An editable shape-memory transparent wood for smart building materials

Abstract: Transparent wood (TW) with excellent optical and thermal management performance has been developed recently as a promising energy-efficient building material. Here, an editable shape-memory TW (ESMTW) is developed through in situ polymerization of epoxy vitrimers into a delignified wood scaffold. The ESMTW possesses high strength at low temperature and flexibility at high temperature, while it exhibits excellent shape-manipulation capability under thermal-stimulus. Meanwhile, the ESMTW shows unique light guiding and directional scattering effects. The light illuminance difference observed in our house model with a common glass ceiling is 81 times, whereas it is only 16 times with a ceiling made of the ESMTW. Most importantly, the transmitted light intensity distribution is tunable owing to its shape-management capability. Additionally, the resultant TW possesses great thermal insulation properties, mechanical strength, and high impact absorption ability. The combination of characteristics enables TW to exhibit great promise as an advanced functional and intelligent building material.

Introduction

It has been forecast that from 2012 to 2040, global energy consumption will increase by 48% and carbon dioxide (CO₂) emissions by 34%.¹⁻³ Residential buildings account for 30–40% of total energy consumption and CO₂ emissions, and their windows...
contribute approximately 10–25% of total thermal loss due to poor thermal management ability.\textsuperscript{4–6} Glass is extensively used in building windows and rooftops owing to its high optical transmittance and low thermal expansion coefficient (7–10 ppm K\textsuperscript{-1}).\textsuperscript{7} However, common glass windows suffer from some weaknesses. First, glass has a relatively high thermal conductivity (approximately 1 W m\textsuperscript{-1} K\textsuperscript{-1}), resulting in high thermal loss and low energy efficiency.\textsuperscript{8} Second, glass is brittle and easy to break under sudden impact, causing potential safety risks. Moreover, massive amounts of CO\textsubscript{2} are emitted during glass production, accelerating the environmental greenhouse effect.\textsuperscript{9} In addition, it may have problems with glaring and shadowing effects.\textsuperscript{10} Therefore, it is urgent to develop alternative transparent materials with great thermal insulation, optical properties, security, and sustainability to be used as a replacement for traditional glass.

Wood has been considered one of the most promising alternatives to green and energy-efficient building materials. Recently, transparent wood (TW) has attracted significant attention as an energy-saving building material because of its many merits, including high anisotropy, high optical transmittance, adjustable optical haze, efficient thermal insulation, great mechanical robustness with shatterproof features, high impact energy absorption, renewability, and great potential for multi-functionalization.\textsuperscript{11,12} TW is generally fabricated by inserting a refractive index-matching polymer into delignified wood (DW) or lignin retaining a modified wood scaffold. The hierarchical and highly oriented cellulose structure of the DW or modified wood scaffold endows TW with anisotropic optical, mechanical, and thermal properties.\textsuperscript{13–15} Additionally, TW has a unique light guiding effect, which can effectively harvest sunlight. The high haze with
broad scattering angles of TW makes a consistent and uniform daylight distribution without a glare effect, which has been demonstrated by the Hu group.\textsuperscript{8} Therefore, TW could be used in rooftops, windows, and transparent decorations to provide buildings with good lighting and visual effects, which is meaningful for comfortable indoor lighting in green, energy-efficient buildings.\textsuperscript{8, 16, 17} Meanwhile, some studies have focused on improving the properties of TW and exploring new functions to expand its smart application as a building material by endowing TW with flexibility, large size, or centimeter thickness. Efforts have also been centered on improving the optical performance by regulating the delignification technique to provide TW with multi-functionalization by incorporating electrochromic,\textsuperscript{14} photochromic,\textsuperscript{18} conductive,\textsuperscript{19} magnetic,\textsuperscript{20} and luminescent materials,\textsuperscript{21, 22} and other improvements.\textsuperscript{23, 24}

Although some progress has been made on functionalized TW for smart building materials, the scope has focused on two-dimensional (2D) applications, such as windows, ceilings, and rooftops. If TW were endowed with shape-manipulation ability, such as shape transformation, shape editing, or even shape memory, its application could extend from 2D to 3D, for example, in curved or irregularly shaped windows, screens, ceilings, rooftops, and transparent decorations. This would be great progress in advanced functional TW fields for smart building materials. However, to date, an editable shape-memory TW has not been reported.

The added refractive index-matching polymers and other doped organic or inorganic components determine the properties and function of TW. Vitrimers, as a new type of polymer with dynamic covalent cross-linked networks, can rearrange their
topology by bond exchange reactions under thermal stimuli without changing the cross-link density.\textsuperscript{25–27} The exchangeable dynamic covalent networks provide vitrimers with great mechanical strength, similar to that of thermoset polymers at low temperatures. They also possess excellent reprocessing properties, like those of thermoplastic polymers at elevated temperatures. These reprocessing properties are regulated by two characteristic transition temperatures: the glass transition temperature ($T_g$) and the topology freezing transition temperature ($T_v$).\textsuperscript{28, 29} Meanwhile, the exchangeable dynamic covalent networks endow vitrimers with stimuli responsiveness, shape memory, and self-healing properties.\textsuperscript{30–32} Therefore, vitrimers exhibit great potential to fabricate functional and smart TW with excellent shape-manipulation ability.

Vitrimers can be divided into different types according to their exchange mechanisms, including transesterification, alkene metathesis, transalkylation, transamination, boronate-diol exchange, disulfide exchange, and siloxane equilibration.\textsuperscript{26, 33} Considering the need for refractive index matching with the wood cellulose skeleton, epoxy-based vitrimers based on transesterification are among the most suitable polymers to fabricate TW. However, epoxy vitrimers unavoidably suffer from a yellowish or brown color, likely because of the high curing temperature and time (usually exceeding 180 °C for multiple hours) and the catalyst effect, resulting in the failure of TW fabrication.\textsuperscript{34–36} Consequently, a mild and rapid synthesis condition and appropriate catalyst are essential to prepare colorless and transparent epoxy vitrimers and successfully fabricate TW.

In this work, an editable shape-memory TW (ESMTW) was developed by \textit{in situ}
polymerization of transparent and refractive index-matching epoxy vitrimers into a DW template with a mild, rapid epoxy-thiol click reaction. The transmittance and haze of the ESMTW with 2 mm thickness were approximately 60% and 95%, respectively. Benefiting from the unique property of vitrimers, the TW exhibited stiffness at low temperature (less than $T_g$) and flexibility at elevated temperature (greater than $T_g$), and it showed shape-memory behavior by $T_g$-induced phase change and editable shape-memory capability by $T_v$-induced topological rearrangement. The shape recovery ratio of the ESMTW was as high as 86.7% along the transverse direction (T-ESMTW) and 94.4% along the longitudinal direction (L-ESMTW) and showed no obvious change after multiple shape recoveries. Thanks to the vertically aligned cellulose nanofibers of the DW, the T-ESMTW and L-ESMTW displayed different optical and mechanical properties. The T-ESMTW showed isotropic optical performance and unique light guiding and directional scattering effects, which could create a uniform and consistent daylight distribution, whereas the L-ESMTW showed anisotropic optical properties. Most importantly, the shape-management capability of the ESMTW could realize the light intensity distribution variation of the transmitted light. Additionally, the resultant TW possessed great thermal insulation properties (approximately 0.3002 W/m·k), mechanical strength, and high impact absorption ability. The combination of characteristics of ESMTW holds great potential in the fields of advanced functional and smart building materials, especially for 3D applications. Meanwhile, it may create new possibilities for transparent and shape-editable optical or electronic devices.
**Results**

**Microstructures and chemical components.**

The reaction and transesterification mechanism of the vitrimers and the fabrication procedure of the ESMTW are shown in Fig. 1. The colorless and transparent vitrimers were synthesized through a mild and rapid click reaction between E51 and Tetra-SH under the Sn(Oct)$_2$ catalyst. The transparent appearance of the vitrimers (thickness: 2 mm) is shown in Supplementary Fig. 1, and the transmittance and haze were approximately 80% and 40%, respectively, in the entire visible light wavelength region.

$T_g$ and $T_v$ are the two characteristic transition temperatures of vitrimers, which represent the molecular mobility and topological rearrangement, respectively. The $T_g$ of the vitrimers was about 35.2 °C as measured by differential scanning calorimetric (DSC), as shown in Supplementary Fig. 2. According to the dilatometry test by thermal mechanical analysis (TMA), the $T_g$ of the vitrimers was 43.2 °C, and the $T_v$ appeared at approximately 169.2 °C (Supplementary Fig. 3). The ESMTW was fabricated by *in situ* synthesis of vitrimers in the DW template after the delignification process. The appearances of the natural wood, DW, and ESMTW with different cutting directions are shown in Fig. 1b. The natural wood was opaque due to the presence of lignin. After delignification, the wood color changed from yellowish to ivory-white. After immersion in the epoxy vitrimers, it became transparent. The appearances of the T-ESMTW and L-ESMTW with thicknesses of 1 mm, 2 mm, and 3 mm are presented in Supplementary Fig. 4. Together, the thermally induced dynamic covalent cross-linked networks of vitrimers and the highly aligned cellulose nanofibers of the DW scaffold
contributed to the shape-manipulation capability (editable shape-memory behavior) and

tunable light guiding and directional scattering effects of the resultant TW, as shown in

Fig. 1c and 1d. A detailed description and analysis is presented below. ESMTW with

excellent optical and shape-manipulation properties is a promising substitute for curved

or irregularly shaped glass, which could be applied to 3D occasions.

**Fig. 1** Reaction process, fabrication procedure, editable shape-memory property, and light guiding

and scattering effects of ESMTW: a) synthesis reaction and exchange mechanism of the vitrimers;
b) fabrication procedure of the ESMTW; c) schematic diagrams of the editable shape-memory
behavior for the ESMTW; d) illustration of the light guiding and scattering effects of the ESMTW

with flat, convex, and concave shapes; e) ESMTW could be used as a building material, especially

for curved glass.
Balsa wood with a density of approximately 0.126 g cm\(^{-3}\) was selected as the starting material to prepare the ESMTW. The wood has a complicated hierarchical structure, which incorporates macroscale, microscale, and nanoscale features. Its cell wall consists mainly of intertwined cellulose, hemicellulose, and lignin. After delignification, the characteristic lignin peaks (1594 cm\(^{-1}\), 1505 cm\(^{-1}\), and 1460 cm\(^{-1}\)) and hemicellulose-related peaks (1732 cm\(^{-1}\) and 1235 cm\(^{-1}\)) disappeared from the FT-IR spectra (Fig. 2a).\textsuperscript{37-39} The density of the balsa wood decreased to 0.065 g cm\(^{-3}\) (Supplementary Fig. 5) and the relative content of lignin and hemicellulose decreased from 25.3% to 4.3% and 28.9% to 17.5%, respectively (Supplementary Fig. 6). The cellulose content increased from 45.8% to 78.2%, indicating the high cellulose content of the DW scaffold. The transverse section of the natural balsa wood showed a honeycomb-like porous, cellular structure with a cell lumen diameter of 30–50 μm (Fig. 2c and c1), and the longitudinal section exhibited highly aligned fiber tracheids and large-lumen vessels (Fig. 2d and d1). After delignification, the honeycomb-like cellular structure was essentially preserved; however, the original compact cell wall became a loose scaffold, and abundant microscale pores appeared in the middle lamella and at the corners of the cell wall (Fig. 2e and e1). Additionally, nanoscale pores were produced among the cellulose nanofibers, as demonstrated in the literature.\textsuperscript{37} The fiber tracheids and vessels also displayed a slight change from the longitudinal view (Fig. 2f and f1).
Fig. 2 Chemical components and microstructures of the balsa wood, DW, and ESMTW samples. a) FT-IR spectra of the balsa wood, DW, and ESMTW; b) FT-IR spectra of E51, Tetra-SH, and resultant vitrimers; c, c1, d, d1- g, g1, h, h1) SEM images of the balsa wood, DW, ESMTW in transverse and longitudinal section at different magnification, respectively.

The vitrimers were successfully synthesized in the hierarchical porous structures of the DW through in situ polymerization between E51 and Tetra-SH, as demonstrated by FT-IR analysis. As shown in Fig. 2b, the characteristic monomer peak, epoxy peak (910 cm⁻¹) in E51, and thiol peak (2566 cm⁻¹) in Tetra-SH disappeared in the spectra of the vitrimers, while the hydroxyl peak (3200–3600 cm⁻¹) appeared.⁴⁰,⁴¹ The FT-IR spectra of the vitrimers and ESMTW samples exhibited high similarity, indicating that a high content of vitrimers filled the porous structures of the DW scaffold. The density of the
ESMTW was approximately 1.232 g cm\(^{-3}\). Scanning electron microscopy (SEM) images (Fig. 2g, g1, h, h1) show that the vitrimers fully filled all the channels and apertures of the DW. From the FT-IR spectra, the hydroxyl peak at 3340 cm\(^{-1}\) of the natural wood and DW samples shifted to 3398 cm\(^{-1}\) in the ESMTW sample, indicating that strong interactions (hydrogen bonding or van der Waals forces) were generated between the cellulose nanofibers of the DW scaffold and filled vitrimers.

**Editable shape-memory capability.**

The vitrimers with thermally induced exchangeable dynamic covalent cross-linked networks endowed the resultant TW with excellent shape-manipulation capability. The ESMTW exhibited stiffness at low temperatures (less than \(T_g\)) and flexibility at elevated temperatures (greater than \(T_g\)). Considering that the \(T_g\) of the vitrimers was approximately 40 °C (according to the DSC and TMA tests), tests of the flexibility at 60 °C and stiffness at 0 °C were performed, as shown in Supplementary Movie 1 and 2. A curved shape in the ESMTW could be obtained by an external force effect at 60 °C and rapidly fixed at 0 °C. The editable shape-memory behavior of the ESMTW is demonstrated visually in Fig. 3a and 3b and Supplementary Movie 3–6. The original shape of the ESMTW was a rectangular strip. It was deformed into an s-shape under an external force at 60 °C and rapidly fixed at 0 °C to obtain a temporary shape, which was stable below \(T_g\). The temporary s-shape returned to the original rectangular shape when reheated to 60 °C. Next, a new temporary u-shape was formed, which also returned to the original rectangular shape at 60 °C. To further investigate the editable
shape-memory behavior during transesterification, according to the result of the
dilatometry experiment (Supplementary Fig. 3), the re-editing temperature was set to
180 °C (above $T_v$). Notably, decomposition of the wood, DW, and ESMTW did not
occur until the temperature was above 200 °C, as shown by Thermogravimetric analysis
(TGA) in Supplementary Fig. 7. The re-editing permanent u-shape was formed through
an external force applied at 180 °C for 10 min, gradually cooled to room temperature,
and then rapidly fixed at 0 °C. The newly permanent u-shape was further deformed at
60 °C and fixed at 0 °C to get the temporary n-shape and s-shape. When reheated to
60 °C, these temporary shapes returned to the permanent u-shape.

The shape-memory recovery ratio of the ESMTW samples at different temperatures
(60, 90, 120, 150, and 180 °C) taken within 30 min was explored by measuring the
bending deformation angles. The variations in the bending deformation angles of the T-
ESMTW and L-ESMTW are shown in Supplementary Fig. 8 and 9, and the
corresponding recovery ratios are presented in Fig. 3c and 3e. The bent samples all
recovered to their original rectangular shape over the heating duration and exhibited a
faster recovery speed with increasing heating temperature. When the heating
temperature was above $T_g$, the recovery ratio of the T-ESMTW was above 86.7%, and
that of the L-ESMTW was above 94.4% within 30 min. Additionally, multicycle
recovery performance at 60 °C within 30 min was conducted, as shown in Fig. 3d and
3f. After the multicycle tests, the recovery ratios of the T-ESMTW and L-ESMTW
showed almost no change, indicating the great shape-memory and recovery capability
of the ESMTW.
A possible mechanism for the editable shape-memory behavior of the ESMTW was proposed, and the potential molecular structure changes during the shape-memory and shape re-editing processes are illustrated in Fig. 3g. The shape-manipulation capability was mainly determined by the vitrimers in the ESMTW sample. The vitrimer networks in the ESMTW sample could not only display shape-memory behavior by virtue of the activated molecular chains mobility around $T_g$ (with the typical transition between the glass state and rubbery state) but also possess re-editable properties because of the dynamic exchange of covalent bonds above $T_v$. In detail, the molecular segments of the vitrimers changed from a frozen to a mobile state as the temperature increased above $T_g$, when the materials deformed under an external force. This temporary shape was maintained by freezing the polymer segments at temperatures below $T_g$. When reheated above $T_g$, the frozen polymer chain was activated again, and the materials recovered to their original shape. When the heating temperature was higher than $T_v$, transesterification was activated, resulting in topological rearrangement of the polymer network. During this process, the internal stress of the ESMTW could be completely relaxed, and the previous shape could be erased, giving a chance to re-edit its permanent shape. Therefore, the combination of the $T_g$-triggered phase change and the $T_v$-triggered topological rearrangement contributes to the editable shape-memory property for the ESMTW. Notably, it could afford great feasibility to edit ESMTW with different shapes without requiring an accurate temperature or complex mold.
Fig. 3 Editable shape-memory properties: a, b) photographs of the editable shape-memory behavior of the T-ESMTW and L-ESMTW samples of approximately 2 mm thickness (scale bar: 1 cm); c, e) shape recovery ratio curves of T-ESMTW and L-ESMTW at 60, 90, 120, 150, and 180 °C; d, f) shape recovery ratio of T-ESMTW and L-ESMTW after 10 cycles at 60 °C; g) schematic diagrams of a proposed mechanism for the editable shape-memory function.

Optical property

The optical properties of the ESMTW samples were evaluated using a light-diffusion system (EEL 57D) with an integrated sphere. The transmittance and haze of the T-ESMTW and L-ESMTW with thicknesses of 2 mm were approximately 60% and 95%, respectively, as shown in Fig. 4a and 4c. The anisotropic structures of the T-
ESMTW and L-ESMTW caused anisotropic optical properties. The ESMTW samples were vertically irradiated by a single-mode green laser, using a detector behind the sample to measure the intensity profile of the transmitted light. The scattered light intensity distribution in both the x- and y-directions for the T-ESMTW and L-ESMTW samples are presented in Fig. 4b and 4d. The incident light rapidly diverged because of the scattering effect in the ESMTW sample. However, the transmittance scattering displayed an isotropic pattern in the T-ESMTW, and the angular distributions of the transmitted light scattering along the x- and y-directions were similar, whereas they showed an anisotropic pattern in the L-ESMTW, and the angular distributions along the x-direction were larger than those in the y-direction because of the highly aligned cellulose nanofibers along the x-direction.
Fig. 4 Optical properties of the EMSTW: a, c) optical transmittance and haze of the T-ESMTW and L-ESMTW, where the insets show digital images of their appearance; b, d) the normalized intensity distribution of scattered light in the x- and y-directions for the T-ESMTW and L-ESMTW, where the insets are photographs of the scattered light spots for the T-ESMTW and L-ESMTW.

**Light guiding and directional scattering effects.**

In order to evaluate the light guiding and directional scattering effects, common glass, vitrimers, and the T-ESMTW samples were irradiated by a single-mode laser with a tilted incident angle, and the transmitted light pattern was captured on a screen. The schematic is presented in Fig. 5a, and the transmitted light patterns are shown in Fig. 5b–d. The light passed through the glass, along the incident light angle and eventually formed a small, bright light spot. Owing to the 40% haze of the vitrimers, the transmitted light along the incident light angle caused a degree of light scattering.
However, for the T-ESMTW sample, light propagated along the wood channel alignment direction, instead of the incident light angle, and scattered directly below the T-ESMTW. The incoming green laser beam illuminated the T-ESMTW sample with incidence angles of 30° and 60°, and the scattered light intensity distribution in both the x- and y-directions are shown in Supplementary Fig. 10. Notably, the beam intensity did not exhibit obvious deviation from a standard Gaussian distribution. These results indicate that the T-ESMTW possesses unique light guiding and directional scattering effects.

The daylight harvesting capability of the ESMTW was conducted, as illustrated in Fig. 5e–f. A wooden house model was designed with glass, vitrimers, and the T-ESMTW (50 mm × 50 mm × 2 mm) as the ceiling to compare their daylight harvesting capabilities. A white light source was applied to illuminate the house with a tilted incident angle of 45° along the upper left. The shadow and obvious strong or weak light distribution were presented in the house model with the glass and vitrimers ceiling (Fig. 5e and 5f), whereas more uniform illumination was observed with the T-ESMTW ceiling (Fig. 5g). The light distribution of eight points inside the house model with each ceiling material was evaluated using an illuminometer. In the house model with a glass ceiling, the maximum illuminance (3567 lx) was approximately 81 times higher than the minimum illuminance (44 lx), exhibiting non-uniform illumination. For the vitrimers ceiling, the multiple was approximately 34. In contrast, for the house model with the T-ESMTW ceiling, the light illuminance difference between the brightest spot (2520 lx) and the darkest spot (153 lx) was only 16 times. Therefore, the T-ESMTW
ceiling not only provided more uniform indoor illumination with improved visual comfort but also enhanced the energy efficiency for indoor lighting and improved privacy protection due to its high haziness. Additionally, the T-ESMTW exhibited varying transmittance yet consistent high haze with different thicknesses, as shown in Supplementary Fig. 11.

To take full advantage of the shape-manipulation capability of the T-ESMTW, the daylight harvesting property of the curved T-ESMTW (50 mm × 50 mm × 1 mm) was further explored. As shown in Fig. 5h–j, the two points (① and ②) inside the house model on the same horizontal plane exhibited different light illuminances with the different T-ESMTW ceilings of concave, flat, and convex shapes. The stronger light illuminance appeared at a far distance from the light resource side in the concave T-ESMTW ceiling (Fig. 5h), whereas it appeared at the near light resource side in the convex ceiling (Fig. 5j). The flat ceiling showed a relatively uniform light illuminance (Fig. 5i). When light enters the T-ESMTW, the cylindrical-like wood channel filled with vitrimers guides the light propagation along the wood channel alignment direction. As illustrated in Fig. 5k–m, the light was reflected at the interface between the cellulose nanofibers and the vitrimers, and each reflection was accompanied by attenuation. Thus, the smaller the angle is between the incoming light and the aligned wood channels, the fewer reflections and attenuations there are, resulting in a stronger light intensity. The combination of the light guiding and directional scattering effects and the shape-manipulation capability opens the T-ESMTW to more possibilities for more advanced
and intelligent applications.

Fig. 5 Light guiding and scattering effects, and daylight harvesting capability: a) illustration of the characterization method for the light guiding and scattering effects of the ESMTW; b–d) light guiding and scattering effects of the glass, vitrimers, and T-ESMTW; c–g) schematics of the light distribution inside the house model and the light illuminance at corresponding point locations with the glass, vitrimers, and T-ESMTW as a transparent ceiling; h–j) the light illuminance at corresponding point locations with concave, flat, and convex T-ESMTW as a transparent ceiling; k–m) the proposed mechanism for the transmitted light intensity distribution variation of concave, flat, and convex T-ESMTW as a transparent ceiling.
Building materials with excellent thermal insulation performance can effectively prevent heat dissipation and enhance energy efficiency. Therefore, low thermal conductivity is favorable for practical building applications. Common glass has a high thermal conductivity (1.0823 W m\(^{-1}\) K\(^{-1}\) measured in this work), which severely impacts the energy efficiency of the building. The thermal conductivity of the vitrimers was 0.2805 W m\(^{-1}\) K\(^{-1}\), and that of the T-ESMTW and L-ESMTW was 0.3002 W m\(^{-1}\) K\(^{-1}\) and 0.2898 W m\(^{-1}\) K\(^{-1}\), respectively (Fig. 6). The ESMTW exhibited approximately one-third the thermal conductivity of common glass due to better thermal insulation. These results demonstrate that the ESMTW is an outstanding thermal insulation material, which could be a great for energy-efficient buildings.

**Fig. 6** The thermal conductivities of the common glass, vitrimers, T-ESMTW, and L-ESMTW.
Mechanical property.

In addition to the light management and thermal insulation capabilities, the mechanical properties of the ESMTW are equally significant for practical application. The stress–strain curves of the balsa wood, DW, and ESMTW along the transverse and longitudinal directions are shown in Fig. 7a and 7b. The fracture strength, elastic modulus, and toughness are listed in Table 1. After delignification, the fracture strength, elastic modulus, and toughness of the DW samples were remarkably lower than those of the natural balsa wood. Due to the synergistic effect between the wood matrix and vitrimers, the ESMTW exhibited dramatically improved fracture strength, elastic modulus, and toughness, relative to natural balsa wood, with values of 4.69 MPa, 429.96 MPa, and 62.29 KJ m$^{-3}$ in the transverse direction, respectively, and 36.62 MPa, 1161.41 MPa, and 667.72 KJ m$^{-3}$ in the longitudinal direction, respectively. The stress–strain curve of the resultant vitrimers is shown in Supplementary Fig. 12. The maximum tensile strength was approximately 20.37 MPa, which was lower than that of the L-ESMTW, demonstrating the synergy between the wood structure and the vitrimers. The anisotropic mechanical properties of the T-ESMTW and L-ESMTW could be attributed to the highly aligned cellulose nanofiber scaffold, resulting in high strength along the fiber direction but lower strength perpendicular to the fiber direction.

Figure 7c and 7d show the resulting morphology of common glass and T-ESMTW after a sudden impact. The glass broke and shattered into pieces, whereas the T-ESMTW maintained its integrity, displaying high impact absorption ability. When experiencing a sudden impact, the microchannels filled with vitrimers could absorb and
disperse the energy, which protected the ESMTW from shattering. Therefore, using the ESMTW as building materials instead of common glass could address safety concerns.

Considering the strength properties at different service temperatures in practical applications, the dynamic thermal mechanical properties of the ESMTW were determined by dynamic mechanical analysis (DMA) with a single cantilever mode. Wood as a viscoelastic material possesses viscose and elastic properties. As shown in Fig. 7e and 7g, as temperature increased, the storage modulus and tanδ of balsa wood tended to increase and decrease, respectively. This tendency is attributed to the thermal mechanical properties of natural wood because of the accelerated chain mobility of the polymeric components of the wood cell walls at elevated temperatures.\textsuperscript{42,43} The curves of the storage modulus and tanδ of the ESMTW were highly similar to those of the synthesized vitrimers, as shown in Fig. 7f and 7h and Supplementary Fig. 13, indicating that the thermal mechanical properties of the ESMTW were mainly driven by the high content of vitrimers. The storage modulus gradually decreased as temperature increased (under $T_g$), and it rapidly decreased as the temperature exceeded $T_g$, up to approximately 50 °C. The storage modulus of the ESMTW was dominated by the storage modulus of the wood itself. Therefore, the service temperature of the ESMTW was determined by the $T_g$ value (35.2 °C measured by DSC; 43.2 °C measured by TMA). This service temperature makes the ESMTW suitable for application as a building material in most parts of the world. In addition, DMA could explain the stiffness of the ESMTW at lower temperatures and its flexibility at higher temperatures. The wide tanδ peaks appeared at approximately 155 °C in the ESMTW and vitrimer
samples, which could be attributed to the relaxation process likely caused by the topology rearrangement ($T_v$ is approximately 169.2 °C according to the TMA).

Table 1. Comparison of mechanical properties of T-wood, T-DW, T-ESMTW, L-wood, L-DW, and L-ESMTW.

|                | Fracture strength (MPa) | Elastic modulus (MPa) | Toughness (KJ m$^{-2}$) |
|----------------|-------------------------|-----------------------|--------------------------|
| T-wood         | 0.49                    | 27.49                 | 5.98                     |
| T-DW           | 0.09                    | 7.50                  | 0.88                     |
| T-ESMTW        | 4.69                    | 429.96                | 62.29                    |
| L-wood         | 5.15                    | 375.731               | 56.44                    |
| L-DW           | 3.32                    | 298.883               | 21.99                    |
| L-ESMTW        | 36.62                   | 1161.41               | 667.72                   |

**Fig. 7** Mechanical strength and dynamic thermal mechanical properties of the ESMTW: a, b) stress-strain curves of T-wood, T-DW, T-ESMTW, L-wood, L-DW, and L-ESMTW; c, d) appearance state of common glass and T-ESMTW after a sudden impact; e–h) DMA curves of T-wood, T-ESMTW, L-wood, and L-ESMTW, respectively.
Discussion

An editable shape-memory transparent wood with unique light and thermal management qualities and high strength was developed through *in situ* synthesis of refractive index-matching epoxy vitrimers into the DW scaffold. The transmittance and haze of the resultant TW with 2 mm thickness were approximately 60% and 95%, respectively. The ESMTW exhibited great shape-manipulation capabilities, including shape-editable, shape-memory, and shape-recovery properties. The shape-recovery ratios of the T-ESMTW and L-ESMTW were as high as 86.7% and 94.4%, respectively. Meanwhile, the T-ESMTW displayed unique light guiding and directional scattering effects, which could create a uniform and consistent daylight distribution. Most importantly, the shape-management capability of the ESMTW could realize the light intensity distribution variation of the transmitted light. The ESMTW also displayed excellent mechanical properties. The T-ESMTW and L-ESMTW showed a fracture strength of 4.69 MPa and 36.62 MPa, respectively, and toughness of 62.29 KJ m\(^{-3}\) and 667.72 KJ m\(^{-3}\), respectively, in addition to high energy absorption. The thermal conductivities of the T-ESMTW and L-ESMTW were 0.3002 W m\(^{-1}\) K\(^{-1}\) and 0.2898 W m\(^{-1}\) K\(^{-1}\), respectively, which were at least one-third that of common glass. All these characteristics enable the ESMTW to be a promising candidate for green, energy-efficient, and advanced and intelligent building materials in 3D applications.

Methods

**Materials and chemicals.** Balsa wood (*Ochroma pyramidale*) with a density of 126 ±
5.4 mg cm\(^{-3}\) was purchased from Zhuhai Dechi Technology Co. Ltd., China. Wood slices with thicknesses of 1–3 mm along the transverse and longitudinal directions were used in this work. Sodium chlorite (NaClO\(_2\), 80%) and glacial acetic acid (CH\(_3\)COOH, 99.5%) were purchased from Aladdin Reagent Co., Ltd. (Shanghai, China). (Tetra-SH, 90%), and stannous octoate (Sn(Oct)\(_2\), 95%) were purchased from Macklin Biochemical Co., Ltd. (Shanghai, China). The epoxy resin (E51) was obtained from Kunshan Jiulimei Electronic Material Co., Ltd, China. All chemical reagents were used as received without further purification.

**Preparation of Delignified Wood.** The wood slices were impregnated with the lignin removal solution (an aqueous solution of 1 wt % NaClO\(_2\) with the pH adjusted to 4.6 with CH\(_3\)COOH), and the solution was changed every 6 h at 80 °C for several hours until the wood became white. The treated wood samples were washed several times with water at 90 °C to remove the remaining reagents. Finally, the resulting wood slices were freeze-dried to obtain the DW templates.

**Preparation of Programmable Shape-Memory Transparent Wood.** E51, Tetra-SH, Sn(Oct)\(_2\) (molar ratio of 1:0.5:0.1) were uniformly mixed in a beaker by vigorous stirring. The DW slices were vacuum-immersed in this mixed solution for 20 min, and the ESMTW was obtained after solidification at 120 °C for 2 h. The ESMTW was labeled as T-ESMTW and L-ESMTW according to the cutting direction of the original wood.

**Characterization and measurements.** The microstructures of the wood, DW, and ESMTW were characterized by scanning electron microscopy (SEM, SU8010, Hitachi)
at an accelerating voltage of 5.0 kV. The chemical components of the wood, DW, and ESMTW were analyzed by ATR-FTIR spectra on a Nicolet iS50 FT-IR spectrometer with an ATR diamond crystal. The components of the wood (cellulose, hemicellulose, and lignin) were measured according to the literature. The optical properties (transmittance and haze) were measured with a light-diffusion system (EEL 57D) with an integrated sphere according to ASTM D1003. The light scattering property of the ESMTW was measured by irradiating the center of the sample with a green laser (532 nm, light spot diameter of approximately 3 mm) at a distance of 50 cm; the distance between the ESMTW sample and the screen was 8 cm. The intensity distribution of the scattered light at different angles was measured using an illuminometer (detector area of $1 \times 1 \text{ cm}^2$). The light scattering patterns were obtained using a mobile phone. The light guiding effect in a house model with common glass and TW rooftops was tested with an LED lamp used as the white light source to simulate sunlight.

Thermogravimetric analysis (TGA) was performed using a TA TGA55 instrument at a heating rate of 10 °C min$^{-1}$ from 30 °C to 600 °C under a nitrogen atmosphere. Differential scanning calorimetric (DSC) analysis was performed using a TA DSC 250 from −80 °C to 250 °C at a heating rate of 10 °C min$^{-1}$ under nitrogen atmosphere. Dynamic mechanical analysis (DMA) was performed on a TA Q800 in the single cantilever mode from −50 °C to 250 °C at a heating rate of 3 °C min$^{-1}$. Dilatometry experiments were conducted on a TMA Q400EM apparatus in tension mode. The length change was measured when the sample was heated from −50 to 250 °C at a rate of 5 °C min$^{-1}$ under a nitrogen atmosphere. To avoid bending, a small constant force (20 mN)
was applied throughout the experiment. The thermal conductivities of the glass, vitrimers, and ESMTW samples with sizes of $25 \times 25 \times 3.0 \text{ mm}^3$ were measured using a Hot Disk (TPS 2500S) Thermal Constant Analyzer at 25 °C. Tensile tests of the samples (80 mm length, 10 mm width, and 2 mm thickness) were performed using a SHIMADZU AGS-X testing machine at a strain rate of 5 mm min$^{-1}$ at 25 °C. The shape recovery ratio of the shape-memory capacity of the ESMTW was quantitatively characterized through the bending deformation mode. The ESMTW strips (10 mm length, 3 mm width, and 2 mm thickness) were gently folded in the middle at 60 °C, and immersed in 0 °C water to fix the shape. The bending angle was measured along the two sides of the folded ESMTW. To investigate the actuation kinetics, the bending angles at various temperatures and times were recorded using digital photographs during the shape transformation process. The recovery ratio was calculated as follows:

$$R_r = (\theta_r/180) \times 100\% \quad (1)$$

where $\theta_r$ represents the bending angle after recovery at a certain temperature and time.

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