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Wood compression in four-dimensional in situ tomography

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Wood deformation, in particular when subject to compression, exhibits scale-free avalanche-like behavior as well as structure-dependent localization of deformation. We have taken three-dimensional (3D) x-ray tomographs during compression with constant stress rate loading. Using digital volume correlation, we obtain the local total strain during the experiment and compare it to the global strain and acoustic emission. The wood cells collapse layer by layer throughout the sample starting from the softest parts, i.e., the spring wood. As the damage progresses, more and more of the softwood layers throughout the sample collapse, which indicates damage spreading instead of localization. In 3D, one can see a fat-tailed local strain rate distribution, indicating that inside the softwood layers, the damage occurs in localized spots. The observed log-normal strain distribution is in agreement with this view of the development of independent local collapses or irreversible deformation events. A key feature in the mechanical behavior of wood is then in the complex interaction of localized deformation between or among the annual rings.

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Introduction. Damage localization in materials under compressive loading leads to unpredictable behavior, which, in recent years, has been an active area of research in theoretical [1–3], numerical [4], as well as experimental studies of, e.g., rocks [5,6], porous materials [7], solid foams [8,9], and wood [10]. Compared to tensile failure, compression is particularly interesting as structures can carry load even after deforming [11] through frictional contacts. Here, we take an ordinary wood sample as an example of a heterogeneous cellular material [12] and crush it under constant stress rate loading, while recording the three-dimensional (3D) deformation using fast synchrotron tomography.

X-ray tomography [13,14] has been growing in popularity as a research tool for material science. It is a method for acquiring 3D images of samples and, in *in situ* setups, can provide sequences of 3D images during an experiment (4D imaging). It has been extensively used, e.g., to observe faulting in rock fractures [15–19] where the focus is on determining the locations of microcracks, which can be done directly from the reconstructed volumes by image segmentation [20].

Used in conjunction with tomography, digital volume correlation (DVC) [21] is a powerful method for determining the local strains in 3D from a set of tomography images. It has been used to study the deformation of a wide variety of different materials, such as metals [22], composites [23,24], bone [25,26], and coal [27]. The advances in computational capabilities now enable the DVC determination of strain fields even for a large number of tomography images, which, with fast tomography, leads to a good time resolution of the 4D imaging. Our test material wood is a ubiquitous biological material with a cellular structure. The arrangement of wood cells depends on the annual growth cycle, which leads to a complex hierarchical structure of alternating softwood and hardwood layers [28,29]. This macroscopic structure—annual rings—and especially its orientation [30] have a large effect on the mechanical properties of wood.

In our previous work [10], we studied the avalanche behavior in wood compression using digital image correlation (DIC) and acoustic emission (AE). Scale-free avalanche behavior, or crackling noise [31], was observed in terms of the AE energies reminiscent of compression of porous brittle media [7,32] and earthquakes [33]. However, concomitantly, we also observed structure-dependent strain localization (collapse of softwood layers), which somewhat contradicts this scale-free picture.

The aim of this Letter is to explore the time evolution of this structure-dependent localization in 3D. The main goal is to determine if imaging the whole bulk sample instead of just one surface yields additional information and if this information can be used to explain the disconnect between structure-dependency and scale-free behavior.

Methods. The experiments were performed on the ID15A beam line at the European Synchrotron Radiation Facility (ESRF). The experimental setup consists of a compression device similar to the Mjölnir device [34] and the whole setup is shown in Fig. 1(a). Our compression device consists of two individually rotating parts coupled together via cables. The bottom part lies on the rotation stage of the beam line and houses a rotationally symmetric sample holder, a compression piston, a load sensor, and a displacement sensor. The top part is rotated separately from the bottom part using a stepper motor and it houses the data acquisition units, power supply, and a WiFi connection to the control hutch.

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FIG. 1. (a) The experimental setup showing the bottom part on the rotation stage of the beam line and the top part above as well as the coupling of the two parts. (b) An image of a sample used, showing a typical annual ring structure. (c) The measured stress-strain curves (gray) and the imaged portion of the compression (colored) for the three experiments considered. The following figures focus on the experiment plotted in blue. (d) The reconstructed sample volume.

The samples [seen in Fig. 1(b)] were $6.2 \pm 0.3 \times 6.2 \pm 0.1 \times 5.9 \pm 0.2$ mm cubes (in order of height, width, depth, and compressed from the top) of dry pine (*Pinus sylvestris*), which means that in a sample, one has 4–6 annual rings. The compression is applied in the direction perpendicular to this annual ring orientation, although there is a slight

angle between the compression direction and the annual ring orientation.

The samples were compressed using a constant stress rate corresponding to a force rate of 3 N/s, which results in a stress rate of 82 ± 3 kPa/s. We record the global deformation of the sample using the displacement sensor (giving the engineering strain $\epsilon = d/h$, where *d* is the displacement and *h* the initial sample height) and the load sensor (giving the engineering stress $\sigma = F/A$, where *F* is the applied force and *A* the initial cross-sectional area of the sample). This gives us a time series for the strain ϵ and stress σ recorded at a frequency of 102.4 kHz [see Fig. 1(c)]. After an application of a moving average, a strain rate $\dot{\epsilon}$ was calculated from the strain time series using numerical differentiation.

Due to the large amount of data produced, only part of the tomography data for the whole compression was recorded, namely, part of the initial elastic regime, and the final densification regimes were discarded. The camera of the beam line operates with an acquisition frequency of 500 Hz and the rotation stage performs half a rotation per second, leading to a time resolution of one full tomography image per second and an angular resolution of 0.36 degrees per projection. The imaging resolution (voxel size) is 11 μ m and the region of interest in the DVC computations is a cube with side length of 10 voxels (110 μ m). These regions of interest are placed 6 voxels apart, giving a DVC resolution of 66 μ m.

The reconstructions of the 3D volumes from the projection data were done using the simultaneous iterative reconstruction technique (SIRT) algorithm implemented in the ASTRA TOOLBOX [35–37]. The reconstructions [an example can be seen in Fig. 1(d)] were computed from 500 projection images spanning a 180 degree rotation. The DVC calculations were done using the AL-DVC software [38] and they result in a displacement vector \boldsymbol{u} for each point from which the 3D Green-Lagrange strain tensor,

$$\epsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_k}{\partial x_i} \frac{\partial u_k}{\partial x_j} \right), \tag{1}$$

can be computed. From this tensor, one can compute various strain invariants [39], such as the volumetric strain ϵ_{vol} and the shear invariant (second invariant of the deviatoric strain tensor) ϵ_{shear} . The results that we show here take both of these deformation modes into account by computing the total strain invariant, $\epsilon_{tot} = \sqrt{\epsilon_{vol}^2 + \epsilon_{shear}^2}$. Additionally, the local total strain rate $\dot{\epsilon}_{tot}$ is computed from the total strain at successive time steps using numerical differentiation.

Results. Due to the high computation time of the DVC calculations, three experiments were picked from a larger dataset for a full DVC analysis. The stress-strain curves obtained from the experiments can be seen in Fig. 1(b) and colored points in the plots correspond to single reconstructed tomography images. The curves clearly show the three distinctive regimes: initial elastic behavior, the compaction with clear intermittent spikes in the strain rate (corresponding to avalanche-like behavior [10]), and the final densification. In what follows, we focus on one representative sample (similar data for other samples can be seen in the Supplemental Material [40]).

The time evolution of the local total strain ϵ_{tot} can be seen in Fig. 2. One can clearly see the structure-dependent



FIG. 2. The time evolution of the strain in the wood sample. The color code indicates the local total strain. The damage starts from hot spots in the softwood layers and then spreads throughout the layer and to the other softwood layers.

behavior of wood—the wider softwood layers get compressed much more, while the narrower hardwood layers maintain their shape. The damage starts from hot spots in the softwood layers and then spreads throughout the layer as well as the other softwood layers. The mechanism does not seem to be damage propagation, rather new hot spots pop up at different parts of the layers.

While the strain localization in planes that correspond to the orientation of the annual rings is clearly visible to the naked eye, this can be seen even more clearly by computing the spatial autocorrelation function of the local total strain,

$$C(s) = \langle \epsilon_{\text{tot}}(r) \epsilon_{\text{tot}}(r+s) \rangle_{r}, \qquad (2)$$

which can be seen in Fig. 3(a). To observe the time evolution of the localization, we fit a plane that corresponds to this orientation of high local strains [the blue plane in Fig. 3(a)] and do a dimensionality reduction by projecting the voxel position vectors \mathbf{r} to the line given by the unit normal of the plane $\hat{\mathbf{n}}$. Taking the average of the local total strain $\langle \epsilon_{\text{tot}} \rangle$ in 100 bins along this single dimension shows the localization evolution in the annual rings in a spacetime plot [top of Fig. 3(b)].

While the evolution of local strain starting from the softwood parts of the annual rings closer to the top of the sample can already be seen from the previous figure, it can be further quantified by computing a localization measure. Here we use the the normalized standard deviation of this reduced quantity $\langle \epsilon_{tot} \rangle$ and define the localization measure as

$$\gamma = \frac{\Delta \langle \epsilon_{\rm tot} \rangle}{\langle \langle \epsilon_{\rm tot} \rangle \rangle},\tag{3}$$

where $\Delta \langle \epsilon_{\text{tot}} \rangle$ denotes the standard deviation of the average local total strain over all the bins along the dimension given by $\mathbf{r} \cdot \hat{\mathbf{n}}$, and $\langle \langle \epsilon_{\text{tot}} \rangle \rangle$ denotes the average of the average total strain over all the bins. The evolution of this localization parameter can be seen in Fig. 3(c) and it shows two things: first, after an initial regime of localization due to damage nucleation, the value of the localization parameter decreases, signifying strain delocalization. Second, the spreading of damage from one annual ring to another can be seen as a dip in the localization parameter. It is noteworthy that the changes in the parameter are fairly small.

The avalanche-like behavior in the compaction regime (second regime, flat part of the stress-strain curves) can be seen as spikes in the global strain rate [see Fig. 4(a)]. The local total strain rate distribution in the sample is fairly wide (fat-tailed) and this can be quantified by computing the normalized

standard deviation of the local total strain rate, $\Delta \dot{\epsilon}_{tot} / \langle \dot{\epsilon}_{tot} \rangle$. Plotting this next to the global strain rate (see Fig. 4) shows that their time evolutions correlate very strongly, indicating



FIG. 3. (a) The autocorrelation function *C* [Eq. (2)] of the local total strain field computed in a $0.44 \times 0.44 \times 0.44$ mm box, showing the alignment of the correlations with the orientation of the annual rings. The blue plane is fitted to this annual ring orientation (direction of high correlations) and is used for the dimensionality reduction in (b). (b) A spacetime plot of the average local strain $\langle \epsilon_{tot} \rangle$ in the direction perpendicular to the fitted plane [see (a)], described by the projection of the position vector \mathbf{r} onto the unit normal of the plane $\hat{\mathbf{n}}$. The time value t = 0 s corresponds to the start of the test and tomography images are collected only after approximately 15 s. (c) The localization measure η as a function of strain.



FIG. 4. (a) The global strain rate $\dot{\epsilon}$ as a function of time, showing the large variations (spikes) corresponding to the avalanches in the compaction regime. (b) The standard deviation of the local total strain rate normalized by its average as a function of time, showing large local variations.

that the avalanches are accompanied by large local variations in the local strain rate. By computing the 1% and 10% fractiles of the local total strain, we have verified that the general strain behavior can be seen to correspond fairly well to the behavior of the 1% fractile and only to a lesser extent to the behavior of the 10% fractile.

Finally, we compute the probability density functions of local strain at each time step (see Fig. 5). The shape of the distributions seems close to a log-normal distribution, except for a large spike at high strains at later stages of the experiments. The spike corresponds to regions of very high strains where the accuracy of the DVC algorithm gets reduced, resulting in strains of unity. Discarding this final spike and computing a maximum likelihood fit (orange lines) indeed shows that the log-normal distribution fits the data well.

Conclusions. We have studied the time evolution of local strain in a wood sample under compression using fast 4D *in situ* tomography and DVC. After an initial elastic regime, we observe a compaction regime where the deformation is intermittent (strain rate spikes) and starts from "soft spots" in the softwood layers of the annual rings. These spikes



FIG. 5. The probability density functions of the local total strain (blue dots) at three points in time: (a) t = 20 s, (b) t = 45 s, and (c) t = 73 s, as a function of the normalized total strain $\epsilon_{tot}/\langle \epsilon_{tot} \rangle$ and a log-normal fit (orange line).

have previously [10] been shown using AE to correspond to avalanche-like behavior with scale-free size statistics. We note that the samples used here are several millimeters smaller than the ones in Ref. [10].

Although most of the deformation is observed localized into the softwood layers, what we actually observe considering the whole 3D local strain field is a spreading of the strain to all the softwood layers, instead of strain localization. The avalanches correlate well with large variations in the local strain rate, suggesting localized avalanches. We interpret this to mean that the localization is happening in regions on planes parallel to the annual ring orientation. Any kind of dimensionality reduction (to 2D or 1D) hides this and shows only the strain spreading into all the annual rings. The observed localization behavior shows that a key feature in the mechanical behavior of wood is the complex interaction between the annual rings. The localization in these is clearly not trivial and, in our small set of small samples, we do not get a comprehensive idea apart from the fact that this interaction does exist and it is important.

The log-normal form observed for the local strain distributions supports this interpretation as this distribution can result as a product of many random variables. Indeed, log-normal strain distributions have been observed in metals [41,42] as a "universal" distribution due to (plastic) strain accumulation. Also, in sea ice deformation, which shows similar fat-tailed local strain rate distributions, the multifractal behavior [43] of the strain rate fields has been mapped to a log-normal multiplicative cascade model [39]. This log-normal observation, however, leaves open the issue as to what happens to the local strain distribution close to failure as the increments become more correlated.

This view is also compatible with the previously observed robust power-law distribution for the AE energies irrespective of the event rate. The structure-dependent softwood layer collapses seem to manifest themselves only in the variations of the AE event rate.

Our results show that when considering inherently bulk phenomena (not just surface effects), such as avalanche behavior, the use of 3D imaging can be extremely useful in unveiling the true nature of the material behavior. An increase in the spatial and temporal resolution would still be needed for the direct observation of the avalanche phenomena in the sample. Likewise, the sample size could be increased well over the current one here.

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