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# Negative Poisson's ratio: A ubiquitous feature of wood

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ABSTRACT

Most materials contract laterally when stretched axially i.e. they have a positive Poisson's ratio. Negative Poisson's ratios (NPR, also auxetic) are largely limited to single crystals or to artificial meta-materials such as honeycombs, foams and composites, which does limit their applications. This meta-study shows that NPR is abundantly present in an extremely common and useful category of natural materials, woods. This effect is so ubiquitous that 87 out of 123 measured hardwood samples and 58 of 62 softwood samples exhibit the property. In wood, NPR occurs predominantly in quite narrow off-axis directions, with values as low as − 3.32. This effect is chiefly attributable to the tubular structure of the wood cells. This suggests that low-cost, large-scale auxetic structural parts can be obtained by cutting low to medium density timber in specific off-axis directions, with potential benefits in a wide range of structural and construction applications.

## 1. Introduction

20 years ago Baughman and co-workers [1] demonstrated that around 69% of cubic elemental metals have a negative Poisson's ratio (NPR, also auxetic [2]) using an extensive meta-analysis of published elasticity data and considering simple geometric models. In this letter, by using similar approaches, we prove that almost all softwoods and most hardwoods (those with a density lower than 0.8 $kg.l^{-1}$) are also auxetic.

More auxetic behaviour has been uncovered, in single crystals [1,3] or in artificial meta-materials such as honeycombs [4], foams [4] and composites [5]. Our study [3] based on full 3D tensor transformations has shown that around 37% of known single crystals display NPR, but normally in off-axis directions over arrow angle ranges. This goes a long way to explain why the property had been elusive. This unusual property is known to have the potential of improving the overall mechanical performance in a wide range of applications such as impact resistance [6], vibration absorption [7], reduced fibre pull-out in composites [8] and workability/synclasticity [9]. However, the lack of a relatively common, easily manufactured, low cost auxetic material is hindering progress.

Wood, a very traditional building material, is used extensively in construction, and environmental concerns are leading to a renewal of interest in a broad range of high-performance structural applications, for instance engineered wood products [10], wood-based skyscrapers [11, 12], transparent wood [13], high-performance densified wood [14]. Structural engineers already fine-tune the mechanical properties of wood beams or panels to improve earth-quake resistance [15], and using NPR could help further in this approach. Double curvatures synclastic wood panels based on multi-angle laminating, modern adhesives and water proofing could even see a resurgence of wooden aircraft, particularly at a time when carbon footprint is so important and when most modern composites are not yet fully recyclable.

The elastic properties of wood are in general well understood [16,17] in relation to the composite structure and geometric arrangement of wood cells (see Fig. 1(a)). The elastic tensors of samples taken far enough from the heart of trees have an orthotropic symmetry (equivalent to orthorhombic in crystals). The majority of wood cells are essentially long, thin columns, of irregular rectangular, pentagonal or hexagonal cross-section (a few mm long, a few tens $\mu$m wide, aspect ratios around 100 albeit with much variability) and therefore wood is much stiffer (by a factor of around 14) in the longitudinal (Axial) L direction. The radial R and transverse T direction are comparatively equivalent, even if the R direction is in general stiffer (by around 1.8). This more modest anisotropy has been attributed to the stiffening effect of rays (a less common, 5–12% in softwood –SW– 10–32% in hardwood –HW–, type of cells oriented in the R direction), and to the less ordered arrangement of cell walls in the T direction, therefore more prone to wall bending while the more regular arrangement in the R directions requires more wall stretching. In addition, the cell walls themselves consist of

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several layers of anisotropic helical composites of crystalline celluloses in a lignin matrix, and the extent of the anisotropy depends on the so-called microfibril angle at which the cellulose coils. As a consequence, cell walls are about 4 times stiffer in the L direction.

Almost all the studies of the elasticity of wood are limited to the three anatomical axes only, and the on-axis elastic properties are conventional. However a few works already allude to the presence of NPR. Rotating from the principal directions, Yamai [18] and Kawahara [19] found NPR in the TL plane in certain Japanese species, at around 30° off the L axis. Sliker [20] observed NPR, also in the TL plane, in three hardwoods, at 20° from the L axis. In a recent study [21], we directly measured NPR in white pine in the RL plane, at 27° from the L axis. The lowest value was reported by Bucur [22] in Douglas Fir, at − 0.95, but the directions were not mentioned in this case. As early as 1948, using typical values of the elastic tensors for a hardwood and softwood, Hearmon postulated the existence of NPR in the TL plane for a wide range of directions [23], although no one seems to have picked up on this.

## 2. Methods

### 2.1. Data collection and conversion

Elastic data for wood were obtained from many experimental studies, the earliest published in 1932, the latest in 2018, see Table 1.

#### 2.1.1. Formats

Elastic constants values can be described in several ways, and the literature for wood does not follow a systematic format at all, which did complicate the data collection.

First of all, the constants can either be the terms of an elastic tensor, compliance or stiffness, or the so-called engineering constants, Young's moduli, shear moduli and Poisson's ratios, or even combinations of elastic tensors and engineering constants. For the orthotropic symmetry, the conversion between engineering constants and compliances is straightforward, but slightly less direct with stiffnesses.

Second, older data is often given in imperial units. Conversion is of course simple, but direct comparison, for instance to gauge if two data sets are related, is cumbersome.

Third, certain terms can be given relative to a leading term, often the Young's modulus along a leading direction. Again, conversion is very easy, but direct comparison is hampered.

Fourth, different frames of reference can be chosen. Often the first direction (x, or 1) corresponds to the longitudinal axis, and the second and third corresponds to the radial and tangential axes, which is denoted by LRT Table 1. But this is by no mean systematic and several authors use LTR and RTL representations.

When we display the collected information in Supplementary Table 1, we choose the RTL representation. First of all, it makes sense for the longitudinal axis to be in the z direction, as would happen in a natural tree trunk. Secondly, this representation is better adapted to conversion to tetragonal and hexagonal systems, where the less symmetric direction is conventionally along z.

Fifth, certain authors use the non-conventional definition for Poisson's ratio $\nu_{ij} = -\frac{\varepsilon_i}{\varepsilon_j}$ instead of the more commonly used $\nu_{ij} = -\frac{\varepsilon_j}{\varepsilon_i}$.

#### 2.1.2. Data sources

Metadata for the different data sources are compiled in Table 1.

The primary sources can be relatively large databases, in which case their naming code references the principal author, sometimes arbitrarily (They can also correspond to collections of articles from university research groups and the naming codes reflect this).

In several cases, a reference uses data from one or more earlier source, but presents it in a different format, and sometimes without proper, detailed, attribution. The oft used "Wood Handbooks" are especially bad in this respect. Because of the relative difficulty in tracing data interrelations as mentioned in Section 2.1.1, Table 1 also contains some of these those secondary sources (in italics), but notes which primary sources they refer to.

Some important works (principally Bodig [24], also Guitard [25]) also used statistical analyses to derive formulae to relate elastic properties to density, and tabulated the corresponding elastic properties for many more wood species. We have decided against using these, and they are not counted in the numbers of hard or soft wood species given in Supplementary Tables 1 and 2.

### 2.2. Experimental approaches

Several approaches have been used to measure the elasticity of wood, from many variations of the direct, "static" method (tension, compression, three point bending, all sort of sample shapes) to acoustic methods. In this study, we do not take into account the type of experimental methods by which the elastic tensor has been determined. Very preliminary analyses do not seem to identify major differences between methods, and all seem to show the existence of NPR. It might be interesting in further work to study more finely the effect of the experimental

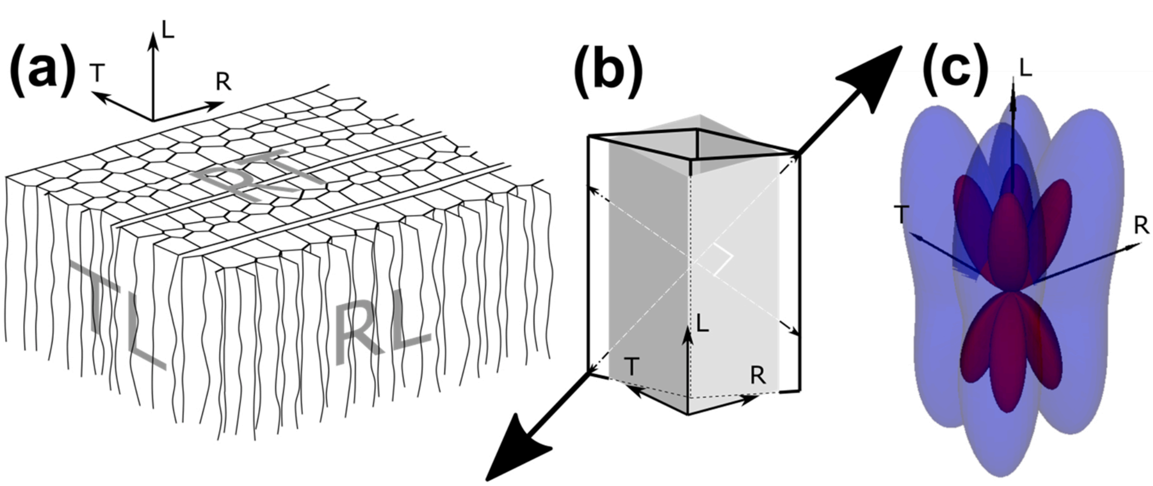


**Fig. 1. Models of wood.** (a) A diagram of cells arrangement and anatomical directions in a typical softwood, L longitudinal, R radial, T transverse. (b) An idealised model of a single wood cell as a thin-walled prismatic tube, illustrating NPR under off axis loading; a "diagonal" extension of the initial square-section tube (solid grey) leads to flattening into a diamond-section tube (wireframe) and to dimension changes. (c) A 3D Plot of Poisson's ratio for Douglas Fir, where the blue envelope represents the maximum value and the red the minimum, negative value.

**Table 1**
Main data sources for elastic properties of wood (Hardwood HW, Softwood SW).

| Code | Date | #HW | #SW | Data type | Units | Directions | References | Notes |
|---|---|---|---|---|---|---|---|---|
| A_Hearmon 1–29 | 1948 | 18 | 11 | *E, G, ν*, absolute | IS | LRT | [23] | Repository of earlier measurements by several groups, too many to reference here. |
| B_Bodig 30–58 | 1973 | 5 | 24 | *E, G, ν*, absolute | Imperial | LRT | [24] | i) Aspen2 has a badly conditioned tensor<br>ii) Many more of the results in this paper are predictions based on density |
| C_Guitard 59–81 | 1987 | 21 | 2 | *E, G, 1/*$S_{ij}$, absolute | IS | RTL | [25] | In French |
| D_Bucur 82–87 | 1984, 2016 | 3 | 3 | *C, G, ν*, absolute | IS | LRT | [26] | |
| E_Yamai 88–96 | 1957 | 5 | 4 | *E, G, ν*, $S_{ij}$ absolute | IS | LTR | [18] | 2 extra HW (Yachidamo and Makaba, but with incomplete tensor) |
| F_Mascia 97–105 | 1991 | 8 | 1 | *E, G, ν*, absolute | IS | LTR | [27] | In Portuguese |
| G_Zuerich 106–153 | 2008–2017 | 38 | 10 | *E, G, ν*, absolute | IS | LRT | [28–35] | Nonstandard definition of Poisson's ratio |
| H_Wang 154–158 | 2004 | 5 | 0 | *E, G, ν*, absolute | IS | LTR | [36] | All $G_{TL}$ and $G_{LR}$ are identical |
| I_Campinas 159–170 | 2011, 2014 | 0 | 12 | *E, G, ν*, $C_{ij}$ absolute | IS | LRT | [37,38] | 2011 Ultrasonic and Static methods<br>2014 All Ultrasonic, both on Discs and Polyhedra |
| J_Various 171–185 | 2014–2017 | 8 | 7 | Various but usually *E, G, ν*, absolute | IS | LRT, LTR, RTL | [39–44] | [40]: rare results on green wood, which do seem to behave differently |
| *Handbook1987* | *1987* | | *7* | *E, G, ν, relative* | *N/A* | *LTR* | | *Secondary source, copies Hearmon [23] and Bodig [24]* |
| *Handbook1999* | *1999* | *15* | *20* | *E, G, ν, relative* | *N/A* | *LTR* | | *Idem* |
| *Handbook2010* | *2010* | | | *E, G, ν, relative* | *N/A* | *LTR* | | *Idem* |
| *Goodman* | *1970* | *6* | *6* | *E, G, ν, absolute* | *Imperial* | *LRT* | | *Same values as Bodig [24], some Poisson's ratio missing* |

method on the existence, preponderance and directionality on NPR in wood.

### 2.3. Calculation of off-axes Poisson's ratio

On-axes Poisson's ratios, for instance $\nu_{xy}$, can be obtained directly from the components of the compliance tensor $S$ as

$$\nu_{xy} = -\frac{S_{12}}{S_{12}}, \tag{1}$$

where the Voigt notation is used to flatten the dimension 3, order 4 tensor into a dimension 6, order 2 matrix.

Off-axes Poisson's ratios require two perpendicular directions, longitudinal and transverse. These can be represented by vectors $\boldsymbol{l}$ and $\boldsymbol{t}$ whose spherical coordinates can be given in terms of the standard Euler angles $\theta$, $\varphi$ and $\chi$ as

$$\boldsymbol{l} = \begin{pmatrix} \sin\theta\cos\varphi \\ \sin\theta\sin\varphi \\ \cos\theta \end{pmatrix} = \begin{pmatrix} r_{11} \\ r_{12} \\ r_{13} \end{pmatrix}$$

$$\boldsymbol{t} = \begin{pmatrix} \cos\theta\cos\varphi\cos\chi + \sin\varphi\sin\chi \\ \cos\theta\sin\varphi\cos\chi - \cos\varphi\sin\chi \\ -\sin\theta\cos\chi \end{pmatrix} = \begin{pmatrix} r_{21} \\ r_{22} \\ r_{23} \end{pmatrix}. \tag{2}$$

These two vectors are also the first two columns of the rotation matrix $[\boldsymbol{r}]$ (the third column vector is not required for Poisson's ratios, see Eq. (4)).

The compliance tensor $\boldsymbol{S}$ transforms in the new basis set formed by $\boldsymbol{l}$ and $\boldsymbol{t}$ as

$$S'_{\alpha\beta\gamma\delta} = r_{\alpha i} r_{\beta j} r_{\gamma k} r_{\delta l} S_{ijkl}. \tag{3}$$

And finally, Poisson's ratio for any two directions is given by

$$\nu(\boldsymbol{l},\boldsymbol{t}) = -\frac{S'_{12}(\theta,\varphi,\chi)}{S'_{11}(\theta,\varphi)} = -\frac{l_i l_j t_k t_l S_{ijkl}}{l_i l_j l_k l_l S_{ijkl}}. \tag{4}$$

This procedure is automated in our dedicated ElAM code [45], and the extrema of Poisson's ratio for all directions were calculated from the axial elastic data The relevant ElAM database and input files are available as part of the supplementary information (files "db_ALL.txt" and "ALL.txt").

## 3. Results

The values for the density, Ledbetter anisotropy ratio [46], extrema of Poisson's ratio and corresponding directions for 185 wood samples from the literature were calculated with the ElAM code [45] and are given in Supplementary Table 2. Selected results for ten representative samples are given here in Table 2. The softwoods are almost all auxetic, as all but three samples (94%) exhibit NPR. Values range from −3.32 to 0.03, with an average of − 1.01 and a median of − 0.91. The maximum values are also rather large, from 0.47 to 4.07. The hardwood samples are also mostly auxetic, but not quite so systematically (72%), and the Poisson's ratios are generally higher than for the softwood, varying between − 2.76 and 0.11 (average −0.21 and median −0.15).

Fig. 2 shows how the minimum Poisson's ratio varies with the density (a) and anisotropy ratio (b) of the sample. The results are scattered, but auxeticity tends to occur only below a certain density threshold (around 0.8 kg/dm$^3$). With a few exceptions, samples with a Ledbetter anisotropy ratio above 8 are auxetic, and higher anisotropy correlates with more pronounced auxeticity.

As wood is a natural material, intra-specie variability is expected, even within a single tree. In addition, different experimental techniques might produce slightly different results. Supplementary Tables 3 to 9 show the elastic results, grouped by species, for 7 of the most commonly studied wood species (Spruce, Pine, Douglas fir, Beech, Oak, Ash and Birch). The elastic results for all 15 samples of Spruce are reproduced here in Table 3. The inclusion of subspecies is somewhat arbitrary, but in general the results are consistent, with one or two exceptions (the early acoustic measurements by the Bucur group (code D) looking particularly out of place).

Auxeticity in wood is highly localised, and in order to better understand the possible mechanisms it is useful to qualify the directions of minimum Poisson's ratio. These can be given in term of the Euler angles $\theta$ and $\varphi$, or more synthetically in term of anatomical directions. Thus, a direction code is constructed first by the sign of the Poisson's ratio (- or +), followed by one letter if on an anatomical axis, two letters if in a plane, or RTL if in a generic direction.

Around 52% of the samples (71% of the softwoods, 42% of the hardwoods) have NPR in a generic direction (code "-RTL"), but the distribution is very narrow with a ($\theta$, $\varphi$) range of (16°-31°, 40°-50°) for the softwoods (ignoring two outliers) and (22°-44°, 41°-68°) for the hardwoods. This corresponds to an average direction at (22°, 46°) with an average deviation of 3.4° (maximum 8.2°) for the softwoods and an average direction at (33°, 50°) with an average deviation of 11°

**Table 2**
Density, anisotropy ratio, Minimum Poison's ratio and direction code for 10 selected wood samples. Full list in Supplementary Table 2.

| ID # | ID name | Specie | $\rho$ (g/cm$^3$) | $A^*$ | $\nu_{min}$ | Dir. |
|---|---|---|---|---|---|---|
| 5 | Spruce1_A | *Picea spp.* | 0.37 | 191.2 | -2.49 | -RTL |
| 91 | Akamatsu_E | *Pinus densiflora* | 0.46 | 81.2 | -1.41 | -RTL |
| 36 | DouglasFir1_B | *Pseudotsuga menziesii* | 0.47 | 63.7 | -0.55 | -RTL |
| 110 | Yew_G | *Taxus baccata* | 0.62 | 15.0 | -0.70 | -TL |
| 14 | Balsa1_A | *Ochroma pyramidale* | 0.1 | 80.6 | -0.88 | -RTL |
| 156 | Birch_Japanese_white_3_H | *Betula platyphylla* | 0.6 | 7.71 | -0.04 | -RTL |
| 119 | Ash_b_G | *Fraxinus excelsior* | 0.6 | 10.85 | -0.14 | -TL |
| 75 | Hetre_C | *Fagus sp.* | 0.63 | 12.7 | -0.07 | -TL |
| 96 | Ichiigashi_E | *Quercus gilva* | 0.84 | 15.2 | 0.01 | +RTL |
| 161 | CupiubaU_2011_I | *Goupia glabra* | 0.85 | 3.06 | 0.07 | +T |

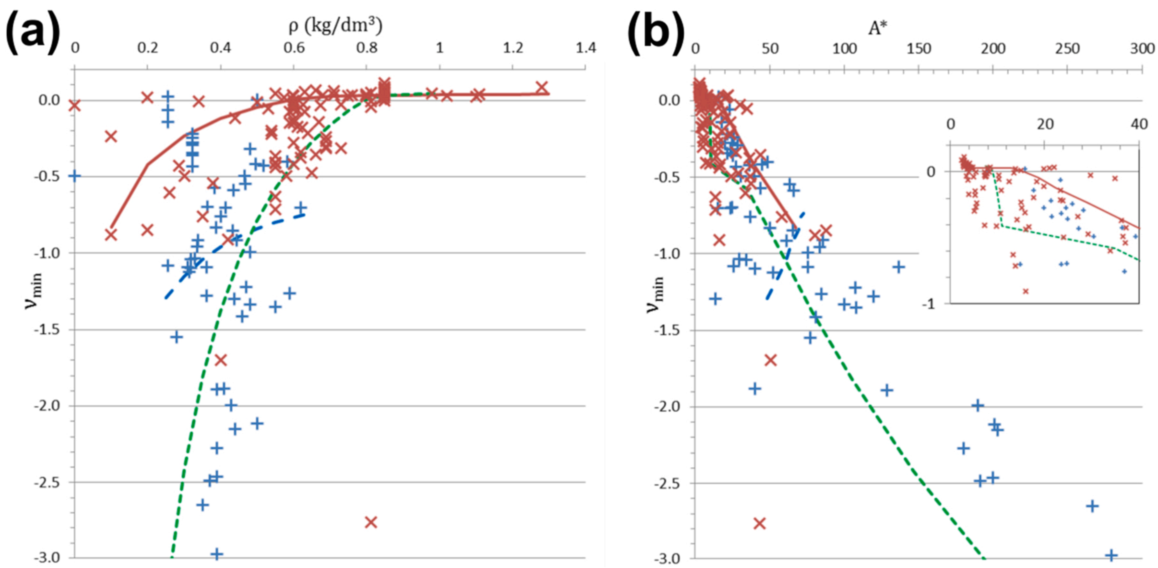


**Fig. 2. Minimum Poison's ratio variability in wood.** The blue "+ " and red "× " symbols refer to experimental data for softwood and hardwood. The long-dash blue line and continuous red line derive from the statistical models of Guitard [25] for softwood and hardwood. The short-dash green line come from the honeycomb model of Gibson [47] for all wood. (a) As a function of wood density. In general, lighter wood are more likely to exhibit pronounced NPR. (b) As a function of the anisotropy ratio (Ledbetter formulation [46]); more anisotropic woods exhibit more pronounced NPR, in line with other materials [3].

**Table 3**
Auxetic properties of spruce samples.

| ID # | Code | Specie | $\rho$ (g/cm$^3$) | $A^*$ | $\nu_{min}$ | Dir. |
|---|---|---|---|---|---|---|
| 53 | Spruce_engelman1_B | *Picea engelmannii* | 0.31 | 52.5 | -1.13 | -RTL |
| 56 | Spruce_engelman4_B | *Picea engelmannii* | 0.32 | 39.9 | -1.10 | -RTL |
| 54 | Spruce_engelman2_B | *Picea engelmannii* | 0.32 | 34.5 | -1.04 | -RTL |
| 55 | Spruce_engelman3_B | *Picea engelmannii* | 0.33 | 29.8 | -1.04 | -RTL |
| 57 | Spruce_sitka_B | *Picea sitchensis* | 0.36 | 119.6 | -1.28 | -RTL |
| 5 | Spruce1_A | *Picea spp.* | 0.37 | 191.20 | -2.49 | -RTL |
| 11 | Spruce_sitka_A | *Picea sitchensis* | 0.39 | 128.60 | -1.89 | -RTL |
| 90 | Yezomatsu_E | *Picea Jezoensis* | 0.39 | 279.30 | -2.98 | -RTL |
| 8 | Spruce4_A | *Picea spp.* | 0.39 | 180.30 | -2.27 | -RTL |
| 7 | Spruce3_A | *Picea spp.* | 0.39 | 200.00 | -2.46 | -RTL |
| 83 | Spruce_D | *Picea* | 0.41 | 40.32 | -1.94 | -TL |
| 9 | Spruce5_A | *Picea spp.* | 0.43 | 189.80 | -1.99 | -RTL |
| 10 | Spruce6_A | *Picea spp.* | 0.44 | 203.10 | -2.15 | -RTL |
| 111 | Spruce_G | *Picea abies* | 0.47 | 107.60 | -1.22 | -RTL |
| 6 | Spruce2_A | *Picea spp.* | 0.5 | 201.20 | -2.11 | -RTL |
| Average | | | **0.39** | **133.14** | **-1.81** | |
| St. Dev. | | + /- | **0.06** | **79.89** | **0.63** | |

(maximum 22º) for the hardwoods. If NPR does not occur in this narrow "cone", it then occurs predominantly in the TL plane (SW 21%, HW 26%). Four hardwood have minimum NPR in the RL direction and one softwood in the L plane.

## 4. Discussion

### 4.1. Idealised hollow-cell model

Most wood cells are essentially slender hollow "tubes", with cross sections of varying shape, mostly irregular hexagons or parallelograms.

In this study, we chose a regular square cross-section but a regular hexagonal cross-section leads to the same results for Poisson's ratio (see the closely related geometrical model in reference [21]). Fig. 3 depicts such an idealised cell, where the model consists of four rigid plates, linked by flexible linear hinges.

It is surprisingly simple to explain the presence of auxeticity in all but a few woods with a very simple geometric model of a wood cell that could be made in minutes with a sheet of paper/card and tape/glue. Manually applying a tensile load (basically pulling the cell) along two diametrically opposite corners naturally flattens it, which produces both negative and positive Poisson's ratio in the two main transverse directions.

More formally, most simple loads (except directly along the axes) affect the hinges and essentially flatten the cell in the load plane if tensile or the plane normal to the load if compressive. In the interest of simplicity, we consider a load across two diametrically opposite corners. This load could be tensile or compressive, it does not matter, and Fig. 1 illustrates a tensile load resulting in a flattening of the cell and therefore a positive Poisson's ratio in the transverse direction perpendicular to the plane of Fig. 3(b) but also a negative one in the transverse direction within the plane of Fig. 3(b). The resulting Poisson's ratio $\nu_{lt}$ can be expressed as the opposite of the quotient of the transverse strain to the longitudinal strain and simplifies to

$$\nu_{lt} = -\frac{\varepsilon_t}{\varepsilon_l} = -\frac{\Delta t/t}{\Delta l/l} = -\frac{\Delta t/\Delta l}{t/l} = -\frac{\tan(\theta)}{\tan(\theta)} = -1, \tag{1}$$

where $\theta$ is the angle between the long diagonal and the base plane, $t$ and $l$ are the initial dimensions and $\Delta t$ and $\Delta l$ are the changes in dimension.

This simple model shows that $\nu_{lt} = -1$ for a single cell. But the argument still holds if the original undeformed square tube is replaced by an array of square tubes. This suggests that off-axis NPR is intrinsic to anisotropic thin walled cellular structures. Although the derivation is done here for a load along diametrically opposite corners of the hollow cell, it is also valid for any angle (except 0° or 90°), as one can just consider a section of the cell. At 0° or 90°, hinging does not occur, and the Poisson's ratio is 0. Even if some form of buckling is likely to occur above some critical loads, it would affect the Poison's ratio of a single cell, but not of an array of cell.

This $\nu_{lt} = -1$ value relies on perfect hinging at the walls' intersection, which becomes less realistic as the wall thickness (and therefore wood density) increases.

### 4.2. Density dependent models

This simple geometric model explains much, but leaves some unanswered questions: What about the variation with direction? What about NPR below − 1? What of NPR in the TL plane? Two types of models of the elastic properties of wood can shed light on directionality and bounding values of NPR. The first type is essentially statistical and aims to find functions that fit observed data, for hardwoods and softwoods [24,25], while the second derives the elastic tensor from a model honeycomb [47,48]. More sophisticated developments [49] of these models use finite element analysis to consider realistic irregular honeycomb geometry and the anisotropy of the wood cell but are thus limited to single species and not useful to our purpose. The resulting auxetic properties for the statistical model of Guitard (hardwood and softwood) and first principle model of Gibson (generic wood) are given in Table 4 and shown in Fig. 2. The models capture the most salient trends well and predict NPR for densities below 0.6 (Guitard) and 0.8 (Gibson) and anisotropy indices above 5 and 20. NPR can certainly take values below − 1, for densities below 0.35 (Guitard) or 0.45 (Gibson). When NPR is present, it is always minimum in an off-axis direction ("-RTL" code). At low densities, NPR bleeds into the anatomical planes RL and TL, albeit with reduced magnitude: in the TL plane at densities below 0.5, from 54% of the off-axis minimum at 0.25 to 16% at 0.5 with the Gibson model and from 46% to 6% with the Guitard model of softwood. This confirms previous in-plane observations, and corroborates Hearmon's early suggestions of NPR in the TL planes, even if auxeticity is more pronounced in off-axis directions. Still, the models do not predict minimum NPR in TL planes: we suspect that lengthy and detailed finite element simulations of realistic wood models might be required to address this level of subtlety.

## 5. Conclusion

This meta-study shows that NPR is present in many woods, albeit mostly in off-axis directions. The property is so prevalent that it occurs in 87 out of 123 measured hardwood samples and 58 of 62 softwood samples. Almost all woods of density lower than 0.8 $kg.l^{-3}$ are auxetic. The lowest value is − 3.32, for *Crypteria Saponica*, and values below − 1.0 are very frequent. A very simple geometric model illustrates how

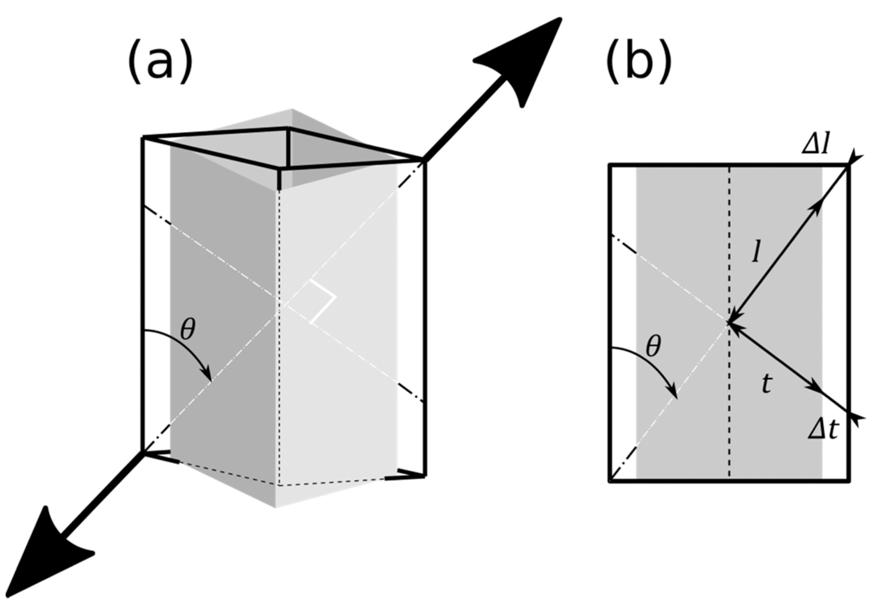


**Fig. 3.** Deformation of an Idealised wood cell model of square section subjected to a diagonal tensile load. The initial undeformed cell is represented by grey walls and thin dashed lines, and the deformed elongated cell by a wireframe of full lines. (a) shows the tensile load in 3D, (b) shows a projection and relevant dimensions.

**Table 4**
Database of auxetic properties for the Guitard and Gibson models.

| | $\rho$ (g/cm$^3$) | A* | $\nu_{min}$ | $\theta$ (°) | $\varphi$ (°) | Dir. |
|---|---|---|---|---|---|---|
| Guitard, statistical model, power laws, Hardwood | 0.1 | 67.56 | -0.83 | 23 | 47 | -RTL |
| | 0.2 | 39.41 | -0.42 | 27 | 50 | -RTL |
| | 0.3 | 28.99 | -0.23 | 30 | 52 | -RTL |
| | 0.4 | 22.37 | -0.12 | 33 | 52 | -RTL |
| | 0.5 | 18.63 | -0.04 | 39 | 54 | -RTL |
| | 0.6 | 15.42 | 0.01 | 47 | 56 | +RTL |
| | 0.7 | 12.98 | 0.03 | 90 | 90 | +T |
| | 0.8 | 11.02 | 0.03 | 90 | 90 | +T |
| | 0.9 | 4.07 | 0.03 | 90 | 90 | +T |
| | 1 | 3.88 | 0.03 | 90 | 90 | +T |
| | 1.1 | 3.71 | 0.04 | 90 | 90 | +T |
| | 1.2 | 3.57 | 0.04 | 90 | 90 | +T |
| | 1.3 | 3.44 | 0.04 | 90 | 90 | +T |
| Guitard, statistical model, Linear, Softwood | 0.25 | 48.45 | -1.29 | 23 | 50 | -RTL |
| | 0.3 | 55.99 | -1.15 | 23 | 49 | -RTL |
| | 0.35 | 60.94 | -1.04 | 23 | 47 | -RTL |
| | 0.4 | 63.98 | -0.96 | 23 | 47 | -RTL |
| | 0.45 | 66.87 | -0.89 | 23 | 45 | -RTL |
| | 0.5 | 69.40 | -0.84 | 23 | 45 | -RTL |
| | 0.55 | 70.13 | -0.80 | 23 | 43 | -RTL |
| | 0.6 | 70.52 | -0.76 | 23 | 43 | -RTL |
| | 0.65 | 72.89 | -0.74 | 23 | 43 | -RTL |
| Gibson first principles honeycomb model | 0.1 | 216.90 | -3.28 | 17 | 47 | -RTL |
| | 0.3 | 146.70 | -2.42 | 19 | 47 | -RTL |
| | 0.35 | 105.30 | -1.82 | 20 | 47 | -RTL |
| | 0.4 | 78.70 | -1.38 | 22 | 47 | -RTL |
| | 0.45 | 60.76 | -1.05 | 23 | 47 | -RTL |
| | 0.5 | 46.48 | -0.79 | 24 | 47 | -RTL |
| | 0.55 | 34.93 | -0.58 | 26 | 47 | -RTL |
| | 0.6 | 10.94 | -0.41 | 28 | 47 | -RTL |
| | 0.65 | 10.44 | -0.28 | 31 | 47 | -RTL |
| | 0.7 | 9.95 | -0.16 | 33 | 47 | -RTL |
| | 0.75 | 9.48 | -0.07 | 37 | 47 | -RTL |
| | 0.8 | 9.02 | 0.00 | 46 | 47 | +RTL |
| | 0.85 | 8.58 | 0.03 | 90 | 47 | +TR |
| | 0.9 | 8.16 | 0.04 | 90 | 47 | +TR |
| | 0.95 | 7.76 | 0.04 | 90 | 47 | +TR |
| | 1 | 7.38 | 0.05 | 90 | 47 | +TR |

the tubular structure of the wood cells automatically generates NPR.

This suggests that truly large scale auxetic parts (beams, panels.) can be fabricated at low cost, as timber is a cheap material.

In addition, the nature of the mechanism responsible for NPR, based on the shape and hollowness of the cells, is such that it is likely to lead to comparable effects in man-made materials.

## 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.

## Data availability

The data are shared as supplementary Information.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.mtcomm.2023.105810.

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