Detection and assessment of wood decay using X-ray computer tomography

Megan McGovern[1], Adam Senalik[1], George Chen[2], Frank C. Beall[3], Henrique Reis[1*]
[1]Department of Industrial and Enterprise Systems Engineering,
University of Illinois at Urbana-Champaign, 104 S. Mathews Ave., Urbana, IL, USA 61801
[2]USDA Forest Products Laboratory,
1 Gifford Pinchot Dr., Madison, WI 53726
[3]Forest Products Laboratory, University of California at Berkeley,
1301 South 46th Street, Richmond, CA 94804

ABSTRACT

Loblolly pine (Pinus taeda) wood cube specimens were exposed to Gloeophyllum fungus (Gloeophyllum trabeum) for increasing periods of time ranging from one week to twelve weeks. The corresponding mass of each of these specimens was recorded before and after they were subjected to the controlled decay. X-ray computed tomography (CT) was then carried out. From the CT scans and recorded mass data, the specimens' corresponding volumes and densities were calculated. Blocks decayed for twelve weeks experienced, on the average, the greatest loss of mass (≈40%), volume (≈30%), and density (≈37%). The observations quantified the well-known effect of non-uniform decay, with the greatest occurring at the surface in contact with the fungi and decreasing to the opposite surface. Wood blocks subjected to controlled decay for twelve weeks lost 47% of density at the surface in contact with the fungi and 28% at the opposite surface, while blocks subjected to only one week of decay experienced over 5% density loss at the surface in contact with fungi and nearly 0% at the opposite surface. While the mass loss of specimens exposed to only one week of controlled decay was difficult to evaluate because of initial moisture absorption, these results indicate that x-ray CT can detect decay in wood specimens exposed to only one week of controlled decay using density measurements.

Keywords: Loblolly pine, wood, wood decay, rot, X-ray computed tomography, wood density.

1. INTRODUCTION

The process of wood decay in wooden structures jeopardizes their structural fitness-for-service creating risks to human life and property. There have been several attempts to inhibit the decay process from occurring altogether. However, the best preservative techniques available today have not been able to truly preserve wood or wood composites against the natural process of decay. Such attempts such as the use of wood preservatives may delay the wood decay process but so far do not prevent it. Wood decay causes the expenditure of significant financial resources annually in repair, rehabilitation and reconstruction efforts. For example, in the United States there are over 20 million wood utility poles for communication and power distribution purposes. These poles are commonly deteriorated by fungi, which effectively decays (or rots) the wood. Pacific Gas and Electric Company (PGE) owns approximately 2.4 million poles. Assuming an approximate replacement cost of $2,000/pole, 1% reduction of removals would save approximately $240,000 annually. The natural process of wood decay is also occurring on wooden bridges and real state structures, where million of dollars in wood real state transactions occur daily without being inspected for decay. This decay process decreases the dynamic strength of the wood considerably, which can lead to unexpected failures. For a comprehensive literature review of wood decay, the readers are referred to Beall and his associates[1-3], who provide an excellent literature review of wood decay in utility poles and in glulam beams.

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[*] Corresponding author. E-mail: h-reis@uiuc.edu; phone: 217 333-1228; fax: 217 244-5705.

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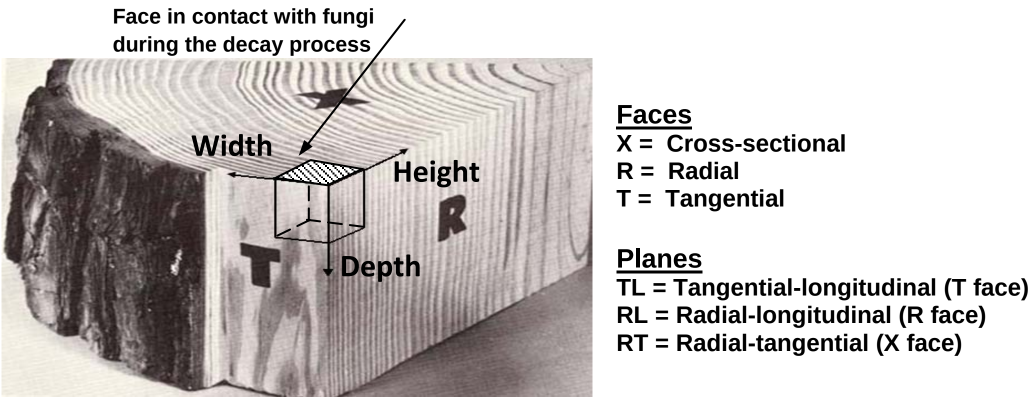


Figure 1. Assigned reference coordinate system for the wooden cubes and terminology used in this study.

For wood decay to occur it only requires the presence of moisture with the appropriate temperature. As a result, monitoring wood decay is still necessary for ensuring structural serviceability and safety requirements. To date, no practical nondestructive testing and evaluation method has proven able to detect and monitor in-situ the entire decay process of a wooden structural component. Typically, these methods detect decay only when it is already visible on the surface of the wooden component, which is already in an advanced state of decay. An ASTM Standard Test Method for Wood Preservatives by Laboratory Soil-Block Cultures (D 1413-99) was developed. This standard provides a test method to determine the minimum amount of preservative that is effective in preventing (i.e., “delaying”) decay of selected wood species by selected fungi under optimum laboratory conditions. In this manuscript, one inch loblolly pine (Pinus taeda) wood cubes (without any preservatives) were exposed to Gloeophyllum trabeum fungus from periods of one week to twelve weeks. The amount of decay (i.e., mass loss) was then evaluated using the ASTM Standard Test Method for Wood Preservatives by Laboratory Soil-Block Cultures (ASTM Standard D1413-99). Then, to add further understanding on the natural process of wood decay and to shed light upon some of the difficulties encountered during attempts to detect and assess decay damage using other methods, such as ultrasonics, these blocks were evaluated using X-ray computer tomography.

2. TEST SPECIMENS AND RESULTS USING ASTM STANDARD D 1413-99

The ASTM Standard (D 1413-99) was used through out this study[4]. Loblolly pine wood (Pinus taeda) was cut into seventy cube block specimens with one inch on the side. The specimens were inspected to confirm that no visible knots, mold, stain or fungi was present. Each block contained 6 to 10 rings per inch (2.5 to 4 rings per cm). The blocks were cut from quarter cut wood to ensure that the rings are nearly parallel to the outer face of the cube, see Figures 1 and 2. While the wooden cubes were not impregnated with a preservative solution, they were brought to constant moisture equilibrium of 30% relative humidity at 27ºC for three weeks, and their weight was measured to the nearest 1/100th gram prior to submitting them to the process of decay. The weight of each of the specimens is shown in Table 1 in Appendix.

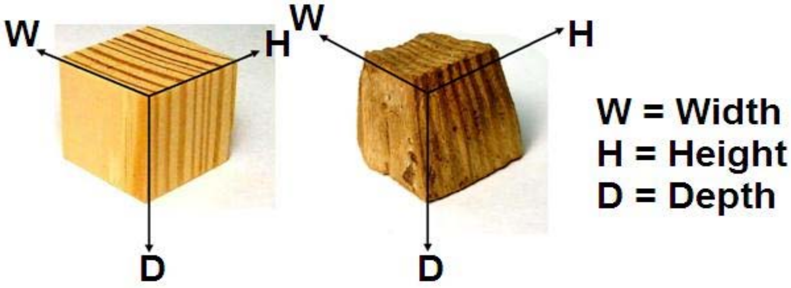


Figure 2. Block of sound wood (left) vs. block of decayed wood (right). The image on the left is block C4 (control group) and the image on the right is block B46 (decayed for 10 weeks).

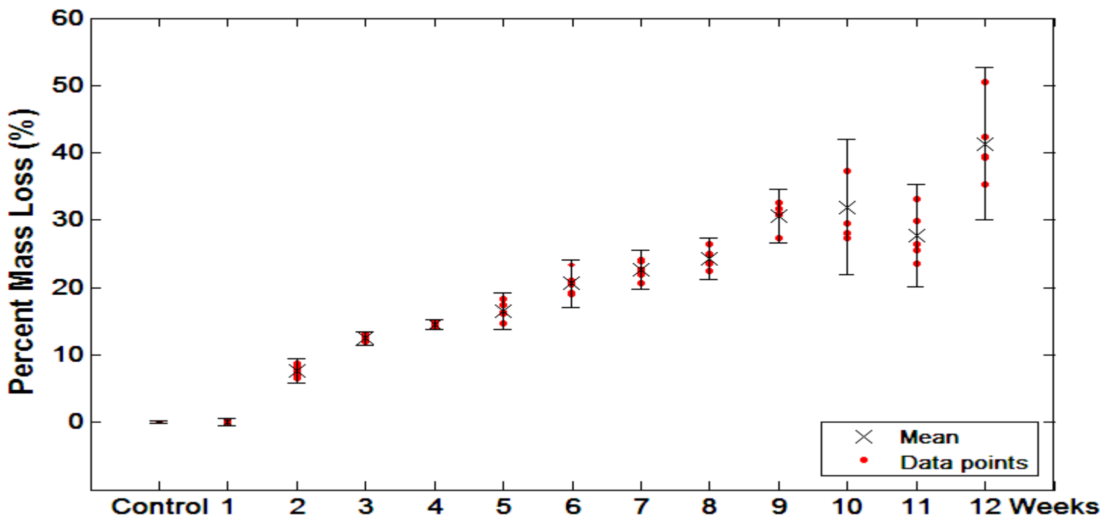


Figure 3. Percent loss of mass of blocks after being subjected to controlled decay, where the lengths of the error bars are equivalent to two standard deviations.

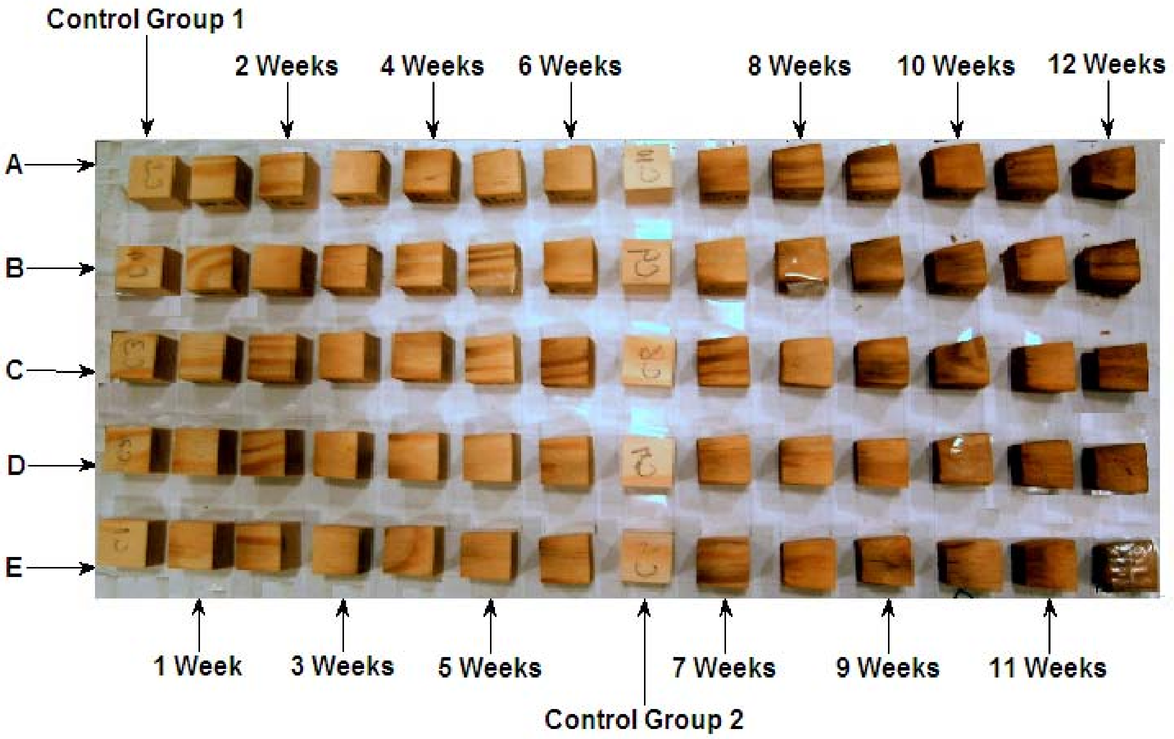


Figure 4. Set-up for Computer Tomography (CT) scans. The wood blocks samples are organized in groups of five samples each and by the number of weeks each group was exposed to controlled decay.

A wood-destroying fungus (Gloeophyllum trabeum) was grown on a feeder strip. Ten blocks were not exposed to the decay process and were labeled as the "control blocks." They were divided into two groups of five specimens each, Group 1 and 2, respectively, see Figure 4 and Tables 1 and 2 in Appendix. The remaining sixty blocks were divided into twelve groups of five block specimens each and were placed in contact with the feeder strip. The blocks were oriented with the grains perpendicular to the plane of the strip as it is illustrated in Figure 1, which also illustrates the coordinate system assigned to the blocks used in this study. These twelve groups of five blocks each remained in contact with the feeder strip from one week up to twelve weeks. At the end of each week, one group of five blocks was removed and each of the five blocks was weighed[4] to the nearest 1/100th gram. The weight of the wood block specimens after being submitted to the controlled decay process is shown in Table 1 in Appendix. Figure 2 shows two blocks for a visual comparison; one block has no decay (it is one of the control blocks) and the other block was exposed to the controlled decay process for ten weeks.

Following ASTM Standard (D 1413-99), the percentage of mass loss for the wood block specimens exposed to controlled decay was calculated. Figure 3 shows the percent of mass loss for the wooden blocks after being submitted to the process of controlled decay from one to twelve weeks. In Figures 3 the error bars represent two standard deviations. Please note that the post-decayed mass of some of the blocks specimens subjected to only one week of controlled decay were higher than the original masses. This is most likely caused by the initial moisture absorption, see Table 1.

Figure 3 clearly indicates that the specimens continuously lose mass during the decay process. In Figures 3, the five specimens associated with the eleventh week of controlled decay have a higher mass that the specimens associated with the tenth week of controlled decay. Please note that the group of specimens associated with the tenth week is different than the group of specimens associated with the eleventh week. It is possible that the rate of decay corresponding to the specimens associated with the eleventh week could have been influenced by the relative location of these specimens during the decay process.

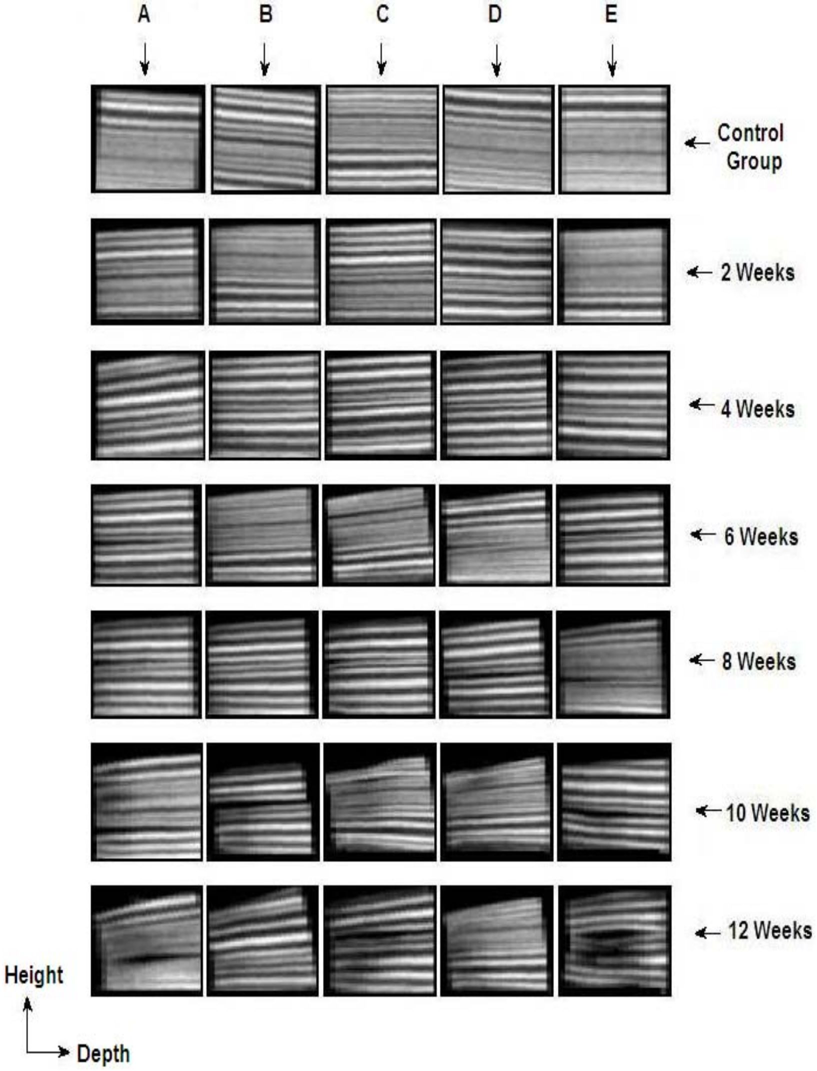


Figure 5. Computed tomography slices taken along the center plane parallel to the depth-height axis for selected cubes.

While the ASTM Standard (D 1413-99) provides a method for evaluating wood species more resistant to the natural process of decay, or to evaluate the effectiveness of different wood treatments against wood decay, the ASTM Standard only provides the final value of mass loss for each specimen. It does not shed any light onto the transition between the sound and decayed wood within each specimen or how the decay progresses within the specimen. To shed additional light into the decay process, X-ray computer tomography of the wood block specimens was also carried out.

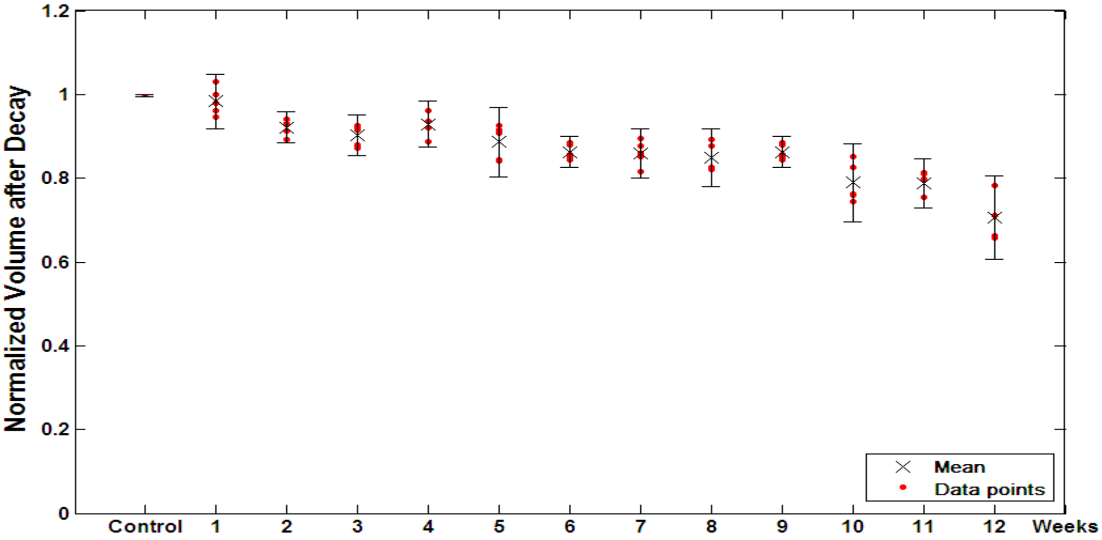


Figure 6. Volume after decay normalized to 1 in^3, where the lengths of the error bars are equivalent to two standard deviations. The volume of the specimens was calculated using X-ray CT data.

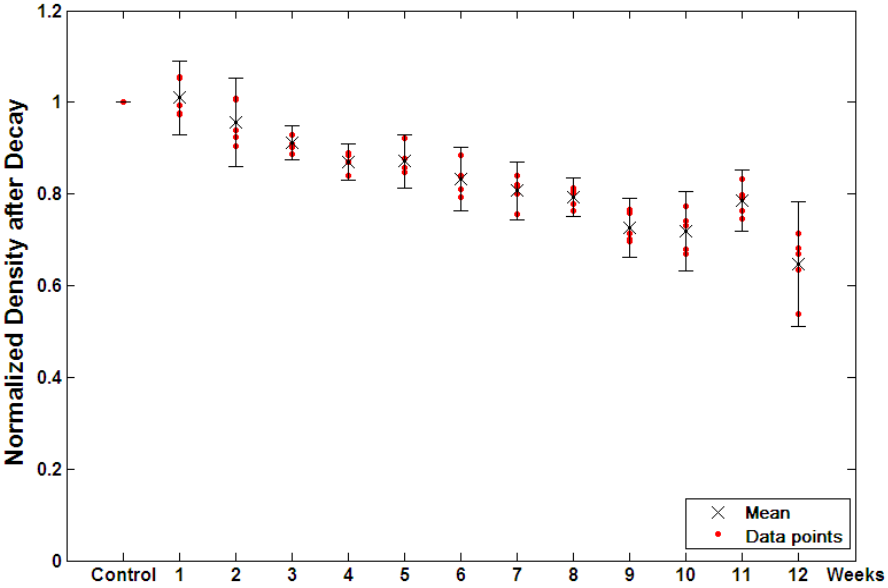


Figure 7. Volume average density of each specimen after decay normalized to its original density (assuming an original volume of 1 in^3), where the lengths of the error bars are equivalent to two standard deviations.

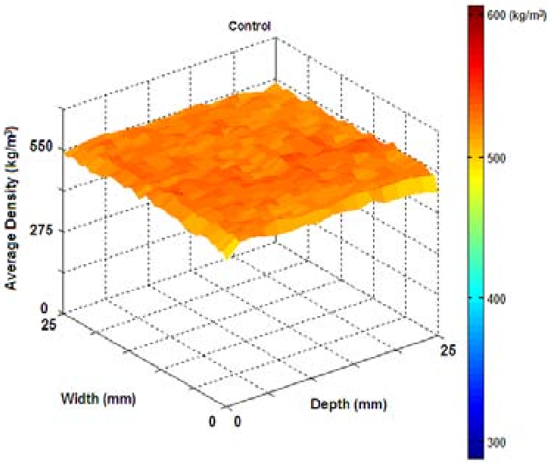


Figure 8. Averaged density for the control blocks. The average was performed along the height for control blocks.

3. COMPUTED TOMOGRAPHY

During the control decay process, a group of five wood block specimens was removed each week for a period of twelve weeks. Each group was then arranged into rows (A to E) according to number of weeks exposed to the process of controlled decay and placed onto a relatively flat surface. Double sided tape was used as an adhesive. The block specimens were spaced no more than one inch (25mm) apart. Figure 4 shows the specimen layout in preparation for X-ray Computer Tomography scanning. A General Electric Computer Tomography (CT) scanner was used to scan the block specimens with a rotation of 0.8 seconds, a field of view of 26.9 cm, and a slice thickness of 1.25 mm at 80 kV and 45 mA. Figure 5 shows tomographic slices for five specimens in the control group and for specimens submitted to two, four, six, eight, ten, and twelve weeks of the controlled decay process (tomographic slices for the remaining slices are not shown because of space limitations).

Volume calculations were also carried out for each block exposed to the controlled decay process using the CT scan data. This was done by counting the number of non-zero pixels for each block and multiplying this number by the slice depth and the pixel to inch conversion factor. The air volume due to the presence of internal splits was also taken into consideration. The calculated volumes are provided in Table 2 shown in Appendix. Figure 6 shows the volume of the specimens computed using the CT scan data, where the length of the error bars represent two standard deviations. To shed light into the possible errors introduced during the volume calculations using the CT scan data, measurements were also taken of the control wooden cubes using digital calipers, where the dimension of each face was measured 5 times in different locations. This led to the volume calculation of the control cubes with a maximum error of 1.3%, see Table 2. The approximations during the volume calculations using CT data introduced the most error. The pixel dimension is 0.5208 mm, and the associated slice depth is 1.25 mm. Therefore, each pixel is associated to a volume of 0.339 mm^3. However, the pixels depicting the outer edges of the blocks may be such that only a portion of the actual material falls within the dimensions of the pixel. In this case, the outer edges appear less dense than the rest of the block, which leads to an error equivalent to a fraction of the pixel dimension. Furthermore, the blocks may not have been perfectly aligned with the start of the first slice; thus, the first and last slices of the blocks may not be entirely 1.25 mm in depth. To mitigate these difficulties, the following approximations were made during the volume calculations:

- In an attempt to minimize the error caused by the outer pixels, their dimension was taken as ½ the regular pixel dimension (≈0.2604 mm).
- In an attempt to minimize the error caused by possible block misalignment, the last slice was assumed to be 0.4 mm thick; however, this approximation assumes that the first slice begins exactly at the front plane of the block and the overall depth is exactly 25.4 mm, which in itself is also an approximation.

With these considerations, the upper bound of the total possible error in the volume calculations using the CT data is 5.8%. To further reduce this error would require a decrease in slice depth and an increase in pixel resolution.

The local density for each wooden block was computed by utilizing the CT data and the measured mass of the wood block specimens after being exposed to the controlled process of decay. Each pixel was assigned a value from a grayscale range. For each wooden block, these assigned pixel values were summed and then divided by the total number of pixels in order to find the average pixel value. The total density (total mass/total volume) was then divided by the average pixel value. Finally, this factor was multiplied by each pixel value to find the local density for that particular location in the wood block specimens.

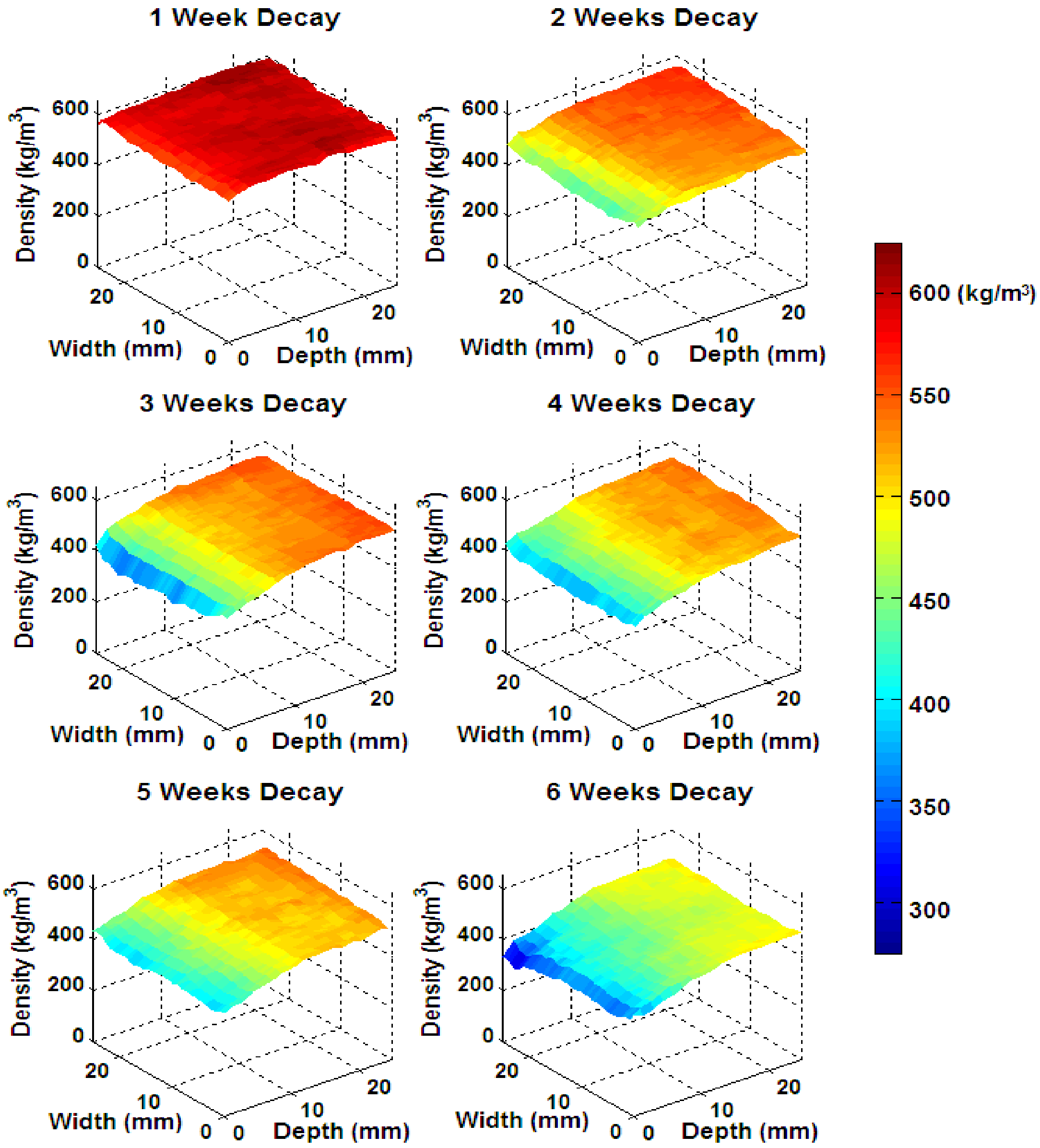
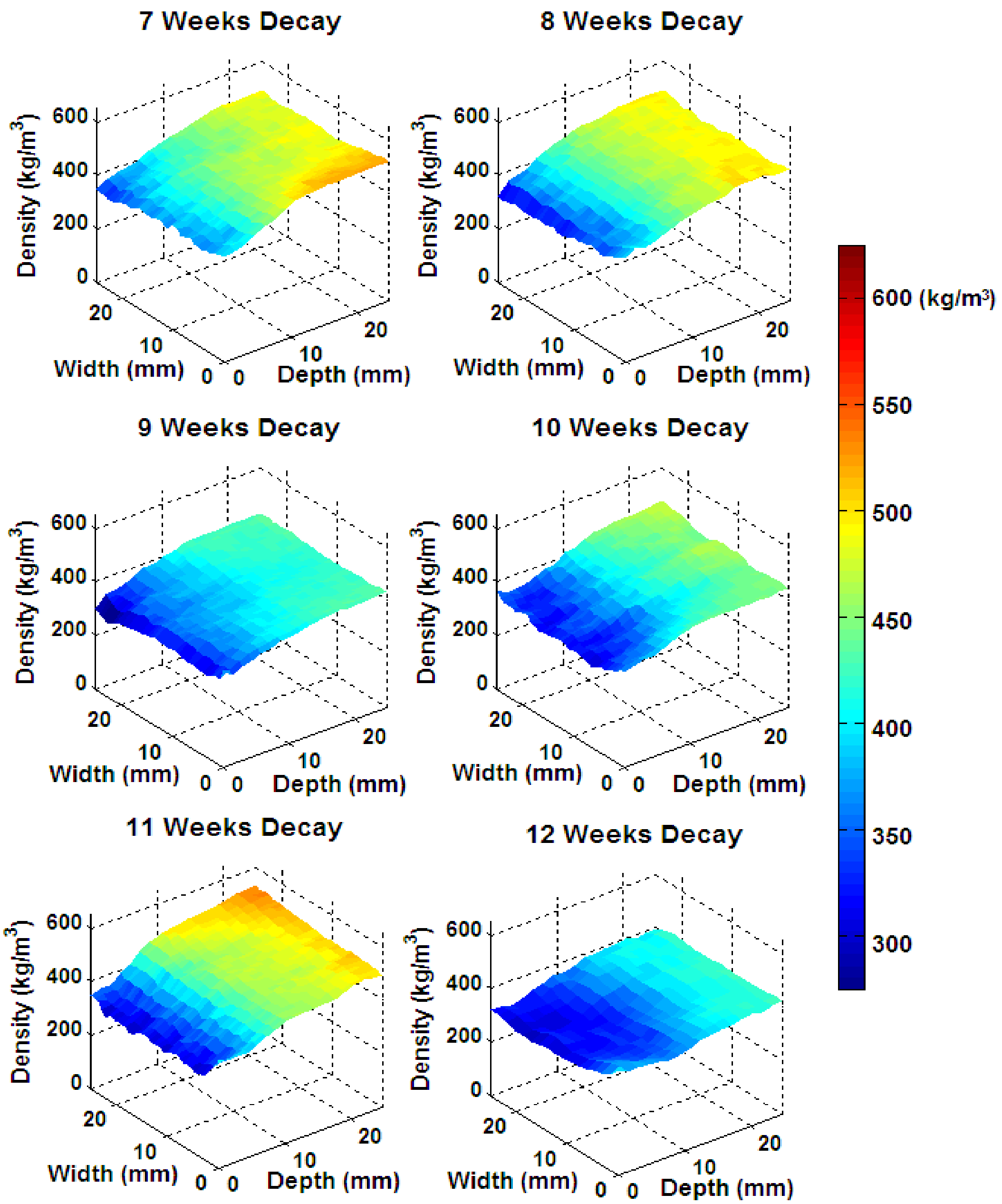


Figure 9. Densities averaged along height for blocks decayed from one week to twelve weeks.


7 Weeks Decay

8 Weeks Decay

9 Weeks Decay

10 Weeks Decay

11 Weeks Decay

12 Weeks Decay

Figure 9 (Cont.). Average densities along height for blocks decayed from one week to one twelve weeks.

Figure 7 shows the computed specimen volume average density normalized to the original density for each group in order to illustrate the approximate average density loss. Again, in Figure 7 the lengths of the error bars are equivalent to two standard deviations. The expected original densities were calculated by dividing the original mass (Table 2 in Appendix) by the volume of a cube 1 in (2.54mm) on the side.

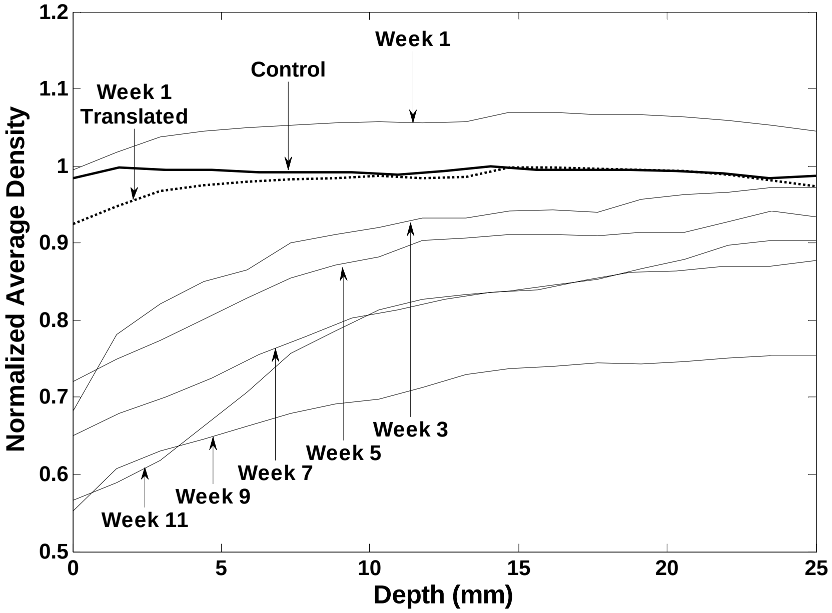


Figure 10. Densities averaged along height and width and normalized to the average of the control density for blocks decayed 1,3,5,7,9 and 11 weeks. The dotted line represents the results for specimens exposed to one week of controlled decay translated so that its maximum values are equivalent to the average density of the control blocks.

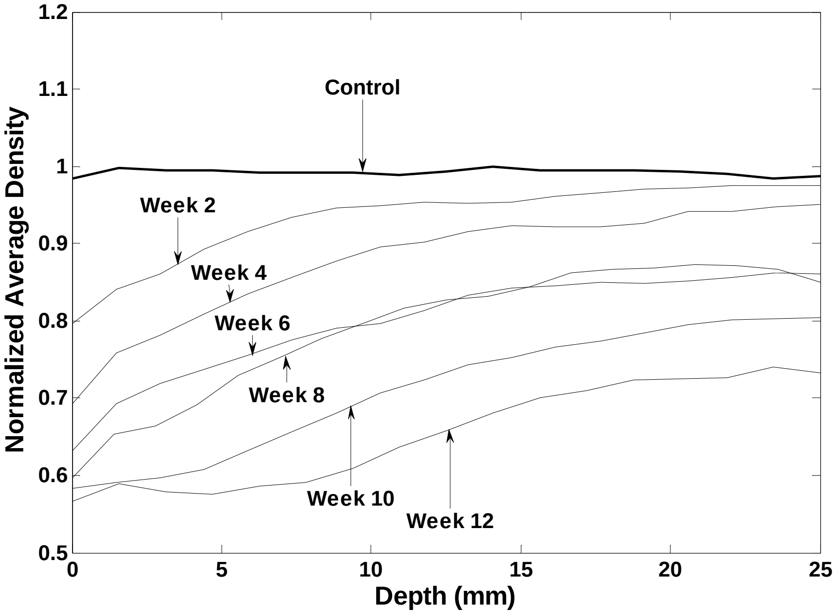


Figure 11. Densities averaged along height and width and normalized to the average of the control density for blocks decayed 2, 4, 6, 8, 10 and 12 weeks.

4. EXPERIMENTAL RESULTS

Visual inspection of the wood block specimens subjected to decay under controlled conditions leads to the observation that wood decay does not occur in a uniform manner. The process of decay starts at the surface in contact with the fungi and progresses towards the opposite surface. Figures 2, 4, and 5 clearly show this phenomenon. Figure 2 shows a visual comparison between a block subjected to 10 weeks of decay and one of the control blocks. Note the difference in color between the two. It can visually be seen on the decayed block that the face in contact with the fungi has experienced a significantly larger volume decrease than the opposite face. As a result, the decayed blocks are not perfect cubes as they become increasingly distorted the longer they were exposed to the fungi as it is illustrated in Figures 2, 4 and 5. Please note that the volume and the density loss increase (in general) with the number of weeks of exposure to decay, where week 12 has the most loss. As illustrated in Figure 3, the mass loss results indicate that considerable mass loss can be associated with increased exposure to wood-destroying fungi (or increased decay). Similarly, as illustrated in Figure 6, the volume calculations confirm that a volume loss is associated with increased decay. Tables 1 and 2 in Appendix also illustrate the corresponding mass loss and volume loss, respectively, for the wood specimens with increase in decay. Note that while some of the blocks subjected to one week of decay experienced mass loss, others appeared to have gained mass. This increase in mass is presumably due to initial moisture absorption, which causes the average mass loss to be negligible for the first week.

The average densities of the wooden blocks (averaged along the height dimension, see Figure 1) were computed and plotted. Figure 8 shows the average density for the control blocks. Figure 9 shows the average density for blocks exposed to control decay from one to twelve weeks. These plots make it easy to see how the blocks experience the most density loss at the face in contact with the fungi and how the level of decay (i.e., mass loss) decreases progressively towards the opposite face. In Figure 9 the blocks subjected to only one week of decay seem to have experienced minimal to no density loss on the surface “not” in contact with the fungi; the average density value at this point is about 600 kg/m^3. At the surface in contact with the fungi, blocks with one week of decay have an average density around 570 kg/m^3; thus, they seem to have experienced a relative small density loss at the surface in contact with the fungi. These results indicate that decay can be detected by X-ray computer tomography as early as one week based on the relative density change. In contrast, Figure 9 also shows that specimens with twelve weeks of exposure to fungi experienced a density loss throughout the entire block with average densities ranging from 275 kg/m^3 at the surface in contact with fungi to 400 kg/m^3 at the opposite face.

Figures 10 and 11 show the average densities of the wooden blocks along cross-sectional areas normalized using the average density of the control blocks. These average density values are plotted versus the specimens depth (see Figures 1 and 2) and two different plots are shown for viewing simplicity. Please note that specimens exposed to decay for only one week had a higher mass post-decay than the control block; thus, the density is higher. For this reason, a dotted line is drawn which depicts week one translated so that the maximum values coincide with the values associated with the

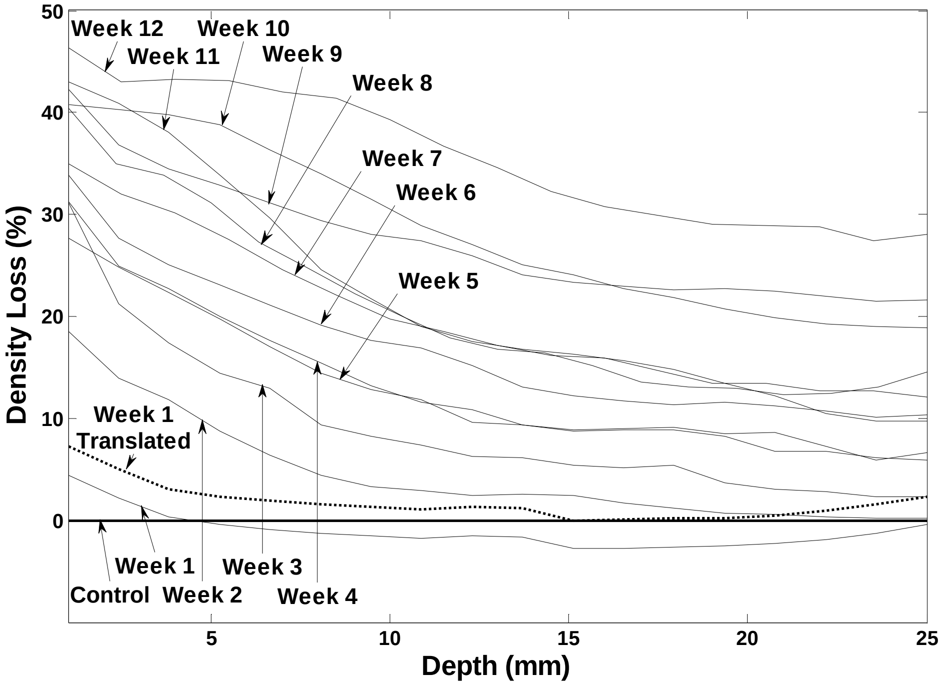


Figure 12. Percentage of mass density loss plotted along the depth for all blocks subjected to controlled decay. Note that a depth of 0 mm corresponds to the face in contact with the fungi.

control blocks. This allows the observation that there is a small measurable density loss at the surface in contact with the fungi when exposed for one week of controlled decay.

The percent density loss versus depth (see Figure 1) is also plotted in Figure 12. This was done with the assumption that the volumes of the blocks were exactly 1 in^3 (25^3 mm^3) before they were subjected to the controlled decay. These results indicate that noticeable density loss occurs from decay in a relatively short period of time (i.e., one week). Note how specimens exposed to twelve weeks of decay lose 47% of its density at the face in contact with the fungi and experience only a 28% loss on the opposite face. Conversely, specimens with one week of decay appear to experience only a 5% density loss on its most decayed face. Again, the dotted line in Figure 12 depicts a translated line for specimens with one week of decay so that its minimum values coincide with the values associated with the control specimens (i.e., 0%).

Traditional ultrasonic approaches to materials characterization rely upon velocity and attenuation measurements. These measurements are usually carried out by taking advantage of a reflective interface where two adjacent materials with different acoustic impedances meet. Figures 10, 11, and 12 indicate that the presence of decay does not lead to a reflective interface between sound and decayed wood because there is a continuous variation of the acoustic impedance values associated to sound and decayed wood, respectively. Given the high attenuation values of decayed wood and the lack of a reflective interface between sound and decayed wood, decayed wood behaves as an energy sink, i.e., no energy is reflected back from a probing ultrasonic beam. Considering the anisotropy inherent in wood products[5], these phenomena contributes to make the detection and assessment of wood decay a difficult task.

5. CONCLUSION

X-ray computed tomography was carried out using loblolly pine wood (Pinus taeda) cubes exposed to Gloeophyllum fungus (Gloeophyllum trabeum) for different known periods of time up to twelve weeks. It was verified that the most decay occurred at the face in contact with the fungi and progressed in a decreasing manner towards the opposite face. It was also observed that a considerable decrease in volume and mass occur with increasing exposure to decay. Based upon the changes in mass and volume, the corresponding change in densities was also calculated. Blocks decayed for twelve weeks experienced the most average mass loss (≈40%), average volume loss (≈30%), and average density loss (≈35%). Specimens exposed to only one week of controlled decay also exhibited some loss in density (≈5%); however, the mass loss was difficult to evaluate due to initial moisture absorption. These results indicate that, based on the relative density change, decay can be detected using CT data at the surface in contact with fungi as early as one week. The non-uniformity in decay through the thickness was quantified. Blocks subjected to controlled decay for twelve weeks lost 47% of density at the surface in contact with the fungus and 28% at the opposite surface, while blocks subjected to only one week of decay experienced 5% density loss at the surface in contact with the fungi and nearly 0% at the opposite surface. Results also indicate the presence of decay leads to a continuous variation of acoustic impedance and not to the creation of an acoustic reflective interface between sound and decayed wood. This lack of a well defined reflective surface separating sound from decayed wood explains some of the difficulties encountered in detecting and assessing decay using traditional linear ultrasonics.

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APPENDIX

Table 1. Mass measurements (g) of specimens before and after the decay control process (to the nearest one hundredth of a gram)

Specimens	**A**		**B**		**C**		**D**		**E**	
	Before Decay	**After Decay**	**Before Decay**	**After Decay**	**Before Decay**	**After Decay**	**Before Decay**	**After Decay**	**Before Decay**	**After Decay**
Control Group 1	8.19	-	8.99	-	8.20	-	8.83	-	8.23	-
Control Group 2	8.19	-	8.99	-	8.20	-	8.83	-	8.23	-
1 Week	9.07	9.09*	9.10	8.94	8.94	8.96*	9.79	9.80*	8.97	8.96
2 Weeks	8.97	8.31	8.93	7.49	8.21	8.17	8.91	7.80	8.19	7.65
3 Weeks	8.98	7.85	8.16	7.08	8.89	7.80	8.94	7.83	8.90	7.84
4 Weeks	9.23	8.00	8.82	7.54	8.75	7.48	8.69	7.46	9.10	7.73
5 Weeks	8.92	7.47	8.90	7.46	9.11	7.77	8.92	7.37	8.21	6.71
6 Weeks	8.58	6.95	8.35	6.64	8.17	6.26	8.16	6.45	8.96	7.24
7 Weeks	8.36	6.50	8.74	6.63	9.01	6.85	9.02	7.04	8.88	7.05
8 Weeks	8.95	6.71	8.97	6.96	8.84	6.75	8.78	6.52	8.70	6.40
9 Weeks	9.22	6.37	8.51	6.18	8.36	5.63	8.21	5.61	8.11	5.62
10 Weeks	8.96	6.51	8.82	6.21	8.68	5.40	8.41	5.27	9.02	6.49
11 Weeks	9.23	6.79	8.46	5.68	8.77	6.53	8.85	6.76	8.97	6.31
12 Weeks	9.10	5.25	9.19	5.95	8.80	5.35	8.15	4.93	8.80	4.36

*Please note the increase of mass after decay due to moisture absorption

Table 2. Volume calculations based on CT scan measurements (mm^3)

Specimens	**A**	**B**	**C**	**D**	**E**
Control Group 1	15782*	15881*	15827*	15853*	15774*
Control Group 2	15884*	15899*	16027*	15835*	15832*
1 Week	15769	15519	16871	16391	16042
2 Weeks	15405	14634	15213	14947	15250
3 Weeks	14289	15097	15157	14428	14981
4 Weeks	15772	15349	15320	15065	14547
5 Weeks	13814	14862	14994	15168	13767
6 Weeks	14053	13818	14418	14479	13896
7 Weeks	13960	14649	14079	14361	13348
8 Weeks	13468	14378	13531	14639	13502
9 Weeks	14053	13818	14418	14479	13896
10 Weeks	12214	13973	12498	12464	13532
11 Weeks	12375	12379	13343	13282	13078
12 Weeks	10871	12820	11635	11634	10789

*Maximum possible error of volume calculations based upon CT scan measurements is ± 5.8%. Maximum possible error on volume calculations of control specimens based upon caliper measurements is ± 1.3%.