Effect of Carpenter Bee Nests on Timber Building Components Based on Computed Tomography (CT)

Yisheng Gao,[a] Zhedong Ge,[b,]* Jiaqi Fang,[b] Xiaoxia Yang,[b] and Yucheng Zhou [b]

The effects of carpenter bee nests were determined for components of timber buildings. An eaves purlin structure was taken as the experimental object, and medical computed tomography (CT) was used to reconstruct the sectional image of the eaves purlin. The digital image reconstruction technology was used to obtain three-dimensional (3D) images of the two eaves purlins. One eaves purlin was not damaged, and the other was seriously eroded by carpenter bees. The carpenter bee nests were displayed, and the two eaves purlins were simulated by the directional force and the uniform directional force. When the eaves purlin was under the downward pressure of the roof, the shear force at both ends of the eaves purlin and the pressure at the middle were relatively large. The results show that CT is an accurate and efficient technology for detecting the mechanical properties of timber building components. Nests are usually distributed in the eaves purlin eroded by carpenter bees, which destroy the stability of the eaves purlin structure and have a great impact on the stability of timber buildings. Therefore, this method to evaluate the damage degree of timber building components is very important for the protection of timber buildings.

DOI: 10.15376/biores.17.2.3320-3331

Keywords: Timber building; Computed tomography; CT; Carpenter bee; Nest

*Contact information: a: School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan, Shandong 250101, China; b: School of Information and Electrical Engineering, Shandong Jianzhu University, Jinan, Shandong 250101, China; *Correspondence: gezhedong@sdjzu.edu.cn*

INTRODUCTION

As an important part of the world cultural heritage, timber buildings are the crystallization of the wisdom of the Chinese people, and they have carried the civilization of the Chinese nation for thousands of years. The quality of timber buildings is greatly affected by the environment. In addition to decay, cracking, and other factors, timber buildings will also be damaged by some organisms (Yuan *et al* 2021). The carpenter bee is an insect that can cause great harm to timber buildings. Carpenter bees are widely distributed in hot provinces such as Guangdong, Fujian, Zhejiang, and Jiangsu (Ma *et al.* 2015; Lawson *et al.* 2016; Ma *et al.* 2021). Researchers have studied the living habits of carpenter bees and found that they often nest and lay eggs in dry wood in May and enclose the larvae in a cylindrical space with a length of 5 cm from June to July (Rau 1928; Frye and Gangloff-Kaufmann 2017). Although carpenter bees may only create a few holes in a timber building, the internal structure of the wood will become seriously damaged, which is a great potential safety hazard in the building. Some structures of timber buildings are affected by carpenter bee nests, which may lead to surface damage, reduced mechanical properties, and even building inclination or collapse. This is because the internal damage of timber buildings is difficult to detect by conventional methods, which is also a difficult problem in the field of industry.

Even though many published articles have mentioned the relationship between carpenter bee nests and timber architecture, there is still a lack of explanation for the causes and detailed understanding of nests, due to the difficulty to visualize nests inside the wood. Most studies of carpenter bees discuss the morphology and nesting behavior, with few studies on the effects of carpenter bee nests on wood mechanical properties (Ostwald *et al.* 2020). Mapping the nests and tunnel systems of carpenter bees has been difficult, with wood dissection being the most common method used. Some researchers collect the wood, close the entrance and exit of the nests, freeze them for 8 to 10 h to kill the carpenter bees, and then dissect the samples containing these nests and record the nest data, such as the number of immature bee pupae and the presence of pollen masses (Hussain *et al.* 2017). The dissection of nests has been carried out and the nest architecture and nesting biology of the species have been described. Although such studies are useful to understand pollination by carpenter bees, only a small amount of nest data can be obtained by destructive methods.

In recent years, X-ray computed tomography (CT) has been developed as a reliable and accurate method to analyze insect nests without destroying the wood structure of the timber building (Fuchs *et al.* 2004; Hu *et al.* 2011; Lehmann *et al.* 2021). The research objects of CT technology are usually termites and nests, and there are have been few studies on carpenter bees. A study by Facchini *et al.* (2019) was the first to report on the use of CT, which was applied to visualize a comb's inner structure. The study found that the morphology and developing status of each pupa, as well as the location and space of these nests were recorded without damaging the brood. In the research of spatial dynamics and nest recognition, scan image slices were collected by CT, and two-dimensional (2D) and three-dimensional (3D) images of carpenter bee nests and tunnels were reconstructed. The exits and entrances of the tunnels were marked with different colors for the study of social organization and nest architecture analysis (Ostwald *et al.* 2019). Although the change patterns of nests in the wood were reported, their findings were limited to insect biology rather than the influence of the nests on timber buildings. Ma *et al*. (2018) used ultrasonic CT to detect defects in timber structures of historic buildings. Some researchers have applied CT to the fields of heritage artifact, industry, and medicine (Sansoni *et al*. 2009; Zhang *et al*. 2012). However, to date, CT has not been used to detect timber building components eroded by carpenter bees. In this study, CT was used to reveal the 3D hidden nests of carpenter bees contained within the eave purlin that were subject to the application of forces in multiple directions. During the measurement and analysis of the timber building, the internal structure of the eave purlin, the holes distribution, and other anatomical properties were found that can provide important insights into how carpenter bees eat wood and make timber buildings collapse, and possibly lead to the development of new detection and maintenance technologies.

EXPERIMENTAL

The image of a section of the damaged wood was obtained by conventional methods, and the erosion of an eaves purlin by carpenter bees makes tunnels in different directions appear in the component. Carpenter bee nests are generated randomly, so the volume and location of these nests also cause different damage to the eaves purlin, which makes the stress distribution inside the eaves purlin very complex under external force. To obtain accurate stress analysis results, the empirical formula was abandoned to check the strength or stability of wood components, and the professional image reconstruction and mechanical analysis software, *i.e.* VGStudio Max (Volume Graphics Inc., Charlotte, NC, USA) was used to model the eaves purlin eroded by carpenter bees. According to the stress characteristics of the eaves purlin in the timber building, some mechanical constraints and loads were set for the statical analysis. The results were compared with the mechanical simulation results of the eaves purlin not damaged by the carpenter bees to confirm the impact of the components eroded by the carpenter bees on the safety of the timber building.

Wood Specimen

All timber samples, which were Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), used for the experiment were taken from an eaves purlin of an ancient building located in Zherong County, Ningde City, Fujian Province, China (27.19 °N, 120.06 °E). The ancient building is a mansion of the Wu Family. The components of this mansion have an extremely high artistic level and a high research value. The building components were rated as key cultural relics protection units in China in 2013 (You 2016).

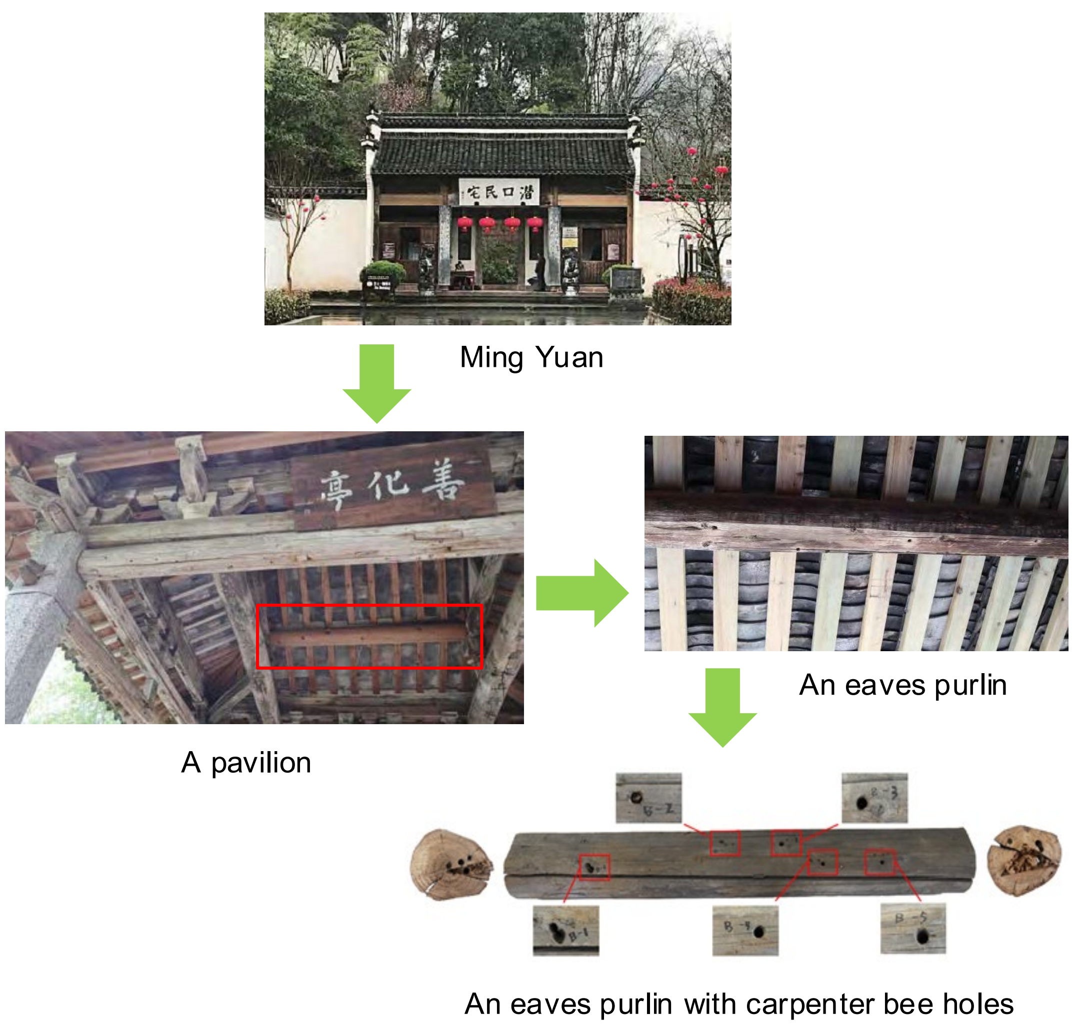

Fig. 1. An eaves purlin with carpenter bee holes in a timber building

To study the influence of carpenter bees on precious timber buildings, three damaged timbers that have a great impact on the ancient building were taken back to Shandong Jianzhu University (Jinan, China) for further research. These timbers were approximately 200 years old, with a diameter of approximately 130 mm, a length of approximately 1,000 mm, and a moisture content of 8%. There were some dry cracks on the surface of these timbers, and the widest part reached 2 mm. The timbers were seriously eroded by carpenter bees and contained many nest structures inside.

Figure 1 illustrates the influence of carpenter bees on the eaves purlin in detail, and a timber located in the middle of the eaves purlin that were most seriously eroded by carpenter bees were selected. While rotating the timber, a picture with a viewing angle of 120 degrees was taken to display the entrances of the holes. Interestingly, these holes were standard circles with a diameter of approximately 10 mm. There were piles of fine sawdust under these holes. The distribution of carpenter bee nests cannot be found, based only on observations of the timber surface, without the help of instruments.

The CT Scanning

As a powerful instrument, CT displays the internal structure of the timber sample through image reconstruction and image analysis technology. The method and related instrumentation are widely used in the medical field. The timber was scanned and imaged by an X-ray CT with scanning aperture of 780 mm (SOMATOM Definition AS; Siemens Healthineers, Erlangen, Germany) at Shandong Jianzhu University, Jinan, China. The timber was placed on a bed that continuously moved during the scanning process, while simultaneously the X-ray tube and the detector were rotated synchronously around and along the entire length of the timber (Fig. 2). The experimental parameters were set in vertical by a 120 kV X-ray source (300 mA). The projection data of the scanned timber were collected and used to reconstruct the sectional image with a size of 512 px × 512 px. Approximately 2,000 sectional images with layer spacing of 0.5 mm were reconstructed into a 3D image of the timber.

Fig. 2. X-ray CT used to investigate the timber in Shandong Jianzhu University, China

The data were processed using a computer equipped with high-performance central processing unit (CPU) and a graphic processing unit (GPU). The Windows 10 professional operating system and VGStudio Max software were installed. The CPU and GPU configurations of the computer were an Intel (R) Xeon (R) gold 6136 CPU at 3.00 GHz and a NVIDIA GeForce GTX 1060 6 GB.

RESULTS AND DISCUSSION

The research object was an eaves purlin of a timber building with a history of more than 200 years. It is very precious and has great historical and cultural value, which needs to be protected and inherited. The CT and VGStudio Max software are a kind of simulation technology, which were used for images reconstruction and mechanical analysis. The operation process was to mark the nest sections of about 2000 sectional images, and the computer would automatically remove the marked holes, which was a very time-consuming experiment. Therefore, there was no destructive physical test on the eaves purlin in this paper. After the experiment, the object was stored in the wood specimen museum of Shandong Jianzhu University.

Damage Characteristics of the Eaves Purlin

Carpenter bees usually make holes in the surface of wood, build nests along the growth direction of wood, and make chamber walls with sawdust, plant fragments, and saliva (He *et al*. 2017). In order to obtain the distribution of carpenter bee nests in the timber, CT was used to construct the 3D image of the eaves purlin. The CT technology hid the wooden materials and only showed the carpenter bee nests. The nests were marked with different colors according to their volume. In Fig. 3, blue, red, and green were used to mark the carpenter bee nests, which indicated that there are three independent unconnected nests in the timber.

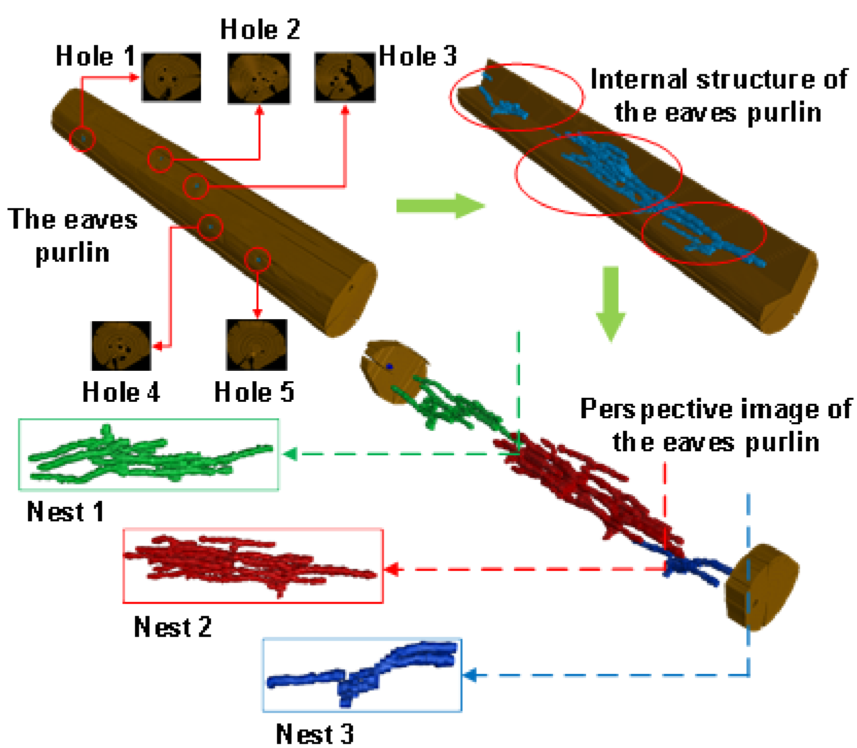

Fig. 3. The internal structure of the eaves purlin

Each nest had one or two holes connected with the outside world. These holes were the entrances of the carpenter bee nests.

The eaves purlin is an approximately cylindrical horizontal component erected on the beam to support the roof. The upper part is covered by the roof and the lower part is exposed to the air. Due to the dry shrinkage and wet swelling characteristics of wood, there is a crack extending from the surface to the pith core along the length direction of the eaves purlin in the experiment. Since CT was used to reconstruct the 3D image of the eaves purlin, three independent and disconnected carpenter bee nests were found, which greatly destroyed the eaves purlin structure. A section perpendicular to the length direction of the eaves purlin was set at the entrance of each carpenter bee nest, which reflected the shape of the nest. It was found that carpenter bees will build nests along the length direction after drilling into the eaves purlin. As seen in Fig. 3, the nests destroy the integrity of the internal structure of the eaves purlin. The size of nests and the distribution of the rearing room of the carpenter bee larvae have a certain randomness, but the construction process have the same characteristics. These holes of nests are usually located in the early wood. Therefore, carpenter bees will avoid the damage to the growth rings when building nests. An explanation for this may be that growth rings are formed naturally by the growth of trees within a year. The early wood grows fast, the wood is relatively soft and easy to erode. By contrast, the late wood grows slowly, and the wood is relatively hard so it is difficult to damage by carpenter bees. A virtual cutting plane along the length of the purlin was created. It was found that there were many tunnels in the carpenter bee nests, and the chamber wall was made of sawdust, plant fragments, and saliva. The volume of carpenter bee nests accounted for 4.35% of the eaves purlin, and its internal structure was damaged by the carpenter bees. This damage can reduce the mechanical properties of the supporting components and the safety of timber buildings.

Directional Force at a Fixed Point

Five holes, distributed from left to right below the eaves purlin, were the entrances of the carpenter bees into the nests. At the entrance, a section perpendicular to the length of the eaves purlin was constructed to obtain the section of the carpenter bee nest. A hole in the section extended from the inside to the outside to the edge, so that the section formed an open circular curve. The two ends of the eaves purlin were subject to constraints, and the downward directional force was applied above the entrance of each nest. This can lead to serious deformation when the eaves purlin is under tension or pressure, as shown in Fig. 4. The elastic modulus and Poisson's ratio of *Cunninghamia lanceolata* were set to 1.0×10^{10}Pa and 0.33, and voxel was 2 in the VGStudio Max software (Long *et al*. 2021; Wang *et al*. 2020). The sections were numbered 1 to 5 from left to right and were subjected to 4,096 N of directional force defined as F_1 to F_5, respectively (GB/T 50165-2020.). The force lines distribution under the five forces can also be seen in Fig. 4. The pressure is represented by the red force lines and the tension is represented by the green force lines. In these section images, blue indicates the minimum stress and red indicates the maximum stress. Comparing the influence of the five directional forces on the eaves purlin, it was found that the position of the eaves purlin under the force had a great effect on the internal force line distribution and the stress on the section of the eaves purlin. The closer the section is to the middle of the eaves purlin, the greater the stress.

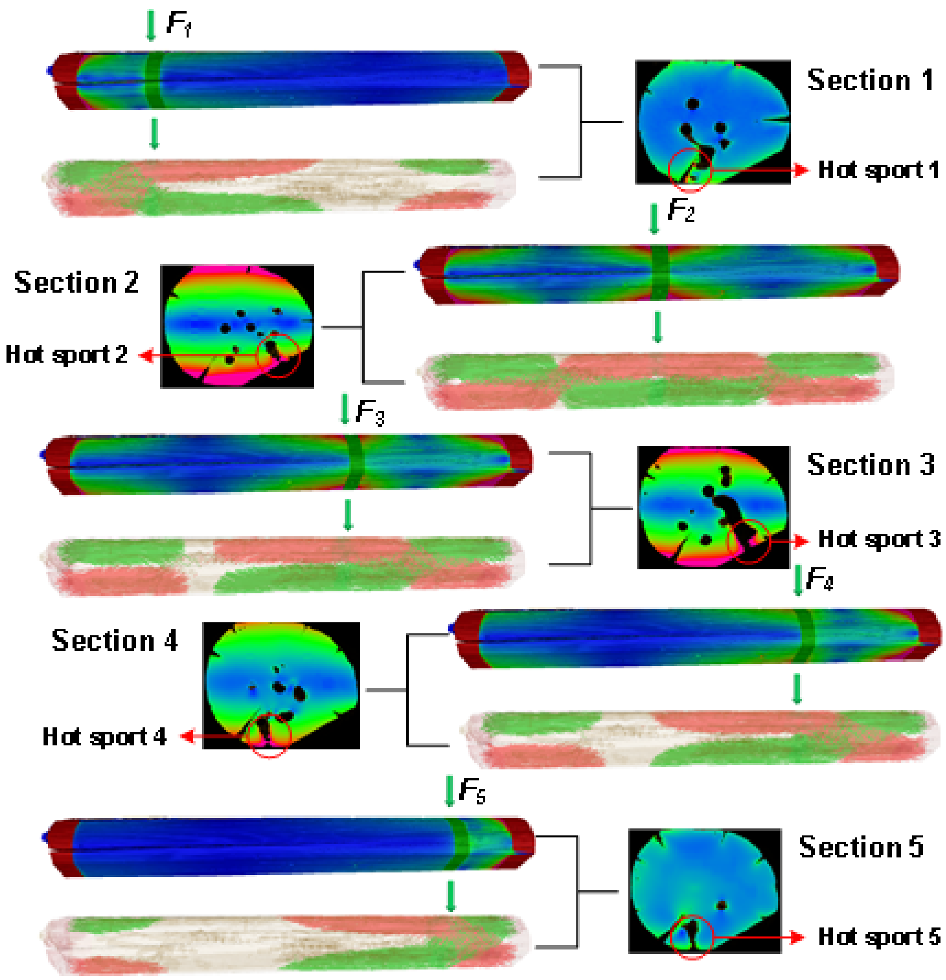

Fig. 4. The distribution of the eaves purlin and force line under a fixed-point directional force

The junction of the fixed area and the load area will produce large shear force, which has a great impact on the structure of the eaves purlin. There were also many hot spots (the parts were prone to fatigue failure) on the edge of the sections of the carpenter bee nests in the eaves purlin. Almost all of the hot spots were concentrated near the holes leading to the entrances, and the stress in the defect was higher than that in the eaves purlin. The section perpendicular to the length direction of the eaves purlin was observed, and it was found that the section similar to the circle was stable. Due to the numerous carpenter bee nests in the eaves purlin, when the directional force was applied, the internal stress distribution was uneven and the average stress increased. The larger the volume of the nests and the cross-sectional area of these holes, the greater the stress around them.

As shown in Table 1, the sections 2, 3, and 4 were closer to the middle of the eaves purlin. The parts prone to fatigue failure on the three sections were marked as hot spot 2, hot spot 3, and hot spot 4. Their average values were 2.29×10^6 Pa, 2.24×10^6 Pa, and 1.92×10^6 Pa, and the volumes of hot spots were 39500 mm^3, 42.7 mm^3, and 6000 mm^3. Comparing the average values between the five hot spots, it was found that the closer to the middle of the eaves purlin, the greater the average values of the hot spots, that is, the easier these positions were to be damaged under stress. The volume and location of hot spots were not related, but they were affected by cracks and holes.

Table 1. The Values of Hot Spots on Five Sections of the Eaves Purlin under Directional Force

Hot Spots	Maximum [Pa]	Minimum [Pa]	Average Value [Pa]	Standard Deviation [Pa]	Volume [mm³]
Hot spot 1	2.44×10^6	1.23×10^6	1.69×10^6	3.96×10^5	37.4
Hot spot 2	3.73×10^6	2.07×10^6	2.29×10^6	1.75×10^5	39500
Hot spot 3	2.40×10^6	2.07×10^6	2.24×10^6	1.35×10^5	42.7
Hot spot 4	3.59×10^6	1.71×10^6	1.92×10^6	2.10×10^5	6000
Hot spot 5	1.46×10^6	1.04×10^6	1.18×10^6	1.55×10^5	42.7

Uniform Directional Force

As an important component of timber building, the eaves purlin is supported by wood at both ends and bears the weight of the roof. It is a downward uniform directional force, as shown in Fig. 5. In this stress state, bending stress and shear stress will be generated in the eaves purlin. In order to simulate the roof load on the eaves purlin, a downward uniformly distributed directional force of 4,960 N was applied to the eaves purlin. It was found that the stress at the junction of the fixed area at both ends of the eaves purlin and the load area was the largest. The stress was much greater than the hot spots values near holes, and the stress in the middle area of the eaves purlin was slightly smaller. This shows that when the eaves purlin of the timber building is under the pressure of the roof and its two ends are supported by the wall, the shear force at the junction has a serious impact on the eaves purlin. The two ends of the eaves purlin were fixed, so the straight-line distance between the middle area and the fixed area was the largest. This creates the maximum displacement under load. The uniform directional force made the eaves purlin bend and deform downward. The upper part of the eaves purlin was under pressure, and the lower part was under tension. The distribution of force lines is shown in Fig. 5. The entrances of the carpenter bee nests were located under the eaves purlin, so they will accelerate the damage of the eaves purlin.

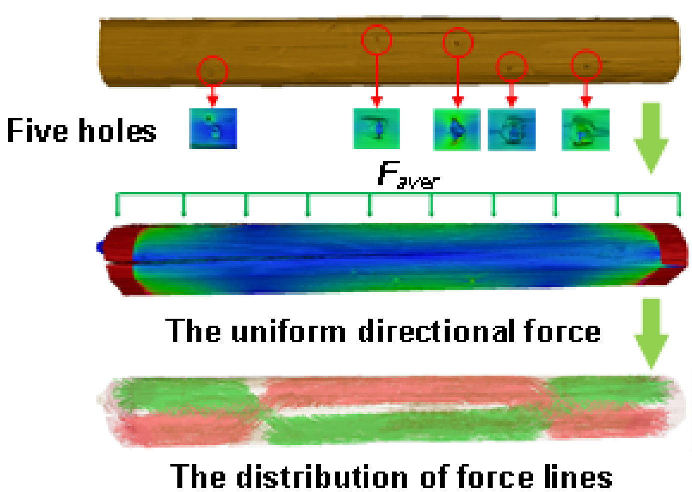

Fig. 5. The eaves purlin under uniform directional force

Mechanical Analysis of the Non-Destructive Eaves Purlin

Another section of the eaves purlin was selected for analysis as the control, and there were no cracks, carpenter bee holes, or other defects in the section. The section was copied and reconstructed into a specimen with the same length as the eaves purlin, the two ends of the specimen were fixed, and a downward uniformly distributed directional force of 4,960 N was applied above the eaves purlin. The non-destructive eaves purlin was simulated under uniformly distributed directional force, and the internal stress change and hot spots distribution were observed. As shown in Fig. 6, the hot spots of the non-destructive eaves purlin were concentrated at both ends of the timber, that is, the junction of the load area and the fixed area. The stress on the upper surface of the eaves purlin and the tension on the lower surface were greater than the stress in the middle. The stress distribution of the eaves purlin was relatively uniform, which basically conformed to the law of large stress in the upper and lower parts of the eaves purlin and small stress in the middle part. When the same directional force is applied, the stress distribution on the upper and lower surfaces of the eaves purlin eroded by the carpenter bees was slightly higher than that of solid wood in the middle of the eaves purlin. Cracks and holes in wood eroded by carpenter bees reduce the strength of the eaves purlin.

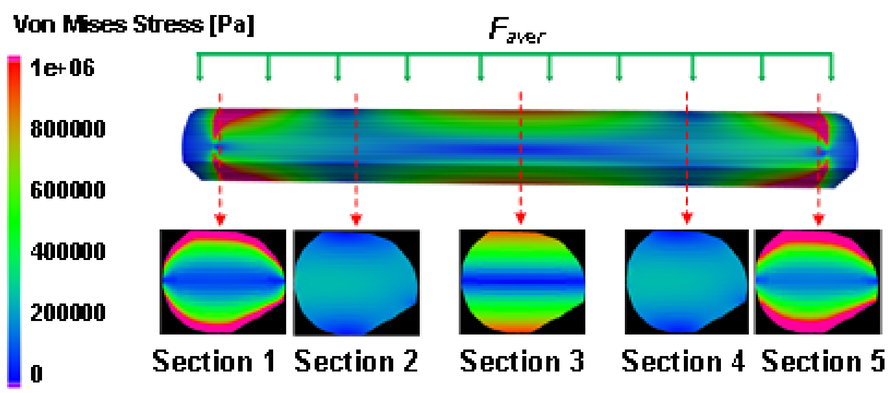

Fig. 6. The non-destructive eaves purlin under uniform directional force

Analysis of Two Kinds of Eaves Purlins

For the eaves purlin with cracks and holes, under the same directional force, the stress on the inner walls of the carpenter bee nests is greater, the upper part is loaded, and the tension on the lower surface of the eaves purlin is greater. Under the same physical model, there was no change in the overall stress distribution law of the eaves purlin. This indicated that under the condition of directional force, the stress distribution of the eaves purlin will hardly be changed by the carpenter bee nests, but the stress will increase and the stability of the timber building will still be compromised.

Two red boxes were added in Fig. 7, identifying the entrances of nests that had destroyed the lower surface of the eaves purlin, and the holes in the section extended to the edge. They destroyed the closure of the section of the eaves purlin, which is equivalent to blocking the path of tension transmission. Under the directional force, the tensile force that should have been transmitted to both ends through the surface was concentrated at the entrances of nests, the value of stress increased rapidly and the hot spots were concentrated. The approximately circular holes had a strong compressive capacity, but the tensile capacity was very poor. Therefore, when the eaves purlin is under pressure, the entrances of nests are very fragile and easily damaged. The numerical analysis of the stress of the eaves purlin eroded by carpenter bees and with cracks showed that the stress at the entrance of carpenter bee nests increased, a large number of hot spots appeared, and a small number of hot spots also appeared at the internal boundary of larger cracks. According to the analysis, the influence of carpenter bee nests on the mechanical properties of the eaves purlin is more serious than that of cracks.

a)
b)

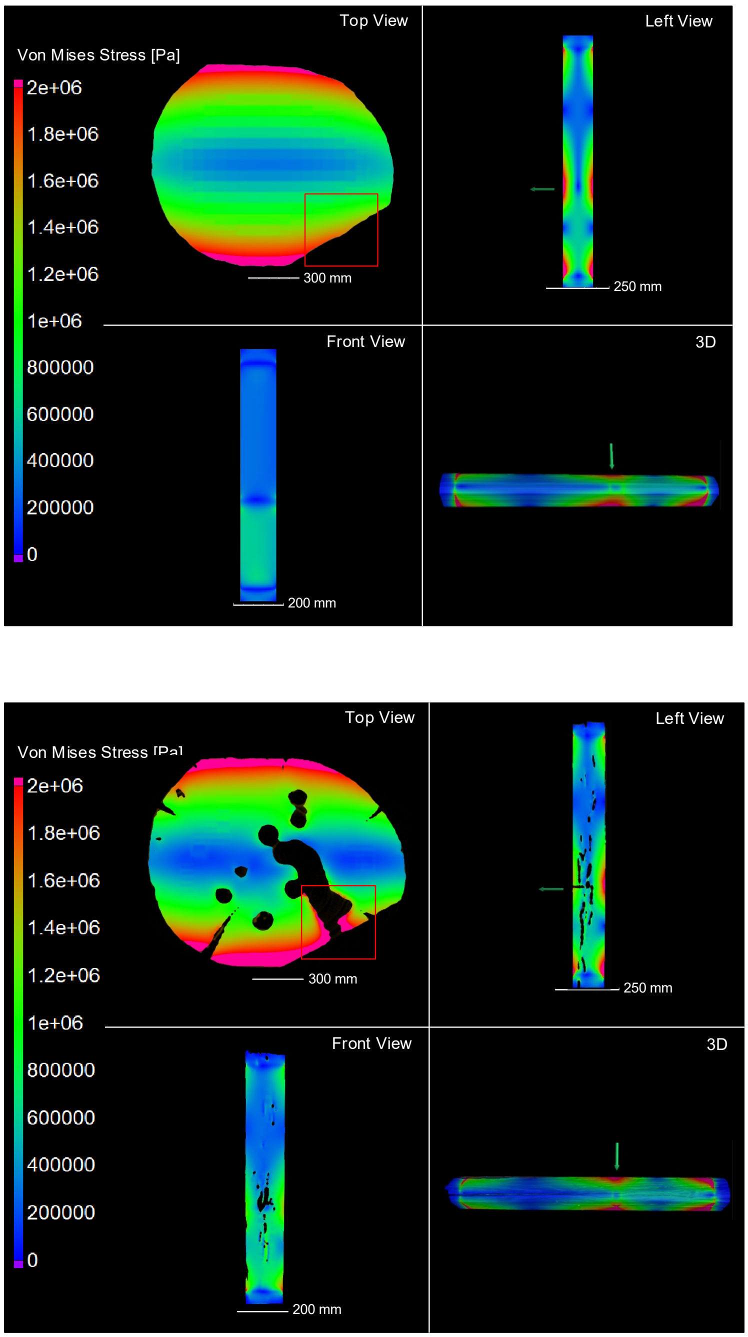

Fig. 7. The 3D images and section images of the two kinds of eaves purlins. The a) non-destructive eaves purlin under directional force and b) damaged eaves purlin under directional force

CONCLUSIONS

1. Computed tomography can be used to visualize the position and shape of nests in the timber building components eroded by carpenter bees, simulate the hot spots distribution and quantification of components under load, and provide a new research idea for exploring the stress analysis of timber building components under load.
2. There is little research on the harm of carpenter bees in the field of architectural heritage protection. In this paper, the damaged eaves purlin of the timber building eroded by carpenter bees was evaluated. It was found that the carpenter bee nest was the main factor causing changes in the concentration of stress in the internal structure of timber building components when under stress conditions. This paper provided important information for the establishment of a carpenter bees risk assessment system.
3. In this paper, the damage model of the eaves purlin was reconstructed by CT, the 3D visualization of carpenter bee nests was completed, and the internal damage form of the eaves purlin was restored. The damage degree of the eaves purlin was evaluated in conjunction with the mechanical characteristics of the carpenter bee nests. It was found that the stress of timber building components will affect the hot spots distribution at the entrances of the nests, which adds new practical results for the application of nondestructive testing technology in timber building protection.

ACKNOWLEDGMENTS

This work was supported by the Application of Computed Tomography (CT) Scanning Technology to Damage Detection of Timber Frames of Architectural Heritage, the Natural Science Foundation of Shandong Province, China (Grant No. ZR2020QC174), and the Taishan Scholar Project of Shandong Province, China (Grant No. 2015162).

REFERENCES CITED

Facchini, E., Nalon, L., Andreis, M. E., Di Giancamillo, M., Rizzi, R., and Mortarino, M. (2019). "Honeybee pupal length assessed by CT-scan technique: Effects of varroa infestation, developmental stage and spatial position within the brood comb," *Scientific Reports* 9(1), 10614. DOI: 10.1038/s41598-019-46474-4

Frye, M., and Gangloff-Kaufmann, J. (2017). *Preliminary Evaluation of Exclusion as a Technique to Reduce Carpenter Bee Damage*, New York State Integrated Pest Management, Geneva, NY.

Fuchs, A., Schreyer, A., Feurerbach, S., and Korb, J. (2004). "A new technique for termite monitoring using computer tomography and endoscopy," *International Journal of Pest Management* 50(1), 63-66. DOI: 10.1080/0967087032000159300

GB/T 50165-2020. (2020). "Technical standard for maintenance and strengthening of historic timber building," Beijing: China Architecture and Building

He, C.-l., Zhu, C.-d., and Wu. Y.-r. (2017). "Morphology and nesting behavior of *Xylocopa rufipes* (Hymenoptera: Apidae)," *Acta Entomologica Sinica* 60(9), 1074-1082. DOI:10.16380/j.kcxb.2017.09.011

Hu, Z., Gui, J., Zou, J., Rong, J., Zhang, Q., Zheng, H., and Xia, D. (2011). "Geometric calibration of a micro-CT system and performance for insect imaging," *IEEE Trans. Inform. Technol. Biomedicine* 15(4), 655-660. DOI: 10.1109/TITB.2011.2159012

Hussain, A., Mohamed, S., Abdulaziz, S. A., and Mohammad, J. A. (2017). "Nesting biology of two species of the large carpenter bees *Xylocopa pubescens* and *Xylocopa fenestrata* (Hymenoptera: Apidae) in north-western Pakistan," *Oriental Insects* 57(2), 185-196. DOI: 10.1080/00305316.2016.1272500

Lawson, S. P., Ciaccio, K. N., and Rehan, S. M. (2016). "Maternal manipulation of pollen provisions affects worker production in a small carpenter bee," *Behavioral Ecology and Sociobiology* 70(11), 1891-1900. DOI: 10.1007/s00265-016-2194-z

Lehmann, P., Javal, M., De Plessis, A., and Terblanche, J. S. (2021). "Using CT in live larvae of a large wood-boring beetle to study tracheal oxygen supply during development," *J. Insect Physiol.* 130, 104199. DOI: 10.1016/j.jinsphys.2021.104199

Long, W. (2021). *Timber Engineering*, 4th Ed., China Archit. & Building Press, 799-835.

Ma, H.-l., Xiang, J.-k., Zhang, G., Ma, T., Yan, B., Wu, C.-k., and Li, Z. (2018). "The use of ultrasonic CT to detect defects in timber structures of historic buildings," *Sciences of Conservation and Archaeology* 30(6), 74-81.

Ma, X., Jiang, M., and Wang, J. (2015). "The climate change effects on boundaries of wood decay and termite hazard zones in China," *Scientia Silvae Sinicae* 51(11), 83-90. DOI: 10.11707/j.1001-7488.20151111

Ma, X., Wang, L., Zhu, H., Liu, B., Zhang, B., Lu, Y., Wang, Y., Jiang, M., and Wang, L. (2021). "Risk zones of carpenter bees for wooden structure of ancient buildings in China," *Scient. Silvae Sinicae* 57(4), 116-123. DOI: 10.11707/j.1001-7488.20210412

Ostwald, M. M., Lyman, B. R., Shaffer, Z., and Fewell, J. H. (2020). "Temporal and spatial dynamics of carpenter bee sociality revealed by CT imaging," *Insectes Sociaux* 67(2), 203-212. DOI: 10.1007/s00040-020-00761-w

Ostwald, M. M., Shaffer, Z., Pratt, S. C., and Fewell, J. H. (2019). "Multimodal cues facilitate nest recognition in carpenter bee aggregations," *Animal Behaviour* 155, 45-51. DOI: 10.1016/j.anbehav.2019.06.023

Rau, P. (1928). "The nesting habits of the little carpenterbee, *Ceratina calcarata*," *Annals of the Entomological Society of America* 21(3), 380-397. DOI: 10.1093/aesa/21.3.380

Sansoni, G., Trebeschi, M., and Docchio, F. (2009). "State-of-the-art and applications of 3D imaging sensors in industry, cultural heritage, medicine, and criminal investigation," *Sensors* 9(1), 568-601. DOI: 10.3390/s90100568

Wang, Z., Shi, A., Wang, T., and Shao, J. (2020). "Research on mechanical properties of chinese fir in Qiandongnan," *Fujian Architecture and Construction* (6), 87-91.

You, Z. (2016). "An analysis of Wu's mansion in Fengqi, Zherong County," *Fujian Wenbo* (1), 61-65.

Yuan, X., Chen, Y., and Guo W. (2021). "Features and prevention of common damages in ancient timber structures," *Chinese Journal of Wood Science and Technology* 35(5), 54-59. DOI: 10.12326/j.2096-9694.2020165

Zhang, X., Blaas, J., Botha, C. P., Reischig, P., Bravin, A., and Dik, J. (2012). "Process for the 3D virtual reconstruction of a microcultural heritage artifact obtained by synchrotron radiation CT technology using open source and free software," *Journal of Cultural Heritage* 13(2), 221-225. DOI: 10.1016/j.culher.2011.08.004

Article submitted: February 15, 2022; Peer review completed: March 26, 2022; Revised version received and accepted: April 24, 2022; Published: April 28, 2022.
DOI: 10.15376/biores.17.2.3320-3331