

STRUCTURAL MATERIALS

Lightweight, strong, moldable wood via cell wall engineering as a sustainable structural material

Shaoliang Xiao^{1†}, Chaoji Chen^{1†}, Qinqin Xia^{1†}, Yu Liu^{1†}, Yuan Yao², Qiongyu Chen³, Matt Hartsfield⁴, Alexandra Brozena¹, Kunkun Tu^{5,6}, Stephen J. Eichhorn⁷, Yonggang Yao¹, Jianguo Li¹, Wentao Gan¹, Sheldon Q. Shi⁸, Vina W. Yang⁹, Marco Lo Ricco⁹, J.Y. Zhu⁹, Ingo Burgert^{5,6}, Alan Luo⁴, Teng Li³, Liangbing Hu^{1,10*}

Wood is a sustainable structural material, but it cannot be easily shaped while maintaining its mechanical properties. We report a processing strategy that uses cell wall engineering to shape flat sheets of hardwood into versatile three-dimensional (3D) structures. After breaking down wood's lignin component and closing the vessels and fibers by evaporating water, we partially re-swell the wood in a rapid water-shock process that selectively opens the vessels. This forms a distinct wrinkled cell wall structure that allows the material to be folded and molded into desired shapes. The resulting 3D-molded wood is six times stronger than the starting wood and comparable to widely used lightweight materials such as aluminum alloys. This approach widens wood's potential as a structural material, with lower environmental impact for buildings and transportation applications.

The shape of a material can be as important as its intrinsic properties (1–4). For example, structural components must be made of materials that can be physically formed to fit specific needs without sacrificing mechanical strength. Furthermore, materials that are also lightweight are particularly valuable for vehicle-based applications (e.g., cars, trains, and aircraft) (5), as weight-saving measures may be the most direct way to improve fuel-efficiency (6). For these reasons, polymers and some metals, such as aluminum (Al), are used for mechanical support, as they feature both low density and facile processability into lightweight structural components of various shapes and sizes by different means such as extrusion, casting, and injection molding (5, 7). However, the development of more-sustainable materials is needed to mitigate the environmental costs of petrochemical-based plastics and the energy costs of metals (8–11).

Wood is one potential candidate for replacing some of these lightweight structural materials, especially given its advantage of being a renewable resource (12, 13). Wood products

can help mitigate climate change by replacing carbon-intensive, fossil fuel-based materials (14, 15), as well as providing extended carbon storage (16). Wood is also mechanically strong, lightweight, and potentially low cost. Various approaches have been demonstrated to improve the properties and functionality of wood for a wider range of applications, including by delignification (17–19), densification (20–22), and other modifications [e.g., thermal treatments (23, 24), organic or inorganic salt impregnation (25–27), etc.]. That said, its formability is generally poor compared with metals and plastics, which makes processing it into complex shapes difficult.

Different methods of forming wood for shape-specific needs have been explored with varying success. For example, wood can be sculpted into complex three-dimensional (3D) shapes using conventional subtractive manufacturing (e.g., carving, sculpting, turning) (28, 29) and conventional carpentry, wherein pieces of wood are joined to make a more complex structure (30). However, these “physical approaches” generally engineer wood at the bulk scale, which does not change the intrinsic microstructure or material properties, thus failing to simultaneously achieve high mechanical strength and good formability, and limiting the practical applications of wood in advanced engineering fields that require both. In recent years, various bottom-up approaches have also been investigated in which wood is broken down into its constituent components and then refabricated into desired shapes and uses. For example, wood can be defibrillated into cellulose nanofibers (CNFs) with exceptional mechanical strength (up to 3 GPa) (31), which can then be processed into 3D forms using high-water-content slurries (up to 98 wt %) (32). However, CNFs are expensive, and the energy required for

water removal is too intensive for the fabrication of large structures. Alternatively, adding polymers to CNFs can improve their processability by enabling casting or injection molding (33). But the high petrochemical polymer content of these CNF composites diminishes their advantage as a sustainable material. Furthermore, such bottom-up approaches come at the sacrifice of wood's naturally hierarchical and anisotropic structure (i.e., the highly aligned channels and fibers that run along the longitudinal direction of the stem) from where much of the material's natural strength and functionality derives.

We report a top-down approach by which wood can be processed into various shapes while also substantially increasing its mechanical strength. The principal concept is based on partially delignifying and softening natural wood, then shrinking its vessels and fibers by drying, followed by “shocking” the material in water to selectively open the vessels (Fig. 1A). This rapid water-shock process forms a distinct partially open, wrinkled cell wall structure that provides space for compression as well as the ability to support high strain, allowing the material to be easily folded and molded. The different shapes and structures that can be achieved with this moldable wood can then be set with air drying to remove the remaining water to form the final 3D-molded wood product (Fig. 1B).

This cell wall engineering process maintains the intrinsic anisotropic wood structure and enhances the interactions among the wood fibers to further increase the mechanical strength. For example, we demonstrated the fabrication of a honeycomb core material from wood veneers (produced using roll-to-roll rotary cutting) that has a tensile strength of ~300 MPa, similar to Al alloys but with a density of just ~0.75 g/cm³ and at potentially lower cost (Fig. 1, B and C). This cell wall engineering approach is applicable to various hardwood species and is enabled by the water-shock process that expands the capabilities of wood as a lightweight structural material beyond conventional planar structures to complex 3D designs and components with greater versatility. Manipulating wood's naturally anisotropic structure will improve its potential as a sustainable and practical alternative for applications that have been traditionally limited to polymers, metals, and polymer composites (Fig. 1C) (34).

We first used a common aqueous-based delignification process (35, 36) to remove ~55% of the lignin and ~67% of the hemicellulose from the lignocellulosic cell walls of basswood (Fig. 1A and figs. S1 to S3). The partial and selective removal of this hydrophobic component results in softening and mild expansion in the wood sample size due to the absorption of water by the remaining cell

¹Department of Materials Science and Engineering, University of Maryland, College Park, MD 20742, USA. ²Center for Industrial Ecology, Yale School of the Environment, Yale University, New Haven, CT 06511, USA. ³Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA. ⁴Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA. ⁵Wood Materials Science, Institute for Building Materials, ETH Zürich, 8093 Zürich, Switzerland. ⁶WoodTec Group, Cellulose & Wood Materials, Empa, 8600 Dübendorf, Switzerland. ⁷Bristol Composites Institute, CAME School of Engineering, University of Bristol, University Walk, Bristol BS8 1TR, UK. ⁸Department of Mechanical Engineering, University of North Texas, Denton, TX 76203, USA. ⁹US Department of Agriculture (USDA) Forest Products Laboratory, Madison, WI 53726, USA. ¹⁰Center for Materials Innovation, University of Maryland, College Park, MD 20742, USA.

*Corresponding author. Email: binghu@umd.edu

†These authors contributed equally to this work.

walls (fig. S1), which feature a higher fraction of hydrophilic cellulose (fig. S2). As a result, the water content of the partially delignified wood is ~300 wt % (fig. S4). We then air dried the partially delignified wood under ambient conditions for ~30 hours to remove water and form the shrunken wood intermediate (~12 wt % water content) (Fig. 1A and fig. S4). Next, we

immersed the shrunken wood in water for 3 min in what we called a water-shock process that partially re-swells the cell walls and leads to some expansion of the sample dimensions in the resulting product, which we call moldable wood (~100 wt % water content) (figs. S1 and S4 and movie S1). Whereas the wet natural wood (Fig. 2A) and shrunken wood (Fig. 2B)

cannot be bent without breaking, the moldable wood is highly foldable (Fig. 2C and movie S2). The wood fibers in these samples run parallel to the folding direction. Wood sheets made with this fiber orientation can be scalably produced by rotary cutting, circumventing the size limitations of the length and width of the raw tree material (37).

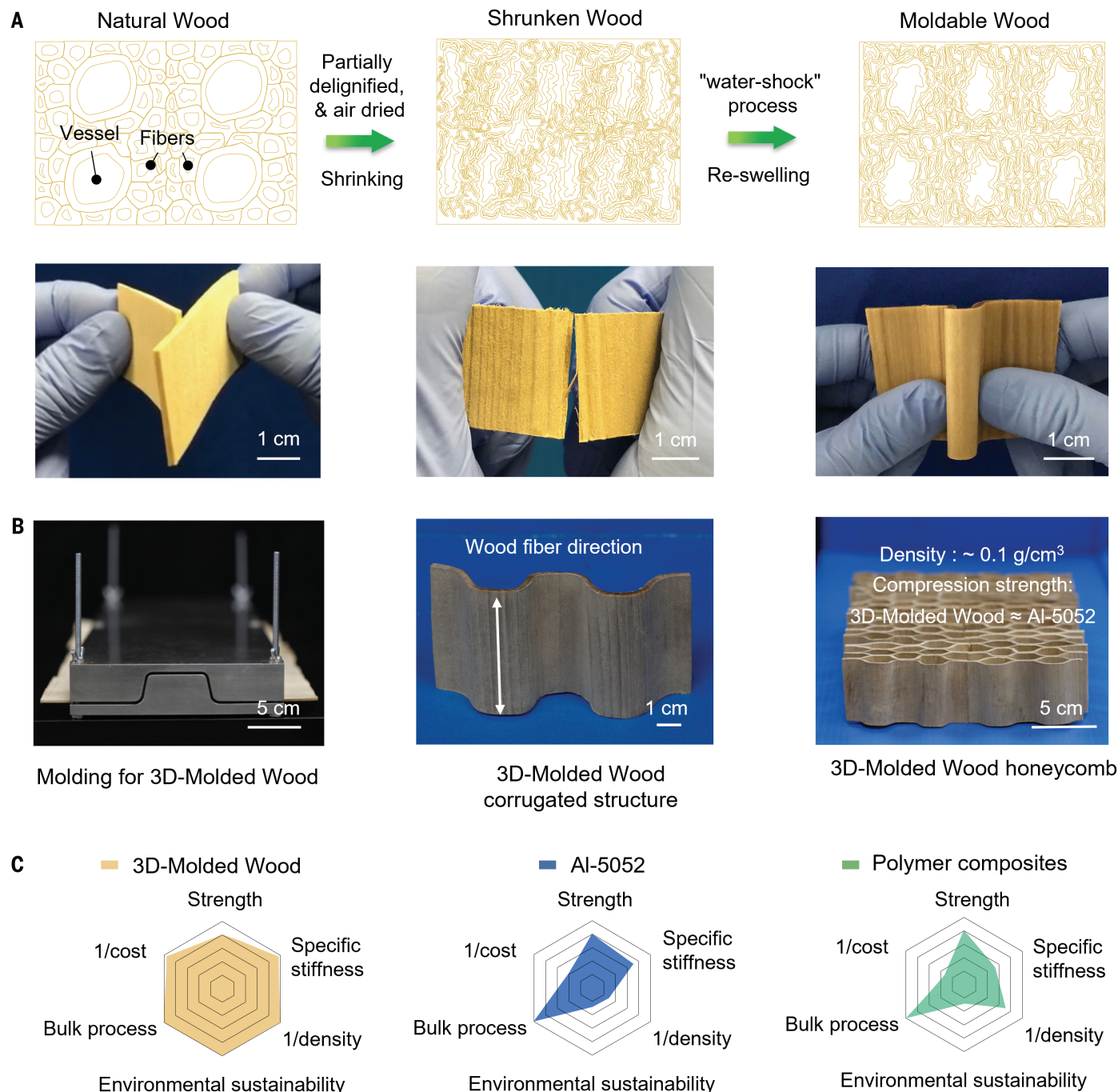


Fig. 1. A wrinkling cell wall engineering strategy through partial delignification combined with a “water-shock” process to make wood stronger and moldable. (A) Schematic illustration of the wood cell wall structures during the fabrication of the moldable wood, highlighting the critical role of the water-shock process, which forms

wrinkled cell walls. (B) Corrugated and honeycomb 3D-molded wood structures made from wood veneers cut parallel to the fiber direction. (C) Radar plots comparing the performance of 3D-molded wood, Al-5052 alloy, and polymer composites (34), in which the results are normalized by the maximum value of each characteristic.

Using scanning electron microscopy (SEM), we examined the microstructures of these wood samples to better understand their process-structure-property relationships. The natural wood starting material has a 3D hierarchically porous cellular structure with many hollow vessels and fibers (Fig. 2D). These open cells become almost completely closed in the shrunken wood owing to the removal of

lignin and water, forming a highly densified structure (Fig. 2E). However, the water-shock treatment that forms the moldable wood results in a distinctive wrinkled cell wall structure in which the vessels are partially open while the fibers are almost completely closed (Fig. 2F). During this treatment, we observed that the reopening of the vessels occurs extremely rapidly (3 s), while the morphology

of the smaller fibers remains nearly unchanged (movie S3 and fig. S5). Such selective opening of the cell wall structure is noteworthy, as it may provide two simultaneous effects. The partially open vessels create space within the moldable wood that may accommodate both compressive and tensile deformation in an accordion-like manner, allowing the material to undergo severe compression and

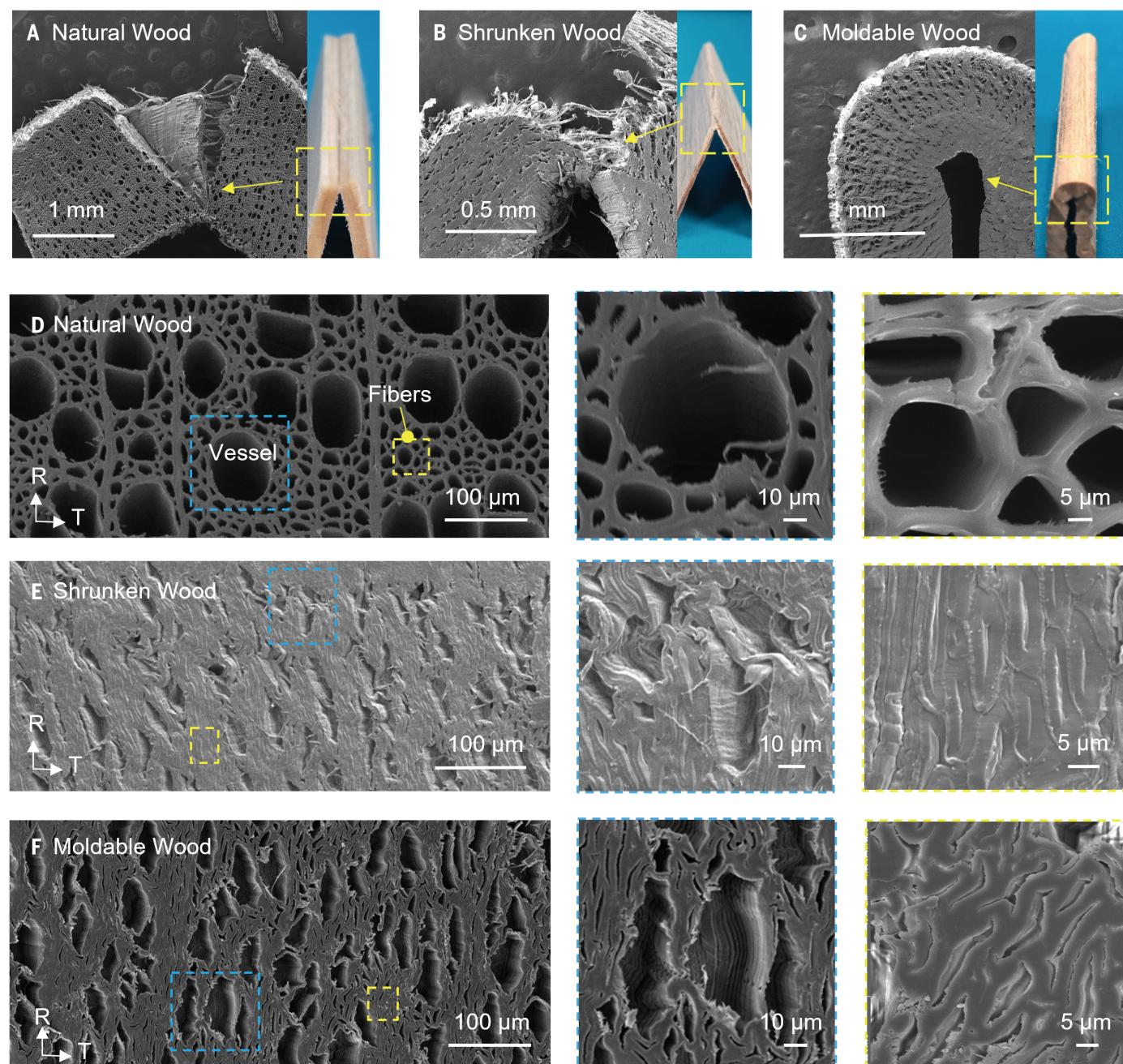


Fig. 2. Microstructures of the natural wood, shrunken wood, and moldable wood. (A to C) Photographs and SEM images demonstrate the (A) natural wood and (B) shrunken wood undergo deformation and fracture when bent, whereas (C) the moldable wood can be easily folded. (D) SEM images of the natural wood, which contains many hollow rigid vessels and fibers.

(E) SEM images of the shrunken wood, which show the severely shrunken vessels and fibers after water removal. (F) SEM images of the moldable wood, which features a distinctive wrinkled cell wall structure with partially open vessels and almost completely closed fibers. R, radial direction; T, tangential direction.

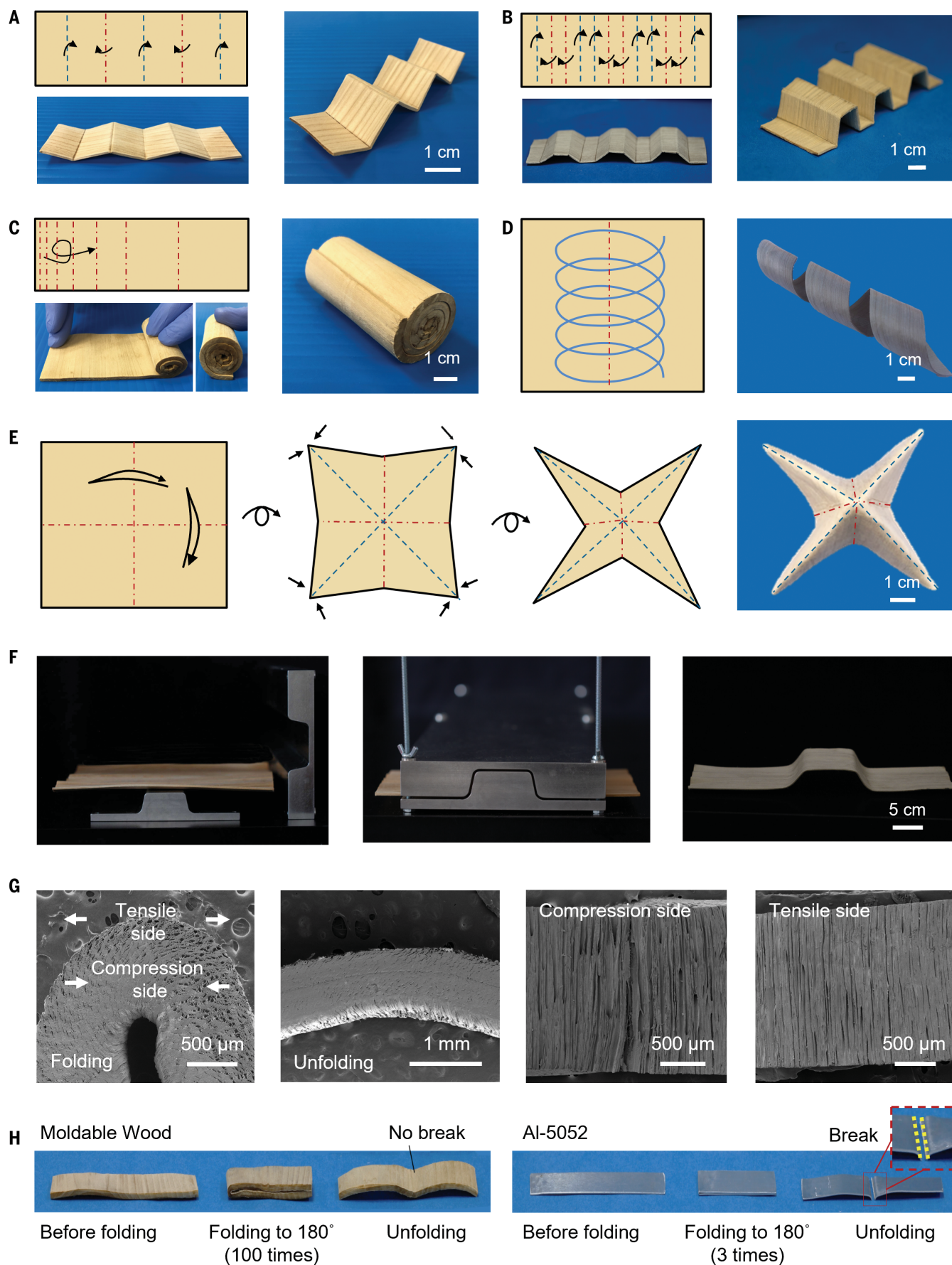


Fig. 3. Fabricating 3D-molded wood into various shapes using the cell wall engineering process. Schematics and corresponding photographs of the 3D-molded wood featuring (A) zigzag, (B) corrugated, (C) rolled, (D) helical, and (E) star-shaped structures. (F) The molding process of the 3D-molded wood corrugated structure (25 cm by 12 cm by 0.12 cm). (G) SEM images of the folded and unfolded 3D-molded wood, produced after air drying the moldable wood after

100 folding and unfolding cycles. We observed no crease in the compression or tensile sides in the resulting 3D-molded wood, demonstrating the excellent foldability and durability of the material when folded parallel to the wood fiber direction. (H) Comparison of the Al-5052 alloy and moldable wood after undergoing multiple cycles of folding and unfolding. The moldable wood remains intact after 100 cycles of folding and unfolding, whereas the Al alloy breaks after just three cycles.

tension while being folded, even up to 180° without cracking (Fig. 2C and movie S2). Meanwhile, the densely packed closed fibers may provide mechanical support for enhanced strength.

To further investigate the impact of this wrinkled cell wall structure, we prepared a control in which we air dried the partially delignified wood for just 6 hours and did not apply the water-shock treatment in order to obtain the same water (~100 wt % water content) and lignocellulosic content as that of the moldable wood (fig. S4). The method we used to fabricate this control is similar to that of a previously reported high-strength wood material (22). The resulting control did not feature a wrinkled cell wall structure, instead demonstrating a similar open cell microstructure as the natural wood but with thinner and more separated cell walls owing to the partial removal of the lignin (fig. S6). Additionally, the material could not be bent without breaking (fig. S4), therefore we called it nonmoldable wood. This control clearly demonstrates the importance of the partially opened, wrinkled cell wall structure in enabling the moldable wood's mechanical flexibility.

We conducted simulations to investigate how the wrinkled cell wall structure enables the release of mechanical stress during folding to prevent the material from breaking. Fiber-scale mechanics modeling shows that the strain level in all cell walls of the moldable wood is extremely low (with a maximum principal tensile strain of 0.23% and compressive strain of 0.31%) even when the moldable wood is subjected to a 60% nominal strain deformation (tensile or compressive) (figs. S7 and S8). In contrast, the maximum principal tensile strain in the cell walls of the nonmoldable wood is as high as 2.3% under an overall elongation of 12.5%, substantially higher than that in the moldable wood (fig. S8). We explain this difference in the mechanical properties of the moldable and nonmoldable wood by their distinct microstructures. Despite both materials undergoing the delignification process, the fibers and vessels are open and only in loose contact in the nonmoldable wood, while the cell structures are more closed and in greater contact in the wrinkled cell walls of the moldable wood because of the drying and water-shock process. As a result, the moldable wood features sufficient hydrogen bonding among the cell walls to resist delamination during

folding, while the nonmoldable wood readily fractures (fig. S9).

Using this cell wall engineering method, we can process the moldable wood into various shapes by mechanical bending, folding, and twisting. When the targeted structure is achieved, we can then dry the wood to fix its shape. For example, we fabricated zigzag and corrugated wood structures by repeatedly folding pieces of moldable wood and then drying the material to set the rigid forms (Fig. 3, A and B). Additionally, we can roll the moldable wood (Fig. 3C) and twist it (Fig. 3D, fig. S10, and movie S4) like metals and plastics. The outstanding foldability and excellent stability after drying allows us to design and fabricate complex 3D structures, such as star shapes (Fig. 3E). Other shapes include a corrugated structure (25 cm by 12 cm by 0.12 cm) using a homemade die to mold the material (Fig. 3F).

SEM morphology studies reveal the dense and integrated structure of the resulting 3D-molded wood. We did not observe any fibers peeling away from the folded corners of these structures, even after 100 folding and unfolding cycles (Fig. 3G). The surface finish remains smooth when folded parallel to the wood fiber direction. This excellent surface finish is likely due to the outstanding flexibility of the wood fibers and the hydrogen bonding between them, allowing the fibers to follow the folded shapes during mechanical deformation in a conformal manner (Fig. 3G). In terms of foldability and durability, the moldable wood also outperforms Al-5052, a widely used Al alloy for lightweight engineering structures, in which the moldable wood can be folded and unfolded 100 times without fracture, whereas the Al alloy broke after only three folding and unfolding cycles (Fig. 3H).

We found that the 3D-molded wood also has improved mechanical properties for lightweight structural applications, including a tensile strength of ~300 MPa and compressive strength of 60 MPa along the wood fiber direction. These values are nearly six and two times higher than that of the raw natural wood, respectively (fig. S11). The improved mechanical properties of the 3D-molded wood are due to its denser structure, which features highly packed intertwined cell walls at the microscale and well-aligned cellulose nanofibrils inside the cell walls at the nanoscale (fig. S12). The 3D-molded wood's low density of 0.75 g/cm³ gives it a high specific tensile strength of

386.8 MPa per g/cm³, which is about five times greater than that of Al-5052 (84.4 MPa per g/cm³) (fig. S13). Furthermore, the stiffness of 3D-molded wood exceeds that of a range of hardwoods (38), softwoods (38), and polymers (39) (Fig. 4A).

The low density, high mechanical strength, and excellent formability of the 3D-molded wood offers broad versatility in designing and manufacturing large, lightweight, load-bearing designs. One example is a honeycomb structure, which is usually made of polymers or metals such as the Al-5052 alloy (40, 41). We fabricated 3D-molded wood honeycomb structures by molding the material along the wood fiber direction (fig. S14). The 3D-molded wood honeycomb unit demonstrates comparable specific compressive strength (51.6 MPa per g/cm³) as the Al-5052 honeycomb unit (46.8 MPa per g/cm³) (Fig. 4B), although the 3D-molded wood features the added advantages of potentially being lower cost (table S1) and with potentially enhanced environmental sustainability. To evaluate the compressive and bending properties of the assembled 3D-molded wood honeycomb core, we sandwiched the structure between two Al plates (fig. S15). The Al-3D-molded wood-Al honeycomb core sandwich demonstrated a compressive strength of 9.1 MPa (Fig. 4C) and a specific compressive strength of 91.0 MPa per g/cm³, which is higher than that of the Al-5052 honeycomb structure (specific compressive strength of 70.9 MPa per g/cm³) (fig. S16). This sandwich structure was able to support the weight of a 1588-kg car, which corresponds to 1526 times the weight of the 3D-molded wood honeycomb core itself (Fig. 4D).

Scaling the manufacturing of corrugated 3D-molded wood structures could be accomplished using the mature roll-to-roll manufacturing processes from the wood and pulp industries (Fig. 4E) (42). For example, rotary cutting produces large wood sheets, which can be treated by the partial delignification, drying, and water re-swelling steps (fig. S17). All of these processes are common in the wood and pulp industries. Additionally, the 30-hour ambient drying step can be shortened to ~2 min using hot air (~80°C) without affecting the material's moldability. Rolling or die forming can then complete the fabrication of 3D-molded wood corrugated structures. Additional gluing and assembling steps can create the desired form, a 80 cm by 6 cm by 1.5 cm

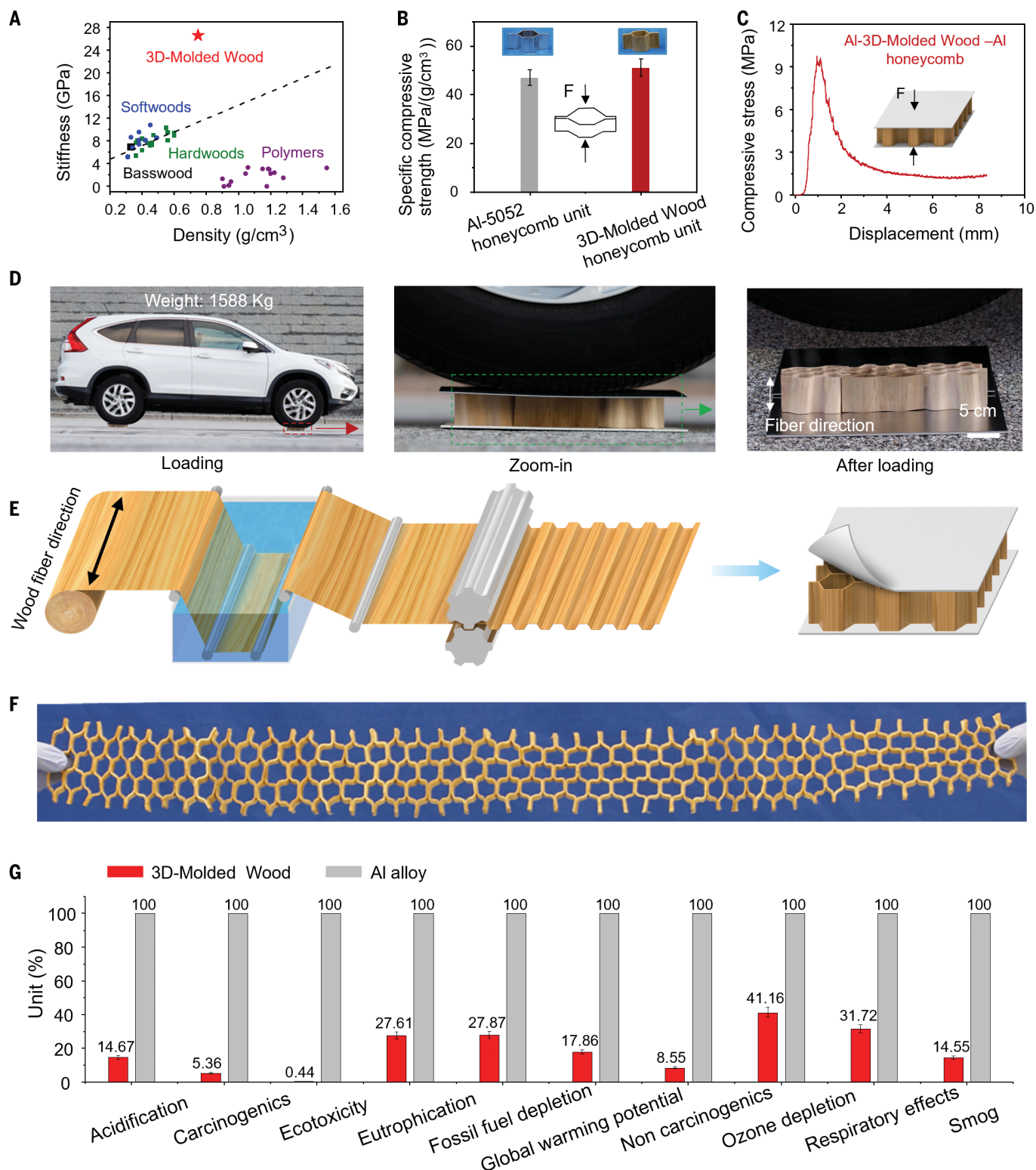


Fig. 4. Mechanical properties and LCA of the 3D-molded wood for strong, lightweight structural designs. (A) An Ashby diagram showing the stiffness versus density of 3D-molded wood, as well as various wood species (38) and polymers (39). (B) Comparison of the specific compressive strength of the 3D-molded wood and Al-5052 honeycomb units (1.5 cm in height by 2 cm in width and 4.4 cm in length). (C) The compressive stress versus displacement plot of the Al-3D-molded wood-Al honeycomb core sandwich structure. The inset shows the compression test schematic. The 3D-molded wood honeycomb core was 1.5 cm in height by 6.5 cm

in length and 6 cm in width. (D) Photographs of the sandwich structure supporting the weight of a car, in which the core structure remained intact after loading.

(E) Manufacturing process schematic for scaling the fabrication of the 3D-molded wood honeycomb core and its potential applications. (F) Photograph of a 3D-molded wood honeycomb core, 80 cm in length.

(G) The environmental impacts of 3D-molded wood and Al alloy (high recycling content of 73.9%) per cubic centimeter per megapascal based on the specific tensile strength, normalized to the higher-impact material for each environmental impact category.

3D-molded wood honeycomb core being one example (Fig. 4F).

In order to replace certain traditional structural materials, such as Al alloys (40), the long-term durability of 3D-molded wood is necessary. Applying a surface coating of polyurethane to the 3D-molded wood can help stabilize it against moisture (fig. S18). Moreover, both the uncoated and coated 3D-molded wood demonstrate antifungal properties superior to those of natural wood (table S2 and fig. S19). However, more weathering tests are required to determine the exact types of modifications needed to ensure the long-term durability of the 3D-molded wood product. Ensuring uniform production during scale-up and specific performance tests when integrated into various system applications will also help determine the best use for the 3D-molded wood.

In addition to its excellent functionality, the 3D-molded wood is directly fabricated from a bio-sourced, renewable material (i.e., hardwood species), potentially providing enhanced environmental sustainability (e.g., a lower carbon footprint) compared with traditional metal and polymer-based structural materials. To investigate this potential, we performed a cradle-to-gate life cycle assessment (LCA) to understand the comparative environmental impacts of 3D-molded wood and Al alloy (table S3 and fig. S20). We calculated the ratio of the environmental impacts per cubic centimeter of the materials to their tensile strength (megapascals) and stiffness (gigapascals) (tables S4 and S5). Our study included different environmental impact categories, such as those related to ecosystem (acidification, eutrophication, and ecotoxicity), global warming potential, fossil fuel depletion, environmental issues (ozone depletion and smog formation), and human health impacts (including carcinogenic and noncarcinogenic health impacts, and respiratory effects). The 3D-molded wood shows substantial reductions (59 to 99%) across all environmental impact categories, even compared with Al alloy with a high recycled content of 73.9% (Fig. 4G). Such reductions are even larger (74 to 99% reduction) (fig. S21) compared with Al alloy with lower recycled content (35%). Additionally, on the basis of the specific tensile strength measured in this study, 3D-molded wood only needs 21 to 23% of the mass of Al alloy to fulfill the same strength requirements (equations S3 to S7). LCA results based on the material stiffness, another important mechanical property for a structural material, also show that compared with Al alloy, 3D-molded wood has lower environmental impacts in most categories, with a few exceptions (figs. S22 and S23). The contribution analysis of the LCA identifies the energy consumption of the wood treatment as the major contributor to the environmental impacts of the 3D-molded wood (table

S6). However, by reducing the delignification time (table S7; see the supplementary materials for more details), the environmental impacts of the 3D-molded wood are drastically reduced and lower than Al alloy across all impact categories (figs. S24 to S28).

In this work, we demonstrate how cell wall engineering can render wood foldable and moldable while simultaneously improving its mechanical properties—endowing wood with a structural versatility previously limited to plastics and metals. The 3D-molded wood also has several advantages as a sustainable material, with a potentially lower environmental impact than Al alloy. 3D-molded wood may also enable substantial fuel savings and corresponding environmental benefits when used as a lightweight structural material for vehicles and aircraft. Additionally, wood products have the added benefit, compared to plastics and metals, of large carbon storage capabilities, which is recognized by the Intergovernmental Panel on Climate Change for mitigating global warming (43). Furthermore, advances in wood processability and functionality could motivate better forest management practices. We note that in addition to basswood, other hardwood species and woods of different tree ages and growth locations can be used to fabricate the 3D-molded wood by the same treatment, suggesting the universality of this approach to hardwoods and its potential for wide-scale application (figs. S29 to S31). Wood cell wall engineering can substantially expand the versatility of this sustainable and high-performance material, making wood a potential alternative to plastics and metals in structural applications.

REFERENCES AND NOTES

1. S. Xu *et al.*, *Science* **347**, 154–159 (2015).
2. Y. Kim, H. Yuk, R. Zhao, S. A. Chester, X. Zhao, *Nature* **558**, 274–279 (2018).
3. C. Wang, C. Wang, Z. Huang, S. Xu, *Adv. Mater.* **30**, e1801368 (2018).
4. Y. Tang *et al.*, *Adv. Mater.* **29**, 1604262 (2017).
5. A. K. Naskar, J. K. Keum, R. G. Boeman, *Nat. Nanotechnol.* **11**, 1026–1030 (2016).
6. A. I. Taub, *MRS Bull.* **31**, 336–343 (2006).
7. K. Zheng, D. J. Politis, L. Wang, J. Lin, *Int. J. Lightweight Mater. Manuf.* **1**, 55–80 (2018).
8. X. Liao *et al.*, *Science* **366**, 1376–1379 (2019).
9. P. Fratzi, R. Weinkamer, *Prog. Mater. Sci.* **52**, 1263–1334 (2007).
10. Q.-F. Guan *et al.*, *Sci. Adv.* **6**, eaaz1114 (2020).
11. *Nature* **557**, 280 (2018).
12. C. Chen *et al.*, *Nat. Rev. Mater.* **5**, 642–666 (2020).
13. E. Toumpanaki, D. U. Shah, S. J. Eichhorn, *Adv. Mater.* **33**, e2001613 (2021).
14. A. Geng, H. Yang, J. Chen, Y. Hong, *For. Policy Econ.* **85**, 192–200 (2017).
15. G. Churkina *et al.*, *Nat. Sustain.* **3**, 269–276 (2020).
16. Y. Pan *et al.*, *Science* **333**, 988–993 (2011).
17. S. Fink, *Holzforchung* **46**, 403–408 (1992).
18. M. I. Shams, H. Yano, *J. Trop. For. Sci.* **21**, 175–180 (2009).
19. J. Gierer, *Wood Sci. Technol.* **19**, 289–312 (1985).
20. R. M. Seborg, M. A. Millett, A. J. Stamm, “Heat-stabilized compressed wood (Staypak),” Report 1580 (USDA Forest Service, Forest Products Laboratory, 1956).
21. H. Yano, A. Hirose, P. J. Collins, Y. Yazaki, *J. Mater. Sci. Lett.* **20**, 1125–1126 (2001).
22. J. Song *et al.*, *Nature* **554**, 224–228 (2018).

23. H. Sivonen, S. L. Maunu, F. Sundholm, S. Jamsä, P. Viitaniemi, *Holzforchung* **56**, 648–654 (2002).
24. B. F. Teejdsma, M. Boonstra, A. Pizzi, P. Tekely, H. Militz, *Holz als Roh- und Werkstoff* **56**, 149–153 (1998).
25. S. Trey, S. Jafarzadeh, M. Johansson, *ACS Appl. Mater. Interfaces* **4**, 1760–1769 (2012).
26. V. Merk, M. Chanana, N. Gierlinger, A. M. Hirt, I. Burgert, *ACS Appl. Mater. Interfaces* **6**, 9760–9767 (2014).
27. C. Mai, H. Militz, *Wood Sci. Technol.* **37**, 339–348 (2004).
28. P. N. Hasluck, *Manual of Traditional Wood Carving* (Courier Corporation, 1977).
29. M. J. Golden, *A Laboratory Course in Wood-Turning* (Harper & Brothers, 1897).
30. B. Bahr, T.-E. Werner, P. Haller, *Constr. Build. Mater.* **229**, 116829 (2019).
31. T. Saito, R. Kuramae, J. Wohler, L. A. Berglund, A. Isogai, *Biomacromolecules* **14**, 248–253 (2013).
32. A. Walther, J. V. I. Timonen, I. Diez, A. Laukkanen, O. Ikkala, *Adv. Mater.* **23**, 2924–2928 (2011).
33. X. Yang *et al.*, *Adv. Mater.* **33**, 2002264 (2021).
34. I. A. Kinloch, J. Suhr, J. Lou, R. J. Young, P. M. Ajayan, *Science* **362**, 547–553 (2018).
35. C. Chen *et al.*, *ACS Nano* **14**, 16723–16734 (2020).
36. Z. Fang *et al.*, *Matter* **2**, 1000–1014 (2020).
37. A. Duplex, L. Denaud, L. Bléron, R. Marchal, M. Hughes, *Eur. J. Wood Prod. Res.* **71**, 163–171 (2013).
38. D. W. Green, J. E. Winandy, D. E. Kretschmann, in *Wood Handbook: Wood as an Engineering Material*, General Technical Report FPL–GTR–113 (USDA Forest Service, Forest Products Laboratory, 1999), pp. 4.1–4.45.
39. D. W. A. Rees, *Mechanics of Optimal Structural Design: Minimum Weight Structures* (John Wiley & Sons, 2009).
40. T. Bitzer, *Honeycomb Technology* (Springer Netherlands, 1997).
41. C. Moes, G. Hibbard, *Mater. Des.* **141**, 67–80 (2018).
42. M. Peresin *et al.*, “Large-scale nanofibrillated cellulose film: An overview on its production, properties, and potential applications,” 4th International Conference of Pulp, Papermaking and Biotechnology (ICPPB 2012), Nanjing, China, 7 to 9 November 2012.
43. B. Netz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer, in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2007), pp. 1–23.

ACKNOWLEDGMENTS

We acknowledge Z. Li, S. He, and Z. Lin for their assistance in the car-lifting experiment. **Funding:** The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency–Energy (ARPA-E), US Department of Energy, under award DE-AR0001025. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. L.H. also acknowledges support from the University of Maryland A. James Clark School of Engineering. We acknowledge the support of the Maryland Nanocenter, its Surface Analysis Center, and AIMLab. **Author contributions:** S.X., C.C., Q.X., and Y.L. contributed equally to this work. L.H. conceived of the concept and supervised the project. L.H., S.X., and C.C. designed the experiments. S.X., Q.X., and Y.L. carried out the wood shaping experiments. S.X., J.L., Y. Yao, and W.G. measured the mechanical properties. Q.X. and Y.L. provided characterization via SEM. A.L. and M.H. performed the compression and bending tests of the honeycomb structures. T.L. and Q.C. contributed to the mechanistic modeling of the foldability of the 3D-molded wood. K.T. and I.B. contributed to the Raman spectroscopy measurements and analysis. V.W.Y. performed the antifungal measurements. Yu. Yao conducted the life cycle assessment. L.H., S.X., C.C., and Q.X. analyzed the data of the manuscript. L.H., S.X., C.C., and A.B. wrote the manuscript. All authors commented on the final manuscript. **Data and materials availability:** All data are available in the manuscript or the supplementary materials. **Competing interests:** The authors declare no competing interests.

SUPPLEMENTARY MATERIALS

[science.org/doi/10.1126/science.abg9556](https://doi.org/10.1126/science.abg9556)

Materials and Methods

Supplementary Text

Figs. S1 to S31

Tables S1 to S7

References (44–66)

Movies S1 to S4

7 February 2021; accepted 14 September 2021
10.1126/science.abg9556

Lightweight, strong, moldable wood via cell wall engineering as a sustainable structural material

Shaoliang XiaoChaoji ChenQinqin XiaYu LiuYuan YaoQiongYu ChenMatt HartsfieldAlexandra BrozenaKunkun TuStephen J. EichhornYonggang YaoJianguo LiWentao GanSheldon Q. ShiVina W. YangMarco Lo RiccoJ.Y. ZhuIngo BurgertAlan LuoTeng LiLiangbing Hu

Science, 374 (6566),

Turning wood into honeycombs

Wood is an attractive material for structural applications, but it usually works best as boards or sheets. Xiao *et al.* have developed a process for engineering hardwood that allows these sheets to be manipulated into complex structures (see the Perspective by Tajvidi and Gardner). The key is to manipulate the cell wall structure by shrinking and blasting open the fibers and vessels by drying and “water-shocking” them. This process creates a window wherein the wood can be manipulated without ripping or tearing. Honeycomb, corrugated, or other complex structures are locked in once the wood dries. —BG

View the article online

<https://www.science.org/doi/10.1126/science.abg9556>

Permissions

<https://www.science.org/help/reprints-and-permissions>

Use of think article is subject to the [Terms of service](#)