integrating origami-based façades for dynamical solar trackers.

Different from dynamic solar trackers by tuning facing direction to improve energy generation efficiency, concentrator photovoltaics (CPVs) use concentrating optics to focus incoming sunlight onto the solar cells. CPVs are often integrated in the solar tracking systems to enhance energy harvesting. Some CPVs examples include Fresnel lenses [72], optical reflectors [73], dishes and other systems using waveguides [74], and free-form optics [75] with static and fixed structural features. To achieve dynamically tunable CPVs optical components, researchers have tried to integrate them onto the kiriagmi (Fig. 7d–e), origami (Fig. 7f), biomimic (Fig. 7g–h), and conventional kinetic façades (Fig. 7i), as discussed in the following.

For kirigami-based CPVs, they have two major parts as shown in Fig. 7d–e: the parabolic optical concentrator and kirigami frame. The kirigami frame is stretched to tilt into different angles for tracking sunlight at different times in one day. Thus, the attached optical CPVs can efficiently receive and reflect density-enhanced solar light onto the preplaced solar cells to improve the energy conversion efficiency. Here, we briefly introduce two representative kirigami façades with CPVs systems. The first one is based on the kirigami design with parallel cuts, which can help CPVs to track solar light upon uni-axial stretching (Fig. 7d, [76]). Compared with non-CPVs solar tracking system, this kirigami-based CPVs system can enhance the density of sunlight reflected on the solar cells over

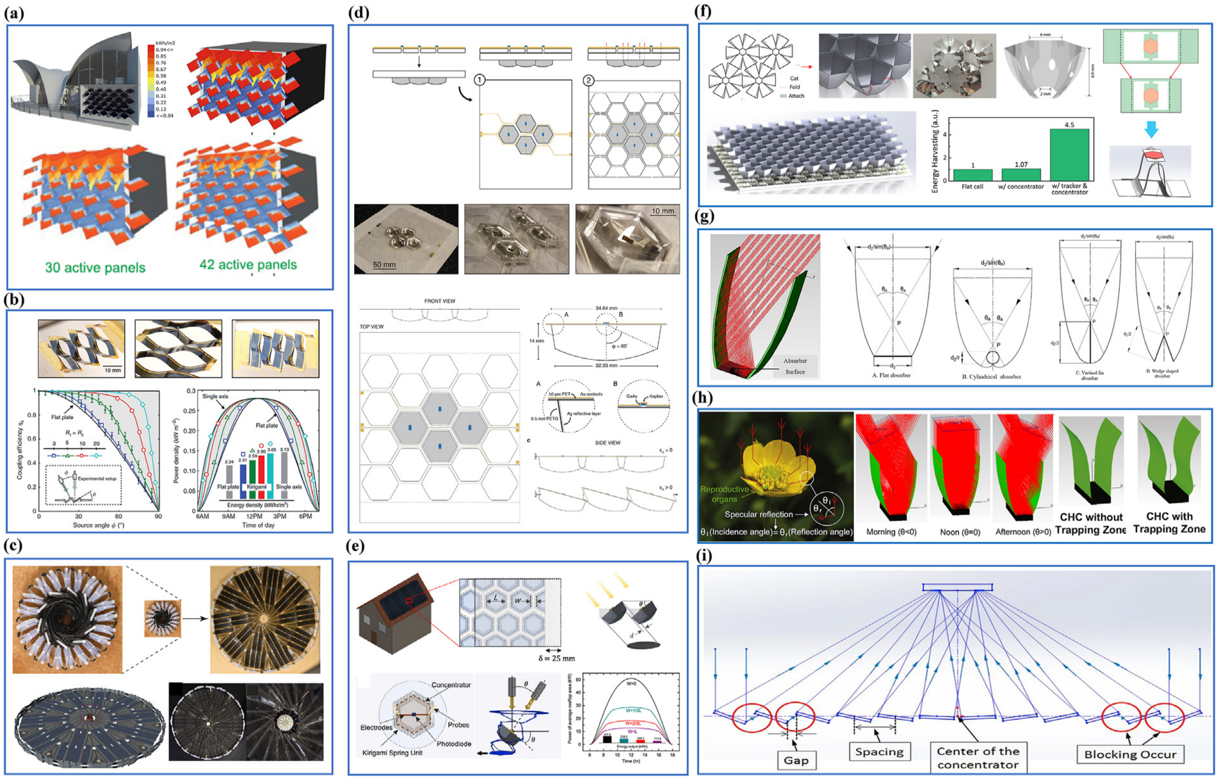

Fig. 7. Structural designs of shape-morphing building envelopes with energy harvesting functionality. (**a**) Kinetic shape morphing façades with energy generation from individual solar tracking units. This design shows both shading effect and photovoltaic energy conversion functionality [53]. (**b**) Dynamic kirigami solar trackers [70]. (**c**) Expandable origami solar panel design [71]. (**d**) Dynamic CPVs systems with tunable solar light incidental angle by stretched kirigami tilted strips [76]. (**e**) Kirigami stretching tuned CPVs system with multi-axis direction changes [77]. (**f**) Origami folding tuned CPVs system [78]. (**g**) Various CPVs structural designs [79]. (**h**) Flower petal inspired shape switching (between parabolic and hyperbolic shapes) origami CPVs design [80]. (**i**) Discrete and individual shape morphing microdishes CPVs system [81].

38–60 times, which could significantly improve the energy generation performance [76]. For example, enhanced by the kirigami CPVs, the reflected sunlight density can increase over 80 times, and the energy harvesting efficiency can maximally improve over 58.5 times than conventional solar tracker system without any CPVs. The second one is based on the kirigami design with hexagonal cut patterns, which deforms like a spring (Fig. 7e, [77]). Different from the unidirectional expanding in the first design, this hexagonal kirigami structure can be stretched and expand along multiple directions. Therefore, it can achieve more degrees of freedom to facilitate the CPVs system facing the incidental sunlight more efficiently, resulting in a higher energy conversion efficiency. Experimental verification showed that to meet the same daily energy requirement, the hexagonal kirigami-based CPVs solar tracking system only needs 0.246 m^2 of GaAs PV cells or 0.368 m^2 of Si PV solar cells. In contrast, the stationary silicon PV panels require a large area of over 22 m^2, which is almost 60 times more area than that via the kirigami design [77]. It is found that using practical dimensions, over 80-fold light concentration can be achieved, which stabilizes its energy harvesting efficiency at a high level. However, factors such as local high temperatures and structural shading will influence the energy harvesting capability of this active building envelope design with multi-axial tracking kirigami CPVs. For example, high local temperature induced by concentrated sunlight will increase the electrical resistance of photovoltaic materials and thus lower energy-generating efficiency. Therefore, the economy should be balanced between these deterministic factors when designing this type of kirigami CPVs enhanced dynamic active building envelope.

Compared with the kirigami approach, the origami-based CPVs are more likely to fold into a parabolic shape (Fig. 7f–h) with different angles to track time-varying sunlight. By combining kirigami and origami designs, Lee et al. [78] proposed a novel dynamical CPVs system. In this design, in addition to using the dynamic foldable origami structure as a CPVs system to concentrate sunlight, the solar cells can also be spatially tunable. Fig. 7f shows that the origami concentrators are folded with parabolic curvatures, whereas the individual kirigami part is built by cutting a rectangular sheet into desired patterns, including two translationally movable ends, two foldable middle ribbons, and one central area for placing solar cells (Fig. 7f, top-right). Upon compression, the solar cell area pops up and translationally changes its position with folding of the ribbons (Fig. 7f, right-bottom), where the position of the lifted solar cell can be tuned by different compression strains. Compared with the non-tracker system, more than 600% sunlight concentration are achieved in this design. Thus, integrating translational solar cell onto the origami façades-based concentrator can achieve more than 450% increase in energy output compared with the case of the static solar panels [78]. Moreover, the energy harvesting efficiency is also relatively improved because of the simple single axial actuation of the tracker system to save energy while with a longer time range (from 8 a.m. to 16 p.m.) to perform stable high-energy conversions. Moreover, optimizing the parabolic-shaped origami-based CPVs with different profiles can further improve the solar light concentration efficiency (Fig. 7g, [79]). Compared with conventional CPVs, these kirigami- and origami-based CPVs could be beneficial as potential energy-efficient shape-morphing building envelopes, such as façades, rooftops, and active windows because of their low cost and light weight.

Moreover, inspired by the diurnal and nocturnal flowers in nature (Fig. 7h, left), Momeni et al. [80] created an active CPVs system with time-varying shape tunability. In responding to the solar movement, the proposed multifunctional CPVs can maintain a parabolic shape in the morning and then change into a hyperbolic shape in the afternoon (Fig. 7h, right). Enhanced by this reversible shape-changing process, the conversion efficiency trend can vary from a peak-valley form to constant-at-peak format; thus, it renders an enhanced overall energy generation. To realize the reversible cycles of shape changes, smart materials with structural anisotropy are used in the design. Experimental results showed that the tunable and adaptive CPVs design with time-varying shapes can effectively improve the optical concentration factor and thus the energy harvesting/conversion efficiency over 25%. Nonetheless, considering the fabrication and structural robustness, the most straightforward structural design for dynamical CPVs is to use the flat non-imaging microdishes reflectors (Fig. 7i, [81]). However, the bulky actuation system remains an issue for the microdish design.

It should be noted that for the energy absorption/conversion rate, the performances of the surface materials used in the aforementioned dynamic façade designs should also be considered. Generally, surface materials with promising energy absorption rate will be favored for enhancing the energy-generating performance of façades. Therefore, optimizing facades structural form design could reduce more energy costs. However, for all the dynamic façades with CPVs or unique structural forms that have similar and optimized sunlight concentrating capabilities, their overall energy absorption rate will be also limited by the properties of the selected surface photovoltaic materials. For example, intrinsically, once the sunlight density reaches a threshold, the energy absorption/conversion rate of the surface photovoltaic material will reach a saturated state and remain a constant value; thus, it cannot further increase even under higher sunlight densities.

To summarize this section, for structural designs of shape-morphing façades with solar tracking CPVs, conventional designs need further explorations for energy-saving actuation methods. The kirigami and origami structures are lightweight and low cost, but they need further experimental verification and optimization for large-scale applications, especially on practical building skins. For future potential designs, other novel structural forms such as hierarchical kirigami (Fig. 8a, [82]), stretching induced titled kirigami sheets with different shaped units (Fig. 8b–c, [83–85]), and origami structures with curve fold lines (Fig. 8d, [86,87]) could provide more choices for dynamic and adaptive façades design with energy generation functionality.

3. Material designs for shape-morphing building envelopes

3.1. Materials for dynamic façade actuation

In this section, we will discuss the actuation of dynamic façades from the materials viewpoint. In addition to the conventional motor-driven façades, other actuation methods have recently emerged for façade made of deformable and stimuli-responsive materials, including pneumatic air, electric field, and environmental temperature.

Fig. 9a shows a pneumatic actuator with three inflating channels, which enables biaxial rotations of the embedded façades [52]. The dynamic façade or kirigami structures can also be actuated by shape memory materials in response to different external stimuli. An et al. [107] proposed a kirigami pattern that can be actuated by shape memory alloy (SMA) wires, as shown in Fig. 9b. SMAs possess shape memory effect because of the phase transition. When heated above the transition temperature, they are able to recover to their initial shapes [88]. In this study, the SMA wires shrink dramatically in length after heated, which leads to the buckling of the bilayer structure along the preferred direction. Shape memory polymers (SMPs) are another type of shape memory materials. SMPs can recover from the intermediate shapes to the permanent shapes in response to various external stimuli (e.g., thermal, photic, and chemical stimuli) [89–91]. Fig. 9c–i presents a dynamic structure with its joints connected by SMPs (circled areas), where Fig. 9c–ii shows the shape-morphing process after heated [20]. Based on the SMP layer, Tang et al. [60] fabricated an active laminated kirigami composite. Fig. 9d shows that the SMP-based shrink paper is sandwiched by two prepatterned cardboards to form a kirigami composite. Upon heating, the SMP shrinks to fold into different 3D structures guided by the cuts. Notably, the intermediate shapes are often reprogrammable (the intermediate shapes can be redefined with necessary conditions such as heating), which could benefit the designing versatility of the dynamic façades and smart windows.

However, the shape morphing in most SMPs is irreversible, which means that the SMPs cannot morph back to the intermediate shapes autonomously after removing the external stimuli. One solution to obtain reversible thermal actuation is to use differential thermal expansions in the structure. For example, Liu et al. [92] designed a thermo-responsive dynamic kirigami structure composed of materials with different thermal expansions. Fig. 9e–i shows the basic unit of the design. It contains a low coefficient of thermal expansion (CTE) frame and a high CTE core, which are made of wood and silicone elastomer, respectively. Upon heating, the soft core buckles and the predesigned kirigami cuts determine whether the shape morphing is in a unidirectional floppy mode (U) or rotational mode (R). A dynamic complex kirigami pattern of the basic unit is shown in Fig. 9e–ii. Similarly, by utilizing the CTE mismatch, Tu et al. [93] fabricated a solar tracker actuator. The bilayer structure contains a high CTE aligned PVDF (polyvinylidene fluoride) layer and a low CTE Ti_3C_2Tx MXene layer (Fig. 9f–i). Fig. 9f–ii demonstrates the different tilting angles of the tracker caused by the varying solar incident power during the daytime. In addition to the thermal actuation, humidity can also be used to actuate certain dynamic structures. For example, Fig. 2b shows a wooden structure that can open and close at low and high environmental humidity, respectively. The composite structure with mismatched expansion induced by hydration can provide autonomously reversible shape morphing, which may be advantageous for dynamic façades. However, it should note that the actuation time is often too long (sometimes can be hours). Therefore, autonomous reversible dynamic façades with fast response still require further exploration in the future.

3.2. Shape-morphing materials for smart windows

The shape-morphing materials for smart windows can be divided into two major groups. One is the surface engineered material that changes its surface morphologies for tunable transmittance. The material itself is often passive, which means that additional actuation system (e.g., motor) is needed to apply the mechanical strain to deform the material. The other is active shape-morphing material. These materials can transform their shapes autonomously under proper external stimuli. In terms of energy saving, the shape-morphing materials can benefit from the capabilities of transmittance and transparency changing. On one hand, the smart windows can reduce the incident sunlight passing through the building by decreasing (or increasing) the transmittance at higher (or lower) indoor temperature in summer (or in winter), which can help reduce the electricity cost of air

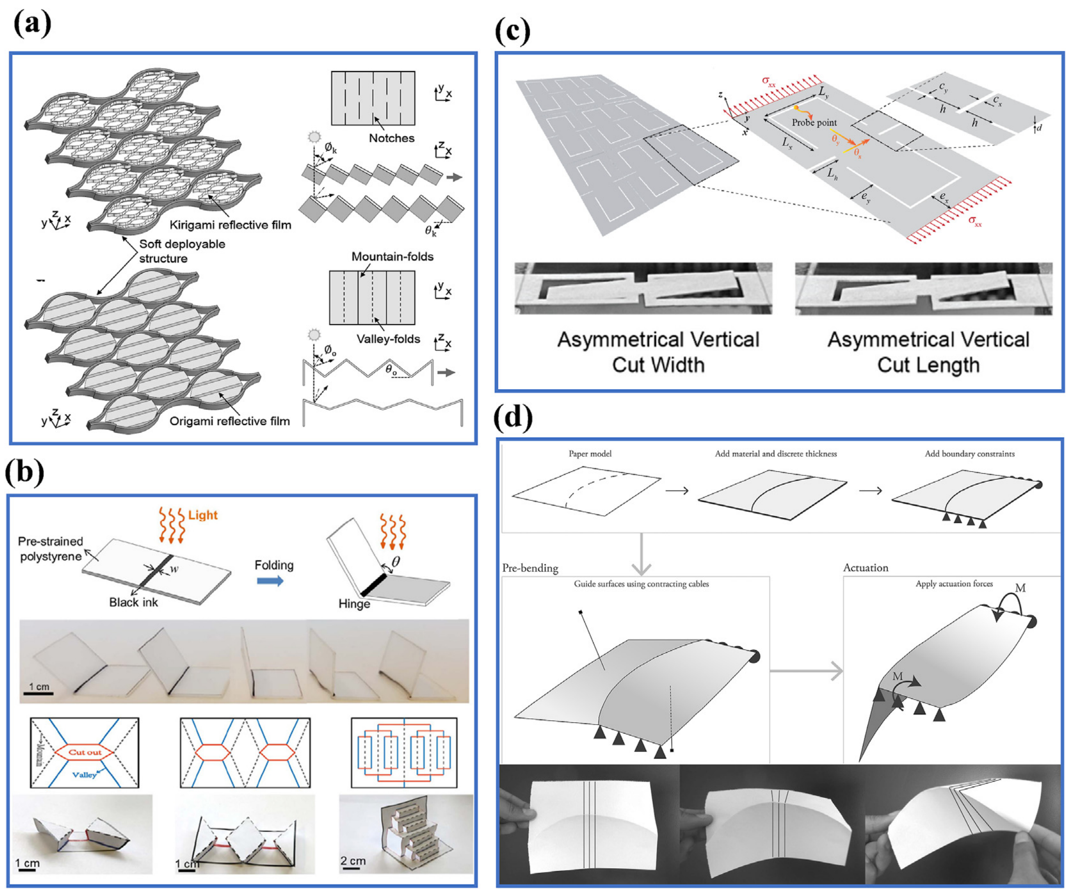

Fig. 8. Other potential kirigami and origami structural designs for shape-morphing façades with solar tracking functionality. (**a**) Hierarchical kirigami structures with pores filled with higher-level kirigami/origami inclusions [82]; (**b**) Active origami and kirigami designs with ink patterns [83]; (**c**) Kirigami design with uniform facing direction [85]. (**d**) Potential origami with curved line folds for CPVs applications [51].

conditioning with proper solar heat gaining. On the other hand, some shape-morphing materials can become translucent so that the indoor areas can have enough lighting without extra electricity consumed, and privacies can also be kept at the same time [94–96].

3.2.1. Changing surface morphologies for tunable transmittance

PDMS is one of the most used materials for designing wrinkling-based smart windows. Surface treatment and surface modification on PDMS are often required to generate wrinkles on its surface. For example, Li et al. [94] etched the pristine PDMS film with ultraviolet/ozone (UVO), resulting in the formation of a thin SiOx layer. Fig. 10a shows that both wrinkles and microcracks appear after stretching the UVO-treated PDMS, which leads to a low transmittance. Notably, the design also possesses high durability, despite the existence of cracks after at least 1000 cycles. Zhang et al. [95] designed a setup that can scalably manufacture wrinkled PDMS, which could facilitate its potential application as large-area smart windows. In addition to the surface engineering of PDMS, the PDMS can be used as a soft matrix for a composite smart window with certain inclusions. For example, Kim et al. [96] proposed a composite smart window by embedding silica NPs into the PDMS matrix. The composite has a wrinkled surface generated via mechanical stretching and oxygen plasma treatment. Fig. 10b shows its special optical performance. Unlike the pristine PDMS sample that has the highest optical transmittance at either the highest applied strain or zero strain, the NPs-PDMS composite shows the peak transmittance at ~10% strain. When applying a small tensile strain of 10%, the wrinkles disappear, resulting in a transparent composite. As the strain keeps increasing, the NPs start to separate from each other, which generates secondary wrinkles and defects. Consequently, the sample becomes opaque again. Compared with surface engineering, the inclusion-matrix composite design needs smaller strains to achieve the different optical transparency by combining both surface wrinkling and internal structural changes.

To achieve higher IR transmittance, Fang et al. [97] replaced the PDMS with styrene–ethylene–butylene–styrene (SEBS) copolymer thin film as the elastomer. Fig. 10c illustrates the sample preparation method and the working principle of the composite optical property shifting. The SEBS hexane solution is first drop-casted on the pretextured silicon wafer. After the SEBS film is fully cured, it is peeled off from the wafer and sputtered with 10 nm titanium as adhesive layer and 60 nm gold layer sequentially under a bi-axially stretched state with 100% strain. The composite possesses three different optical modes: emission mode (high absorptance), reflection mode (high reflectance), and transmission mode (high transmittance), which correspond to the states of 0% (textured state), 100% (flat state), and 200% (discrete state) biaxial stretching, respectively.

3.2.2. Active shape-morphing materials

In addition to the strain-induced shape-morphing structured surfaces (e.g., wrinkles and cracks at small scale), active shape-morphing materials, such as liquid crystal elastomer (LCE) and hydrogel, could be an alternative strategy to achieve switchable transparency for smart windows. Such active materials can be actuated under different external stimuli. For example, LCE can

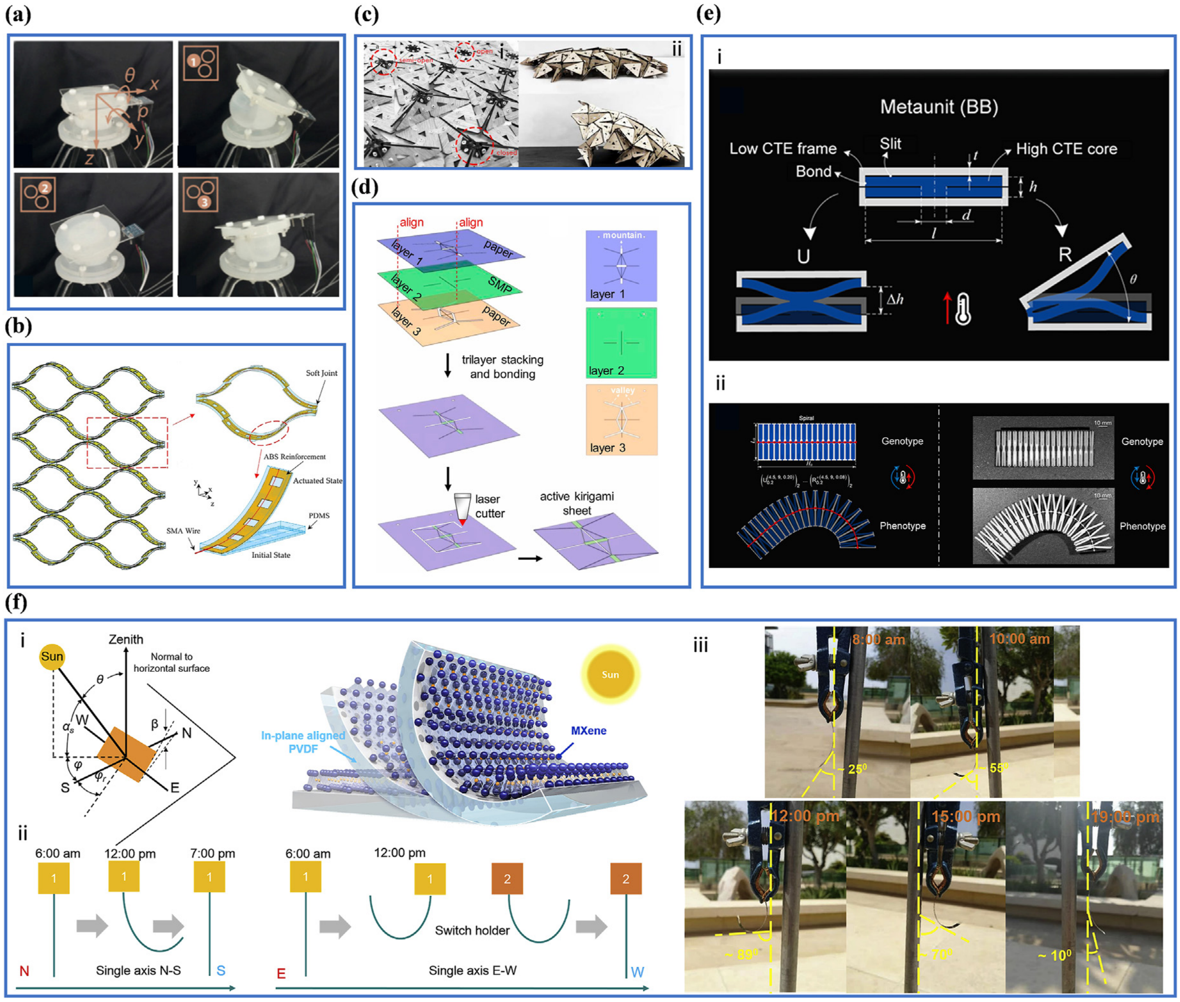

Fig. 9. Actuating materials for shape-morphing building envelopes. (**a**) The pneumatic actuator with different rotation angles [52]. (**b**) The schematic of a kirigami pattern actuated by SMA wires [107]. (**c**) (i) Joints made of SMP are circled. (ii) The initial and deformed shape after heating [20]. (**d**) The schematic of an active kirigami-laminated composite [60]. (**e**) (i) The schematic of the basic unit of the temperature-responsive kirigami structure. (ii) An example of active kirigami structure [92]. (**f**) The structure (i) and the solar tracking performance (ii) of the solar tracker actuator [93].

reversibly morph its shape (i.e., two-way shape memory effect) in response to heat or light [98–100]. Hydrogel can swell or shrink because of solvent absorption or evaporation [101,102]. These materials can work as actuators and integrate with the aforementioned kirigami/origami structures to modify the blockage of light and visibility. Meanwhile, these materials can be engineered with local patterns or structures to change their transmittance.

3.2.2.1. Liquid crystal elastomer (LCE). Apart from being used as actuation materials, some LCEs also can change optical transparency with external strains. For example, Fig. 10d shows that LCEs can shift from white color to transparent with the applied strain [103]. The transmittance change in LCEs is because of the orientation shifting from isotropic to be aligned in the mesogens at the molecular level. When heated above the transition temperature, the partially cross-linked LCEs can shift from white color to colorless transparent state. However, after fully cross-linking upon UV curing, it will become fully transparent even at a lower temperature. Therefore, it is feasible to control the temperature-responsive localized transparency switch by UV curing of LCE samples, which could potentially provide the customized comfort zones in smart windows for occupants.

3.2.2.2. Hydrogel. Hydrogel is another shape-morphing candidate material for smart windows. Lee et al. [104] designed a special microstructured hydrogel that can reversibly change the transparency with its swelling property. Fig. 10e–i and iv illustrate the array of slanted hydrogel pillars with a slanting angle of 30°. When the sample is soaked in water bath, the pillars swell and transit to the clustered state (Fig. 10e–ii and iv) because of water absorption. After the sample is fully dried, the array returns to its initial slanted state (Fig. 10e–iii and vi). The optical images at the three states in Fig. 10e (ii to ix) show that the sample becomes transparent at the clustered state, while it is opaque at the slanted state (before swelling and after drying). It is speculated that the slanted pillars could scatter more light than the clustered state. Wang et al. [105] also fabricated a hydrogel-based composite with switchable transmittance. Rather than mechanical stretching, this work provides an alternative method to shift the transmittance through pressing. Fig. 10f–i show that the composite consists of two plies of hydrogel and agar films. Initially, the agar film is opaque, whereas the hydrogel film is transparent without applying external pressure. The composite is sandwiched between two glass slides. Pressing the composite leads to the lateral expansion and generates a conformal coating on the interface. The hydrogen bonding enables the firm interfacial connection, which results in high transparency of the smart window upon pressurization. Fig. 10f–ii and iii demonstrate the transparency switch performance. This composite also shows stable optical properties

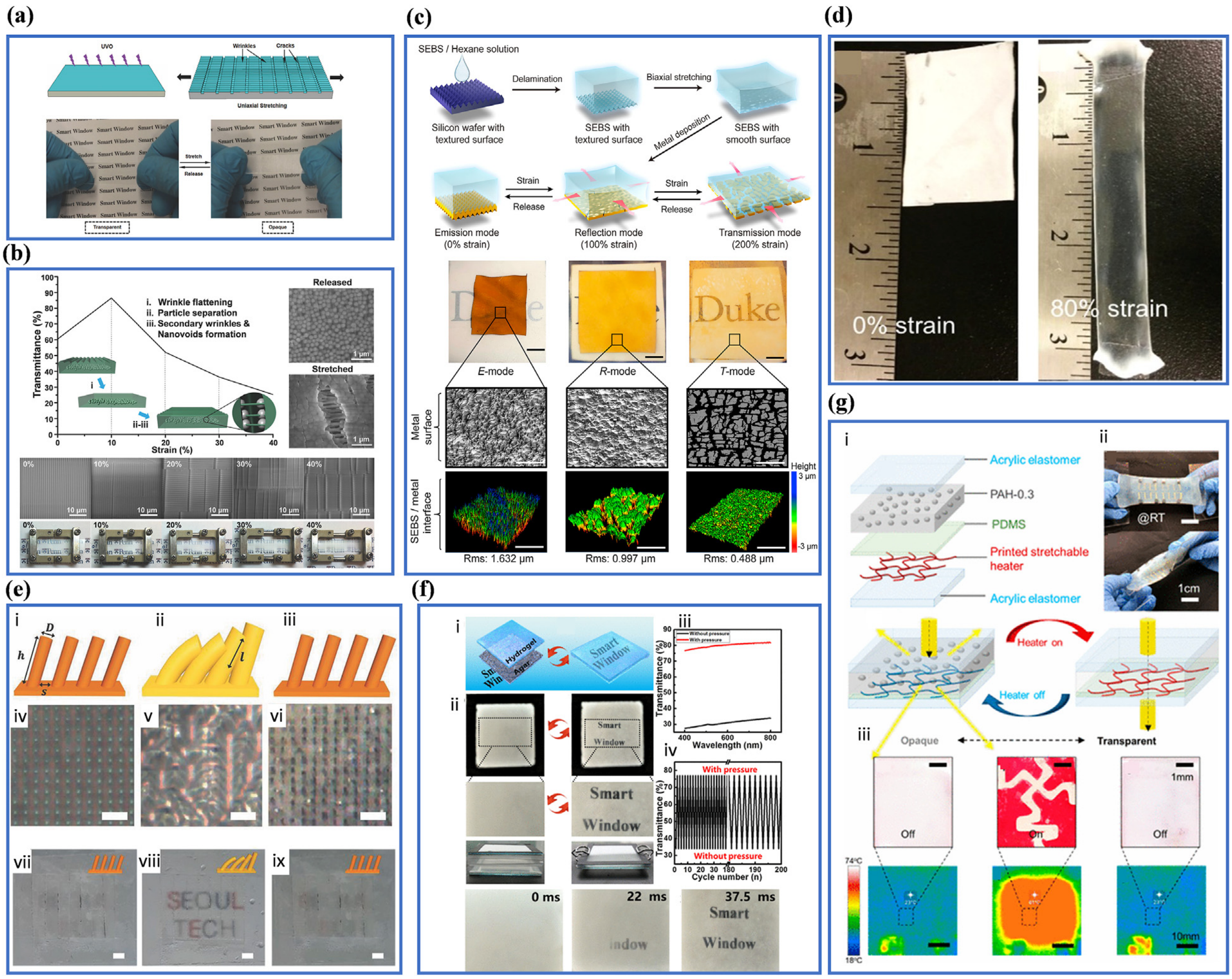

Fig. 10. Switchable optical materials for smart windows. (**a**) The schematic of the sample preparation and the reversible transmittance of the PDMS film [94]. (**b**) Tunable transmittance with different strains of a PDMS-based composite film [96]. (**c**) The schematic of the film sample preparation and the three modes (E-mode, R-mode, and T-mode) at different biaxial strains (scale bar 50 μm) [97]. (**d**) The LCE sample becomes transparent with 80% strain [103]. (**e**) The schematics and the optical microscope images of the slanted hydrogel pillars before swelling (i, iv), after swelling (ii, v), and after drying (iii, vi). The transparencies before swelling (vii), after swelling (viii), and after drying (ix) (scale bar 10 μm) [104]. (**f**) The schematic (i) and digital images (ii) of the hydrogel composite transparency change. (iii) The transmittance with and without pressure. (iv) The transmittance change after 200 loading/unloading cycles [105]. (**g**) The schematic (i), the stretchability (ii), and the transparency change (iii) of the stacked layers of the hydrogel composite [106].

after 200 cycles (Fig. 10f–iv). Notably, because the composite is sandwiched by two glass sides, the gap between the agar and hydrogel is small, which can effectively eliminate the evaporation of the water in the hydrogel. Since the water content can influence the mechanical properties of the hydrogel, evaporation elimination could be beneficial for a prolonged stability of the smart window.

In addition to mechanical actuation, hydrogels can also be electrically actuated using Joule heating for potential smart windows application. For example, La et al. [106] fabricated a hydrogel-based laminated composite that has tunable transmittance triggered by temperature. Fig. 10g–i shows the schematic of the laminated structures by stacking an acrylic elastomer layer, a hydrogel layer, a stretchable heater network printed on a PDMS layer, and another layer of the acrylic elastomer together. The acrylic elastomer is a type of VHB tape that can bond the hydrogel and heaters well, as well as prevent water evaporation. The polyampholyte hydrogel (PAH-03) acts as the functional ply, which switches from opaque to transparent upon heating, arising from the phase separation mechanism. A fluoro-elastomeric conducting ink pattern is 3D printed on a PDMS layer that serves as the Joule heaters. The hydrogel can adhere to the PDMS firmly because of the chemical anchoring, which is beneficial for long-term device stability. Since all the materials are flexible, the fabricated device also shows a high stretchability (up to 80% strain in Fig. 10g–ii). Fig. 10g–iii demonstrates that the optical performance of the smart window under applied electrical current. The heating and cooling time for the transmittance switch are 25s and 45s, respectively. The short actuation time is advantageous because the response time of hydrogels are often very long (minutes to hours). In general, the exploration on newly emerged dynamic shape-morphing materials for smart windows is still in its early stage. Controllable shape-morphing optical materials with fast response and their implementation as building skins or smart windows are highly needed for further exploration. Different kinds of controllable shape-morphing optical materials with fast response and their implementation as building skins or smart windows are highly needed for further exploration. In addition to the optical property, shape-morphing–induced insulation shifting may be another perspective in terms of energy-saving smart windows.

Table 1
Common used structural forms for dynamic building envelope design and their actuation methods or/and materials.

Types	Structural form		Author/resource	Year	Deformation	Actuation	Advantages	Limitation
Passive dynamic building envelopes	Conventional designs	Rigid plates	Kiefer Technic Showroom [24]	2007	Rigid rotation	Eletrical motor	Easy to control and program the structural deformation; Structure easier to fabricate; Low initial construction fee; Low maintance cost	Difficult to construct since their bulky structural forms; high actuation cost; most of these designs are too heavy
			HelioTrace Robotic Façade [25]	2010	Rigid translation			
			SDU Kolding building [22]	2015	Rigid rotation			
			Mahmoud [26]	2016	Rigid translation			
			Hosseini [23]	2019	Rigid rotation			
		Rigid loop mechanism	Tabadkani [30]	2019	Rigid rotation			
		Flexible plates	Shiver house [31]	2019	Shell bending	Natural winds	No deed for actuation cost	Not able to control
		Inflatable membranes	MEDIA-TIC [27], Water, Cube [28]	2011 [27], 2008 [28]	Shell inflation	Pneumatic	Light structural weight; easy to control	High maintenance cost; low structure robustness
		Elastic fabrics	Kinetic Wall [29]	2014	Elastic stretching	Eletrical motor	Easier for local visual programming	No practical and onsite test
	Bio-inspired designs	Buckled thin shells	Schleicher [33]	2015	Shell buckling	Electrical motor, SMA	Low energy to actuate	No onsite test
		Flexible shells	Reichert [36]	2015	Shell bending	Humunity with water	Light structural weight	Hard to program
	State-of-art designs	Kirigami structures	Zhang [45], Tang [46,47], Ke [48]	2015 [45], 2017 [46], 2018 [47], 2019 [48]	Beam/plate bending	SMP, SMA, LCE, etc.	Light structural weight; easy to actuate	Not able to locally program
		Origami structures	Al-Bahr-Towers [50], Vergauwen [51], Powell [52]	2012 [50], 2017 [51], 2018 [52]	Crease folding	Electrical motor SMP, SMA, etc.	Light structural weight	Actuation need onsite test
	Smart window	Stretchable thin film	Kim [64], Jiang [65], Lin [66],	2013 [64], 2018 [65], 2017 [66]	Thin film buckling	Mechanical stretching, LCE, Hydrodel, SMP, etc.	Deformation easy to control; all sunlight spectrum block	Less no-site in practical use and low structual robustness; complex fabrication process
		Inflatable membranes	Tomholt [68]	2020 [68]	Ballon like inflation	Pneumatic		
Active dynamic building envelopes	Without CPVs	Rigid plates	Jayathissa [53]	2018	Rigid rotation	Electrical motor	Deformation easy to control; high robustness; Solar shading and high-energy harvesting efficiency	Too bucky and too heavy; hard to construct; high maintance cost
		Kirigami structures	Lamoureux [71]	2015	Shell bending	Mechanical stretching, SMA, SMP, etc.	Lightweight; easy to fabricate; easy to actuate	Short working period because of the uni-axial deformation tunability
		Origami structures	Chen [72]	2019	Crease folding	SMP, SMA, etc.	Lightweight; easy to fabricate	Hard to fabricate
	With CPVs	Curved shells	Madala [79]	2017	Plate bending	SMP, SMA, etc.	Time-varying shape form	Low optical concentration factor
		Rigid dishes	Tan [80]	2018	Rigid rotation	Electrical motor	Easy to program shape and thus track sunlight	Bulcky control system
		Kirigami structures	Lamoureux [76], Evke [77], Lee [78]	2017 [76], 2021 [77], 2016 [78]	Beam bending	Mechanical stretching	Efficient track sunlight and high optical concentration factor	Easy to cause with high local temperature; shading effect
		Origami structures	Lee [78]	2016 [78]	Beam bending	Mechanical stretching		

4. Conclusions and outlooks

This review briefly summarizes the recent progress in energy-efficient shape-morphing building envelopes from structural design and material sides. We reviewed several structural design strategies and their corresponding working mechanisms for dynamically tunable façades and smart windows. We also discussed different material strategies for actuation and fabrication of these shape-morphing structures.

With shape-changing capability, all the conventional kinetic façades, biomimic building skin, kirigami/origami-based structures, and morphable wrinkled surface–based smart windows can provide different levels of adaptability. In response to external climate fluctuations, these designs can be beneficial to occupants with tunable indoor daylight performance, comfortable visual and thermal conditions, natural ventilation, and efficient building energy-saving choices. However, the conventional kinetic façades with sole solar shading functionality are generally energy inefficient because of their bulky structures and complicated actuation systems. Thus, the lightweight façades in the form of kirigami/origami-based structures could be an alternative for improving energy-saving performance in buildings. Moreover, as demonstrated in Ref. [69] with onsite trials, equipping façades with energy generation/harvesting capability is a more promising way to build multifunctional façades beyond sole solar shading purpose.

In addition to the conventional kinetic building envelopes driven by electric motors, it is becoming feasible to actuate the lightweight building envelopes such as kirigami and origami structures using smart active materials (e.g., SMA and SMP). However, their slow response and the difficulty in quickly recovering to their initial states limit their broad applications in practice. Therefore, it demands further exploration to either speeding up the response time in shape memory materials or developing/exploring new active materials with fast response and quick recovery for building envelope applications. For smart windows, different strategies for designing shape-morphing optical materials, including surface engineering and stimuli-responsive materials (e.g., based on thermochromic materials [108,109]) have been proposed to modulate the optical transmittance switch. However, their practical applications for onsite large-scale buildings are rare, and it needs future exploration and examination on their energy saving performance on buildings. Moreover, their combinations with other façades are also worthy of exploration to achieve multi-functionalities as the case demonstrated in Refs. [48,68].

The design and implementation of future energy-efficient building envelopes will combine both engineering technologies and aesthetics. Given the research advance in the fields of robotics and computer science, future building envelopes could be more intelligent for active control and interaction with individual occupant. Meanwhile, artificial intelligence and machine learning techniques could be used to guide and control envelopes' dynamical environment-adapting process, ultimately making envelopes design more active and autonomous to sense the surrounding environmental changes for the most energy saving efficiency and residence comfort.

From the cost and durability aspect, sometimes because of the use of novel materials or new actuation techniques, innovatively designed facades may have a high cost during the initial construction stage. However, from the long run in the buildings service life, new building envelopes with optimal designs can always exhibit their advantages by saving energy consumption spending to balance initial construction costs. Moreover, future innovative designs of building envelopes will be favored for not only passively tuning indoor lighting and thermal conditions but also constructing with multifunctionality [110] such as by integrating energy harvesting materials to produce more energy than consumption. For example, the already in-use active facades designed from Ref. [52] have verified this fact, that is, capable of annually and continuously outputting additional electrical energy to make the building energy positive and potentially bring additional financial benefits. From durability view, given the fast development of material science, innovative facades can be promisingly designed to be robust in both materials and mechanical performances and outlive the building's service life, as experimentally demonstrated in Ref. [52]), as well as keep the maintenance cost at a very low level.

The research on energy-efficient building envelopes needs multidisciplinary efforts from architectural, civil engineering, mechanical engineering, materials science, and electrical and computer engineering. We summarized almost all reviewed literature in Table 1 in terms of commonly used structural forms for dynamic building envelopes, their actuation methods/materials, as well as their potential advantages and limitations. By briefly reviewing the recent progress of structural and materials designs, we hope this review could be insightful for developing new generation of shape-morphing building envelopes, which can autonomously adapt to dynamically changing environments and promote more energy-efficient, aesthetically friendly, and physically comfortable living conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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