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Bamboo structures: Innovative methods and applications for structural health monitoring and dissemination☆

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ABSTRACT

Bamboo is gaining more and more attention in the field of building materials thanks to its unique characteristics, such as resistance, lightness, sustainability, and flexibility. However, the widespread adoption of bamboo as a building material presents some challenges, especially in relation to the durability of the material. In fact, being a natural material, it requires protection from atmospheric agents, such as rain and sun, as well as from attacks by insects and animals. Ensuring the longevity of bamboo involves implementing tailored treatments, precise precautions, and regular structural inspections to detect any potential degradation over time. In this context, the article focused on the monitoring of a structure made of bamboo and on the testing of an innovative system to identify the structural critical issues present, in the context of a FISR project which envisaged a cultural exchange between China and Italy. Starting from the survey of the structure carried out with a drone, a 3D model was then built using a commercial software. For the monitoring phase of the structure, an innovative system was used that exploits the YOLO v5s6 algorithm to identify structural critical issues, supported by a Virtual/Augmented/Mixed reality app developed by the authors. This app is useful not only during the monitoring phase, but also in the subsequent phase of disseminating information relating to the potential of the use of bamboo in the field of structural engineering. The tested and proposed methodologies have proven to be particularly useful and high-performance, especially regarding the monitoring of bamboo structures, in relation to the resolution of problems linked to their possible fragility and limitations in certain application areas. The contribution provided in this paper by Geomatics methodologies is evident to better highlight the potential of this eco-friendly material for its desirable ever-increasing use in the construction sector by becoming aware of its potential.

1. Introduction

Bamboo is a plant that is part of the Graminaceae (or Poaceae) family and the Bambusoideae subfamily. It is a woody herbaceous plant, characterized by hollow and knotty stems called culms. It is a material known for its rapid growth and resistance and it is widely distributed in many parts of the world, especially in tropical and subtropical regions, (Cheng et al., 2023; Ben-Zhi et al., 2005). Globally, there are approximately 1250–1500 species of bamboo, comprising approximately 75–107 genera, (Kumar et al., 2023; Han et al., 2023).

From an environmental point of view, bamboo is attracting more and more interest globally for its sustainability. The research develops on two main fronts: on the one hand, it is studied and appreciated as a sustainable material that does not require complex manufacturing processes; on the other hand, it is engineered (Janssen et al., 1981) through the lamination of bamboo or LBT (Laminated Bamboo Timber), which involves dividing the material into strips and recomposing them through the use of glues (Sharma et al., 2015; Shu et al., 2020). This technique allows to overcome the natural geometric limitations of bamboo, although it could be considered a loss of some of its intrinsic structural characteristics. There are many advantages of this natural material; in fact, it grows quickly, requires few resources for its cultivation and has a low environmental impact compared to other traditional building materials such as wood or steel. This makes it an attractive option for sustainable construction and carbon emissions reduction. In fact, there are several studies that aim to quantify the carbon emissions of bamboo buildings and analyze their potential for reducing carbon emissions (Zhu et al., 2023). Xu et al., 2022 differs from

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previous studies because it explores the carbon emissions and storage of bamboo building materials by considering each phase (planting phase, transportation phase, production phase and construction phase) and where an overview of carbon emissions and storage of bamboo assembled components is presented.

Bamboo is a renewable natural resource characterized by a unique fibrous structure that imparts remarkable strength and flexibility to the material. Its tensile strength is comparable to that of steel, while its lightweight nature makes it an ideal choice for a wide range of structural applications. However, to fully harness the potential of bamboo in construction, it is essential to understand its mechanical properties in detail.

From a structural point of view, bamboo has various characteristics that make it unique in its kind. These mechanical characteristics are influenced by its structural composition and there are many studies aimed at determining the parameters that influence them (Emamverdian et al., 2020; Wang et al., 2020; Lou et al., 2021).

As it is known, the specific characteristics of bamboo can vary depending on the species (Escamilla et al., 2018; Fahim et al., 2022), age and growth conditions, but those common to all types of bamboo can be summarized in resistance, lightness and flexibility.

Particular attention from an engineering point of view is being paid to the so-called Glubam. Glubam is produced by joining thin layers of bamboo together using adhesives and pressure to form a strong and durable composite material. The process of making Glubam involves the selection and preparation of bamboo, which is cut into thin strips and then glued together. The layers of bamboo can be arranged in different directions, like the thread of wood, to achieve the desired mechanical properties. The resulting material is then subjected to pressure and heat to ensure good adhesion between the layers and greater solidity of the structure. Glubam offers several advantages as a building material. First, it has excellent mechanical properties, including tensile, compressive, and flexural strength, making it suitable for a variety of structural applications. Additionally, this material is known for its dimensional stability, meaning it is less prone to warping than solid bamboo. This makes it a reliable option for use in buildings and structures. Another advantage of Glubam is its greater resistance to weather, insects and animals compared to untreated bamboo. Thanks to the use of adhesives and the lamination process, Glubam is more resistant to humidity and degradation, thus increasing its durability over time. The use of Glubam as a construction material offers several advantages, primarily due to its ability to reduce overall environmental impact compared to conventional building materials. Bamboo is a renewable resource that requires fewer resources and less energy to produce, resulting in a lower carbon footprint. The utilization of Glubam in construction also promotes sustainable forestry practices. Bamboo grows rapidly and can be harvested without causing long-term damage to the environment. Additionally, its strong and versatile nature makes it suitable for a wide range of construction applications, further enhancing its appeal as an environmentally friendly alternative. Therefore, it enables a greener and more environmentally conscious approach to construction.

Although bamboo is a natural material, it can boast a set of regulatory documents that legitimize and regulate its use. Unlike other natural materials, bamboo has gained widespread regulatory acceptance. In some countries such as Colombia, Peru, Ecuador and India, bamboo is included in national legislation with the same rights as materials commonly used in construction. In other parts of the world, there are standardization rules that establish criteria for the structural use of bamboo. Beginning in 2000, the ICBO Evaluation Service, Inc., under the International Code Council, introduced evaluation standards for bamboo in the United States. In 2004, ISO standards were established for bamboo in Europe. These standards provide guidelines for the design, construction, and safe use of bamboo in structures. The presence of regulatory documents specific to bamboo indicates recognition of its validity as a building material and provides a basis for the widespread and safe use of bamboo in architectural and construction practices. This helps promote the adoption of bamboo as a sustainable and versatile resource in the construction industry.

The possibility of using bamboo as a primary material in the construction industry is given by the resistance capacity of the material. As known, it develops over time, reaching its maximum between 3 and 5 years of growth, in conjunction with the process of formation and hardening of cellular tissues. It is important to note that the resistance varies depending on the different components of the bamboo, influencing the response to external agents in diverse ways. In areas where there is a greater concentration of vessels and fibers, the specific weight increase in a manner correlated to the performance of the material: the greater the density and specific weight, the greater the resistance. For example, in general, the upper part of a bamboo culm will have higher mechanical performance than its lower part, and the same applies to the external part of the section compared to the internal one. However, this is not always true. From the literature, it emerges that if bamboo has been subjected to unfavorable environmental conditions or structural damage, there may be a variation in the distribution of mechanical properties along the culm. Additionally, factors such as bamboo species, age of the plant, and growth process can influence the mechanical characteristics of the material. Another principal factor is the moisture content as reported by Sylvayanti, et al. (2023): "Moisture content is crucial, especially on hygroscopic materials, because it affects their volume and mass, affecting other properties." The compressive strength of bamboo varies depending on the direction in which the load is applied. When the load is parallel to the orientation of the fibers, resistance is maximized, while when the load is orthogonal, resistance is minimized. Furthermore, bamboo's behavior varies depending on where the load is applied along the culm, with greater performance in the internode areas., (Greco, 2017).

In other words, as it can be seen from the different bibliography present in international literature, bamboo shows a notable ability to resist tensile and bending forces with resistance values comparable to those of steel and which indicate its suitability as a structural element. These results highlight the exceptional mechanical properties of bamboo as a structural material, (Hegde and Sitharam, 2015; Yadav and Mathur, 2021).

For this reason, in recent years, bamboo has gained new prestige in the field of architecture at an international level. Another factor that favors the widespread use of bamboo is its adaptability to emergency situations, such as in the case of natural disasters or immediate housing needs. Its affordability, availability, simplicity, and speed of use, combined with its high mechanical performance, make it an excellent and frequent choice in these situations, especially in Asian countries.

As regards shear strength, the literature reports average shear strength values of around 12 MPa for (Greek) bamboo. These relatively low values must be considered in light of the structure of the material itself, which has no transversal fibers but only a cohesive matrix that is unable to resist significant stress. The joints between the elements represent a weak point in the design of bamboo structures. This is due to several reasons, including:

1. Differences between the elements to be connected: Bamboo is a natural material, and the elements used may present variations in diameter, thickness, and section. These differences can affect the strength and stability of the joints.

2. Circular and hollow profile: It has a circular profile and a hollow section, which makes the connection between the elements more complex than materials with more regular sections, such as wood or steel.

3. Rigid and smooth outer surface: The outer surface of bamboo is stiff and smooth, which can make it difficult to achieve good adhesion and tensile strength in joints.

4. Poor shear strength: It has poor shear strength due to its composite structure, which consists primarily of a cohesive matrix without significant transverse fibers. This can limit the material's ability to withstand shear stresses in joints.

5. Orthotropicity: Bamboo is an orthotropic material, which means

that its mechanical behavior varies depending on the direction of the applied stresses. Since bamboo fibers grow only in the longitudinal direction, the material is inhomogeneous in its response to stresses applied parallel or orthogonal to the surface of the element. This can result in uneven stress distribution in the joints. However, when it comes to diaphragms, there might be a greater dispersion of fibers, thus leading to variation in mechanical properties compared to parts of the culm with more directional fibers.

Therefore, when designing bamboo structures, it is crucial to address these joint challenges and adopt appropriate solutions to ensure the overall strength, stability and durability of the structure.

To address these issues, several connection, and jointing techniques specific to bamboo have been developed. These techniques include the use of nails, screws, bamboo bindings, metal connectors and the use of resins or glues (Moran and García, 2019; Widyowijatnoko and Harries, 2020; Ghavami and Moreira, 1996; Seixas et al., 2021).

In addition to the connection problems between the various elements, as mentioned previously, bamboo presents problems related to durability. The bamboo used in structures, in fact, can present various degradation problems which can compromise its resistance and durability over time. Bamboo is a porous material that can absorb moisture from its surroundings, encouraging the growth of mold, mildew, and rot, which can weaken the structure. Another widespread problem is attacks by insects and parasites. Bamboo is susceptible to attacks from termites, ants, and beetle larvae, which can burrow into the material, causing considerable damage to the structure (Yadav and Mathur, 2021). Natural degradation is another factor to consider. Over time, bamboo can undergo a process of aging and degradation linked to exposure to atmospheric agents. This can lead to a loss of strength and the formation of cracks or fractures. Finally, movement and deformations of bamboo can be a problem. This material is subject to movement and deformation, especially in response to changes in humidity and temperature. Such movements can cause cracking or detachment of joints in structures. To prevent and address these issues, it is essential to adopt prevention and protection measures. This may include the application of pesticide and antifungal treatments, the use of protective finishes to reduce moisture absorption, as well as the use of robust joints and connections to ensure structural stability (Zhang et al., 2023). A full comprehensive review by Bala and Gupta, 2023 reports not only the physical and mechanical properties of bamboo structures and a detailed description of the fire performance of bamboo culm and engineered bamboo but also summaries the principal key issues of bamboo elements and their solutions: “Round culm bamboo is not suitable for structural applications whereas, laminated bamboo and bamboo scrimber are value added EBPs, most popular for structural applications due to their standard shape and size with controlled variation in physical and mechanical properties along the longitudinal, radial and tangential directions.” Furthermore, it is important to conduct regular checks and maintenance to promptly identify signs of deterioration and intervene accordingly.

In this context, the ability to manage information regarding the state of degradation of bamboo and in particular of the joints in constructions made with this material is undoubtedly useful.

In relation to the survey and monitoring phases of structures and infrastructures in general, there is a growing interest in the use of UAVs (Remotely Piloted Aerial Vehicles). These technologies allow to carry out detailed surveys, becoming a versatile tool to identify problems at a structural level, such as cracks, lesions or any type of damage to the building or structure. In the literature, it is possible to find several studies that deal with the use of drones for structural surveying. UAVs, in fact, are frequently employed to construct 3D models and for inspections especially regarding reinforced concrete structures and infrastructures (Ivić,et al., 2023); however, there is limited literature on their use in monitoring the condition of a structure and conducting quantitative analysis with Structure from Motion techniques, less can be found regarding the use of this technology to monitor bamboo structures (Chaudhry, et al., 2020; Heichel et al., 2023)

The process through which it is possible to conduct these types of investigations is based, as is known, on Structure for Motion technology. It involves the use of the images captured by the drone to create a point cloud (first sparse and then dense) and, consequently, a 3D model, using conventional photogrammetric techniques. The photogrammetric dataset, in fact, rather than coming from an airplane, comes from a drone, which, following a pre-set flight plan, depending on certain parameters, takes a certain quantity of images which, once processed using appropriate image processing software, provide as output the 3D model of the detected structure or infrastructure, which is measurable and scalable (Barrile et al., 2021; Candela et al., 2019). Within the panorama of photogrammetric software, it is possible to choose between algorithms and programs with distinct functions and methodologies, each optimized for certain types of survey or instrumentation used. In this study, we focused on the Agisoft Metashape software, based on the Structure for Motion algorithm, which allowed to reconstruct a point cloud using photographs and from this a measurable and usable three-dimensional mesh for the purposes of the study (Kleinsmann et al., 2023; Godone et al., 2020).

Regardless of the use of the images acquired by the drone for the construction of the 3D model, they can still be processed subsequently or in real-time with Machine Learning techniques which, using sophisticated algorithms, allow the identification of particular regions of interest. There are several types of algorithms depending on the objectives and desired results, and numerous studies highlight their advantages and disadvantages. In the context of Structural Health Monitoring, artificial intelligence and machine learning are gaining more and more importance (Gupta, 2023; Zhong et al., 2022).

In fact, machine learning algorithms can analyze enormous amounts of data and predict potential structural problems with high precision. In general, they can be used for structural monitoring, highlighting structural variations or anomalies, and identifying potential problems. These algorithms allow the prediction of structural deterioration, (in some cases particularly relevant for bamboo structures), using historical data and other parameters characteristic of the environment and the structure under examination. Identifying structural problems is, in fact, an area where the application of machine learning algorithms can be extremely useful. For example, Zhou et al., 2021 used Support Vector Machines to develop an automated method to translate hysteresis loop analysis results obtained from structural health monitoring into nonlinear fundamental models. Other studies, such as Chang et al., 2018, have employed neural networks to interpret damaged structures in terms of damage locations and severity, as well as the residual performance of damaged elements. In another study, Gu et al., 2021, a method based on evidence theory and a random forest algorithm was developed to extract the factors influencing a dam. There are also algorithms capable of detecting objects in real time in images and videos, such as YOLO (You Look Only Once) (Lan et al., 2018; Liu et al., 2018; Chandana and Ramachandra, 2022).

Although its original application was designed for the purpose of identifying people or objects in the frames of a video or image, YOLO algorithm can be used to identify objects or patterns in complex structures. This algorithm uses a convolutional neural network architecture to divide the image into a grid and create "bounding boxes" in which the object fits within a cell of the grid (PyTorch, 2023).

The information acquired through the analysis of the structure, as well as the characteristics of the material themselves, need to be shared with an increasingly wider audience (both for the personnel responsible for managing the infrastructure and for the simple user who wants to know its potential), the concept of digitalization of information is becoming increasingly established. To this end, the information acquired relating to a 3D model and more generally that relating to the state of deterioration of structures and infrastructures can be professionally managed using suitable dedicated virtual/augmented and mixed reality apps. Such applications are widely known in this field (Chiang et al., 2022; Arena et al., 2022; Wang et al., 2022) and allow the acquired information to be visualized, analyzed, and disseminated. In fact, if on the one hand these apps allow to analyze the data collected for monitoring structures, on the other hand they can represent powerful tools for informing on the potential of still little-known materials, such as bamboo (Kohli et al., 2022; Hasan et al., 2022; Martins et al., 2022).

In this context, the present study addressed the survey of a structure whose roof is made of bamboo as part of the FISR/GoForIT/CRUI Foundation Project "Seismic assessment of bridges and viaducts with Remotely Piloted Aircraft Systems (RPAS) and Artificial Vision" in collaboration with Zhejiang University (China) and the Department of Engineering Structure of the Sapienza University of Rome. The CRUI Foundation made a research grant available to the Mediterranean University of Reggio Calabria which allowed a PhD from the Mediterranean University to gain professional experience in a foreign institution, namely Zhejiang University in China.

Initially, the survey was carried out using a DJI Mavic 2 Pro drone and subsequently the images were processed using a commercial software called Agisoft Metashape, which uses typical Structure from Motion algorithms. This process allowed to create a three-dimensional model of the structure in a detailed and accurate manner. Subsequently, through the YOLO v5s6 algorithm, an automated and innovative method based on a deep learning object detection model (YOLOv5s6) was implemented to capture and identify deteriorations in bamboo structures using bounding boxes which allowed the identification of problems relating to joints of the selected bamboo structure. The authors then concentrated on the implementation of a virtual, augmented and mixed reality application, which made it possible to analyze the different parts of this structure as well as disseminate the information, thus making it better available and usable by both the operators assigned to maintenance and to the individual user in order to know the properties of these types of structures. This app is particularly useful during the monitoring and management phase of the structure, and it has some advantages. The application, in fact, allows to view the structure in an immersive and interactive way, allowing operators to explore details and specific parts of the structure without having to be physically present on the site. This reduces the need for travel and physical access to potentially dangerous or difficult to reach areas, increasing operator safety. Furthermore, the application can provide additional information on the state of degradation of the structure, through the integration of data obtained from the use of YOLO. This allows a more accurate assessment of the structural conditions and facilitates the planning of maintenance or intervention activities. Finally, it can promote communication by raising awareness about the use of this innovative and eco-friendly material. This therefore allows an innovative and dual purpose of monitoring but also of disseminating the opportunities that this material can bring.

2. Materials and methods

The methodology advanced in the following study was applied to a structure located at the entrance of the Zhejiang University, Yuhangtang, Hangzhou, located in the eastern part of China, a higher education institution that hosts the Faculty of Civil Engineering (Civil Engineering College) in relation to FISR/GoForIT/CRUI Foundation Project "Seismic assessment of bridges and viaducts with Remotely Piloted Aircraft Systems (RPAS) and Artificial Vision" in collaboration with Zhejiang University (China) and the Department of Engineering Structure of the Sapienza University of Rome. Fig. 1 shows a map of the area in which the detected bamboo structure is located.

The roof system structure, erected in 2017, consists of a space beam composed of Glubam and steel, with dimensions of 12 m x 3.6 m. This structure is composed of 2 $\times$8 identical square pyramids, with the vertex positioned on the lower curb. The base of each module is 1200 mm$\times$1200 mm, while the height is 849 mm. Accordingly, the in-plane dimensions of this space structure are 2400 mm$\times$9600 mm.

In order to develop a virtual/augmented/mixed reality application with the dual purpose of visualizing and monitoring the state of damage and deterioration of structures, as well as disseminating information on this eco-sustainable material and its engineering applications, it is necessary to follow a series of steps: the survey, the 3D modeling of the structure, the application of the YOLO v5s6 model to the images of the structure, and the import of the model and information relating to the structure within the virtual/augmented/mixed reality application.

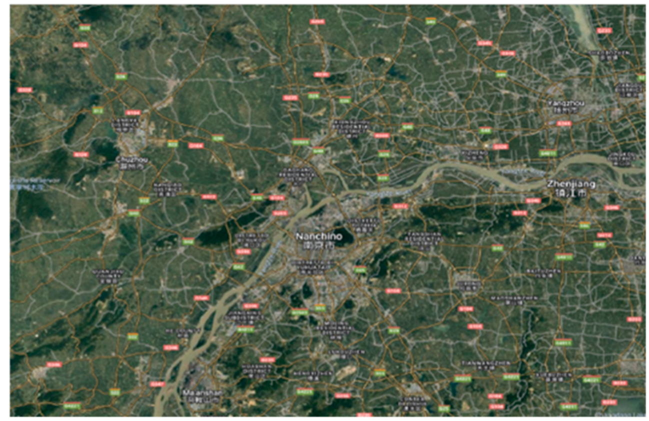


Fig. 1. Cartographic representation (extrapolated with the QGIS software via Google Labels and Google Satellite basemaps) of the area in which the bamboo structure is present at Zhejiang University, China.

As regards the survey of the structure, we proceeded using the Mavic 2 Pro drone. This drone uses a high-resolution camera with integrated GPS to geotag each photo and record the location information in EXIF files. The main characteristics of the drone mentioned above are shown in Table 1:

Table 1
Characteristics of the Mavic 2 Pro drone used for the survey phase.

Sensor	Sony FC220 – CMOS 1/2.3"
Image resolution	12.35 megapixels
Lens	28 mm f/2.2
Real focal length	5 mm
Effective sensor width	6.7 mm
ISO range	100–1600
Electronic shutter speed	8 s – 1/8000 s
Image size	4000 $\times$3000 pixels
Geotagging	Built-in GPS

The flight plan for this study was programmed in such a way as to obtain a Ground Sampling Distance of 0.5 cm/pixel guaranteeing a horizontal overlap of 80% and a vertical overlap of 20%. To set the flight plan, the commercial application Pix4D was used in free flight mode, taking photos on a 1 m x 1 m grid both vertically and horizontally. The reason we chose to use drones for the survey, along with the YOLOv5s6 algorithm, stems from several key advantages they offer over available alternatives. Beginning with drones: their flexibility and accessibility are among the primary benefits. Thanks to their ability to reach areas difficult to access with traditional methods, such as rugged terrain or hazardous environments, drones ensure comprehensive coverage of the survey area. Additionally, due to the high spatial resolution of the images captured by drones, we can obtain precise details to analyze and map terrain features accurately. Economically, drones are a cost-effective choice and provide near-real-time data, allowing for rapid decisions and timely responses to any changes in the survey environment. Turning to the YOLOv5s6 algorithm, it was chosen for several reasons. Firstly, it offers state-of-the-art performance in real-time object detection. Its speed and accuracy are extraordinary, making it ideal for integration with drones, where limited processing capability requires efficient algorithms. Its excellent precision and generalization capabilities make it suitable for a wide range of object classes and environmental conditions. Additionally, the ease of deployment and integration of YOLOv5s6 into existing workflows is another significant advantage. Thanks to its open-source nature and detailed documentation, it can be customized and adapted to specific use cases.

The image processing phase involves several steps: cleaning the images to remove noise and artifacts using Gaussian blur; color correction, which adjusts brightness, contrast, and color balance; and pre-processing, the most fundamental step, where the image is prepared for input into the YOLO model. This involves standardizing the size and normalizing pixel values. For training the YOLO model, datasets specifically collected for the task and sourced from the web were chosen, and data augmentation was performed. The YOLO variant was configured in its architecture by selecting the number of layers (200 layers) and anchor boxes. In this particular case study, a moderate learning rate was chosen since the focus was on bolt detection. Since inferences were conducted on batches of images, a Batch Size of 32 (i.e., Speed V100 b32) was determined to be the most effective. As is well-known, "batch size" is a parameter indicating the number of samples (e.g., images) processed together in a single pass through the neural network during training or inference. In other words, during model execution on a dataset, the "batch size" denotes how many examples are processed simultaneously. Subsequently, the model was trained using the prepared datasets.

The structure of which the survey was carried out is characterized by the presence of metal bolts that connect the various parts of the structure. Bolted joints are common elements of many engineering structures which due to extreme service conditions and load factors can often be subject to deterioration or loosening. Real-time monitoring of the structure can be particularly useful in identifying loose bolts to ensure the safety and durability of structures. As mentioned above, in the literature it is possible to find several studies in relation to the application of machine learning and deep learning methods for the identification of deteriorated or loose bolts. However, most studies involve the use of these algorithms in laboratory conditions, i.e. optimal conditions with well-controlled light, distance and angle conditions. It is clear that this practice is not practicable in large-scale monitoring because there are many factors that influence the images taken by the drone. For this reason, in the present study, we chose to train the neural network model via images taken by the drone.

This aspect, together with the combination of the YOLO algorithm to identify deteriorations and loosening and the application which allows simple and intuitive use of the information, both for trained personnel and for the common citizen, constitutes the distinctive feature of this study.

Following the image acquisition phase with the drone, a process of image cleaning, color correction and segmentation of the affected areas was therefore carried out using the KNIME software. Within this software it is possible to insert the KNIME Image Processing extension which allows the processing of images within the work environment, (Alhajahmad et al., 2023). The primary features of the KNIME Image Processing extension are manipulation, analysis, filtering and visualization. Once this treatment process was conducted, we proceeded with the structural analysis for different deterioration scenarios by training the neural network also using datasets freely available on the web (Fotia et al., 2022). Its integration capabilities allow seamless merging of image datasets with other data types, enabling holistic analysis. Through Knime, users can perform transformative tasks like resizing, cropping, and rotating images, ensuring uniformity across datasets. Moreover, Knime facilitates sophisticated image enhancement techniques such as contrast adjustment and noise reduction, crucial for improving image quality. Additionally, Knime's ability to normalize pixel intensities and support batch processing ensures consistency and scalability in preprocessing tasks. As for YOLO, there are several models available. The parameters for evaluating the best model (Terven and Cordova-Esparza, 2023; Jiang et al., 2022; Majumder and Wilmot, 2023) are based on:

- size in pixels of the model which influences precision and speed
- Mean Average Precision (mAP) evaluated on a scale ranging from 50% to 95% which represents the overall accuracy of the model in object detection
- Mean Average Precision (mAP) assessed at a threshold of 50%.
- CPU execution speed in milliseconds (ms) for a single input image
- Execution speed on CPU (in this specific case V100) in milliseconds (ms) for a single input image.
- Execution speed on CPU (in this specific case V100) in milliseconds (ms) for a batch of 32 input images.
- The number of model parameters in millions.
- Number of floating-point operations per second (FLOPs) in billions (G) during inference on an image with size 640 $\times$640 pixels.

Despite its effectiveness, we encountered several challenges during testing. One major challenge was the variability in lighting conditions, which affected the algorithm's performance. In some cases, shadows or reflections could obscure critical structural features, leading to false negatives or inaccurate detections. Addressing this challenge required extensive preprocessing of the images to enhance contrast and minimize the impact of lighting variations, partially addressed with the KNIME software. Another challenge was the presence of occlusions, where structural anomalies were partially obscured by other objects or background clutter. This posed a challenge for the algorithm, as it sometimes struggled to distinguish between the structural anomaly and surrounding elements. To overcome this challenge, we experimented with different augmentation techniques and fine-tuned the algorithm parameters to improve its robustness against occlusions. Moreover, obtaining enough annotated data for training the model can be difficult, especially for rare or specialized types of bolt deterioration. Augmentation techniques may be necessary to artificially expand the dataset.

Once the results of this analysis had been obtained and the structurally deteriorated elements had been identified, it was possible to view the information acquired (3D model, point cloud, images of deterioration) in an app appropriately created by the authors. The innovation of this app consists in allowing to view information relating to a structure or infrastructure in a fast and complete as well as interactive way, allowing to have access to fundamental structural and construction information. Furthermore, by inserting the complete descriptive/technical sheet, which can be consulted by the user, it is possible to analyze the properties as well as the physical and structural characteristics of the material used, in this case bamboo. This perspective has important advantages. Users can analyze the Bamboo structure with an in-depth level of detail allowing a close-up view of its components, including the joints used to create the structure. Detailed visualization through the app can reduce inspection times in the field and allows for more in-depth analysis without the need to be physically present. Furthermore, the application could allow early visualization of signs of deterioration in the structure, allowing preventive interventions before the damage becomes serious. This can therefore be particularly useful in training any operators on the detection and management of deterioration. VR offers, in fact, an immersive experience in which users can explore the structure from different perspectives and provides detailed documentation that can be archived for future reference and evaluation purposes. Furthermore, users can collaborate from different geographical locations by discussing any interventions to be carried out in real time via shared MR. Through multiple shots taken with the drone it is possible to create multiple datasets useful for realizing a temporal evolution of the structure under examination.

In the panorama of possible software for creating virtual, augmented and mixed reality applications, Unity 3D platform stands out among all. This is a development environment that is often used in the field of these applications. It uses the integration of two types of code for its development: Javascript and C#. Within this environment, scripts are called "behaviors" and are used to capture assets in scenes and make them interactive. Furthermore, GameObjects were used which represent fundamental objects such as characters and props, equipped with graphic representation, which were associated with Mono-Behavior scripts to increase their functionality (Moiseienko et al., 2023; Jitendra et al., 2021; Wang et al., 2021; Juliani et al., 2018).

The app developed allowed the digitization of the information acquired, presenting itself as a catalog of 3D models and images that were easily accessible and consultable, also for maintenance operators for possible interventions. The app was designed to display the hologram of the structure's survey phases when the device frames the building, both on site and remotely. In detail, the application allows to view the hologram by aligning the coordinates of the device with those of the structure within a radius of 10 km from it. Alternatively, you can view the facility model and related information remotely. Mixed reality was made possible thanks to the use of the Microsoft HoloLens tool with an extension called Mixed Reality Toolkit through which the connection between the virtual and augmented reality app and the HoloLens tool was made possible (Karthika et al., 2017). Through HoloLens 2, it was then possible to allow multiple users to interact in the same mixed reality scene, allowing collaboration in virtual environments (Park et al., 2021). The app displays the 3D model of the structure on the map, associated with multimedia content, structural analysis, and links to other nearby structures (Fotia and Barrile, 2023). Additionally, choosing whether to enable GPS causes additional models to be displayed within a 10 km radius of the user. This application, in fact, uses external augmented reality which uses GPS (but also the device's accelerometer and compass) to identify the position of the device with high precision; it does not require special markers and uses technologies such as GPS to position virtual objects in the real world.

For the implementation of Microsoft HoloLens, we proceeded through various phases and commands, reported below:

1. Set up unity Environment:

- Unity Standard Configuration and Project Settings.

- Check universal Windows Platform Settings.

- Mixed Reality toolkit and application of Mixed Reality Project Settings.

2.Structure Settings:

- Addition of Open Scenes, Select Universal Window Platform and Selection of Target Device.

- Selection of Unity C# Projects and enablement of C#.

- Application of Mixed Reality Scene Settings and Starting without debugging from Drop-down menu.

Once the developed environment has been defined, we proceed with the 3D model import, associating the scripts and the basic settings to ensure interaction with it through tags and labels. The Mixed Reality Toolkit includes other scripts and tools to enhance the MR experience.

3. Results

During the survey phase of the structure, 459 photos were taken (for a total of 2.5 GB) with a total time spent for the survey of 30 minutes. Once a photogrammetric dataset suitable for the creation of the 3D model was obtained, the image processing process was started using the Agisoft Metashape software, after having previously used the KNIME software for image pre-processing. Using this software, the 3D point cloud and 3D mesh were generated separately. The generated point cloud contained 3 million points and took 6 hours to complete. Fig. 2

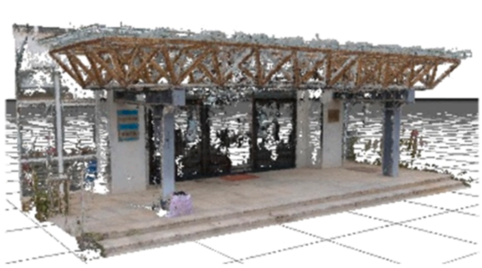


Fig. 2. Point cloud of the Bamboo structure after the 6-hour processing phase.

Fig. 3. Detail of the 3D model created using the Agisoft Metashape software.

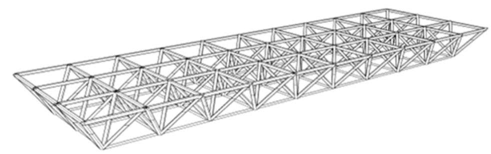


Fig. 4. CAD model of the structure obtained from the survey conducted by UAV.

shows the points cloud once processing is finished. The mesh consisted of 952,634 points and 1867,241 triangles and took 1.2 hours to complete. Fig. 3 4. shows a detail of the completed 3D model.

Once the 3D model was obtained, it was simplified using the 3D graphics software Rhinoceros 6 and the Mesh2Surface plugin transformed the acquired mesh into a CAD model.

From this 3D model, it was subsequently possible to extrapolate the geometric characteristics of the structure, shown in Fig. 5.

Once the 3D model was created to be imported into the application created by the authors, we proceeded with the analysis of the joints of the structure under examination. These joints are made of metal, and we wanted to check whether they could have deteriorated or loosened following significant loads and atmospheric agents. Through successive temporal shots of the drone, it is possible, in fact, to make important comparisons of these connections through the comparison between two different frames acquired at two successive time instants t and t+1. The possibility of easily comparing frames acquired at different moments is made possible thanks to the use of UAVs by designing the acquisition points through a suitable flight planner, with the aim of keeping the distance and angle of the camera constant. The frame obtained at time t is processed using an edge detection algorithm of the KNIME software to improve the edges and facilitate comparison with the frame acquired and processed at time t+1 (Fig. 6). In Fig. 6 the white line outlines the edge of the bolt at time t while the red outline outlines the edge of the bolt at time t+1. Obviously, the analysis was conducted on all the bolts and any significant deviation identified between the delimitation lines of the same bolt at different times suggests the need for a more detailed analysis on the potentially affected bolt.

For this reason, the images were then processed with the YOLO v5s6 algorithm (appropriately trained with datasets of images of bolts with the characteristics of interest) to identify potentially deteriorated bolts. In this case, there are two reference categories applied to the detection of

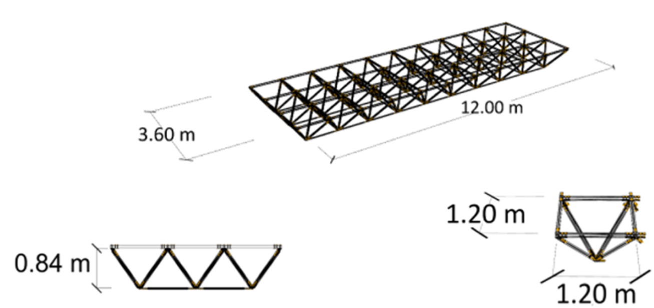


Fig. 5. Geometric characteristics of the Glubam structure of the entrance of Zhejinag University, China.

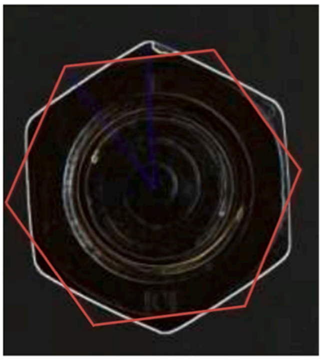


Fig. 6. Comparison of the bolt at time t and time t+1 after applying the edge detection algorithm present in KNIME.

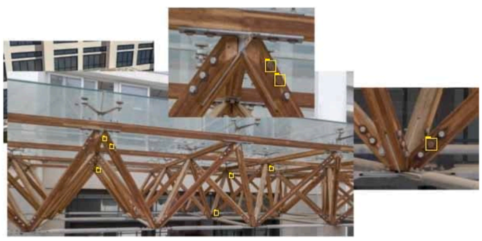


Fig. 7. Identification of bolts using YOLO v5s6 in the bamboo structure under examination. The yellow boxes highlight the bolts that present marked deterioration and loosening characteristics.

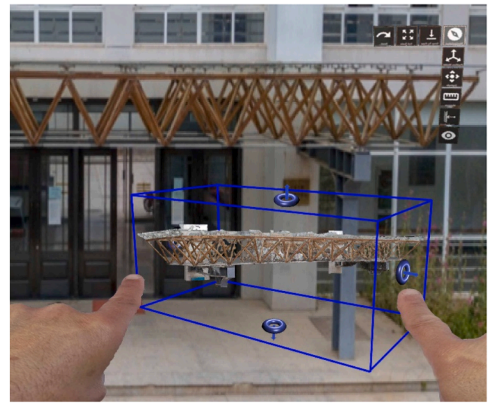
objects: "deteriorated" and "not deteriorated". Fig. 7 highlights the results obtained on the structure under investigation through the identification of the selected bolts identifiable via the yellow bounding boxes. This processing is sufficient to identify deteriorations, such as slips and breakages. Sometimes identification can be difficult due to overlapping portions of frames; therefore, to identify the bolts in these portions, multiple frames are used which, using homologous points, allow their identification.

Finally, for the main purpose of creating an information collection tool for the possible planning of maintenance interventions by the managing bodies and for the possible dissemination of information regarding both the structure and the characteristics of the materials used (bamboo), it was created a VR/AR/MR app as described in the Materials and Methods section. Fig. 8(a) shows the hologram of the 3D model of the structure when the device (with GPS activated) is near the structure. Fig. 8(b), instead, shows the interaction of the 3D model remotely from the Geomatics Laboratory of Mediterranea University of Reggio Calabria. From the drop-down menu it is then possible to view other useful sheets, which can be consulted both on site and remotely, such as the technical sheet of the materials or a BIM model of the structure which the user can share with other users simultaneously.

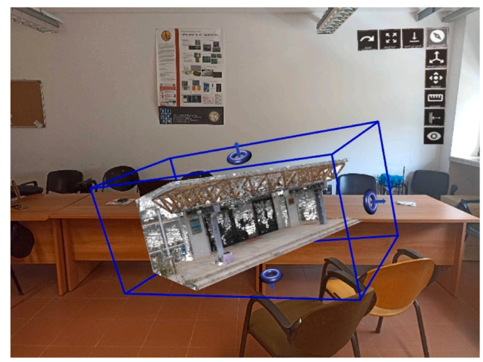
The potential of such an application is therefore evident both in terms of information management in a simple and fast manner by the managing body and in terms of engineering valorization of this material whose mechanical and physical characteristics go well with the sustainable nature of this material.

4. Discussion

The present study focused on the survey and evaluation of a bamboo roof structure located in China. The approach adopted by the authors involved the use of a DJI Mavic 2 Pro drone for the initial survey and image processing initially with KNIME, then with the commercial software Agisoft Metashape, based on Structure from Motion algorithms. Subsequently, a model was trained using the YOLO v5s6 algorithm to



(a)



(b)

Fig. 8. (a) App: virtual representation of one stage of the surveyed structure. (b) App: visualization of 3D model remotely, highlighting the possibility to interact with it.

identify issues relating to the structure's joints, made up of metal bolts. This innovative approach allowed the creation of an automated deep learning-based method to capture and identify deteriorations, using bounding boxes. The authors then focused on the implementation of an application that could allow an immersive and interactive approach to analyze the different parts of the structure and disseminate related information. In addition to the practical benefits, the application can contribute to raising awareness about the use of bamboo by disseminating the opportunities offered by this material among the users who use it.

Data collection using the drone has proven to be an efficient technique for obtaining detailed information about the structure. The image processing time, although considerable (6 hours for the point cloud and 1.2 for the mesh), reflects the complexity of the structure and the richness of the captured results. Future strategies for optimizing substantial processing time could be the parallel processing to distribute the workload across multiple CPU cores or GPU units. Parallelizing computations can significantly reduce processing time. Moreover, the use of GPUs for accelerating intensive computations can speed up tasks like point cloud and mesh generation. Another solution could be to upgrade hardware components like CPU, GPU and memory to improve overall system performance.

Viewing the point cloud and 3D model illustrates the accuracy achieved by the process.

Regarding the analysis of junctions, the analysis of temporal frames allowed detailed comparisons at different instants of time. The implementation of YOLO v5s6 subsequently enabled the automatic identification of deteriorated bolts, highlighting the capabilities of the trained model to accurately identify joint issues and underlining the effectiveness of deep learning-based approaches in complex structural contexts.

The use of the app then introduced an element of innovation and practicality in monitoring the structure. The possibility of consulting information sheets such as the technical data sheet of the materials or possibly even a BIM of the structure adds further value to the application, facilitating the planning of maintenance interventions.

The innovative monitoring system and Virtual/Augmented/Mixed Reality (VR/AR/MR) app are fundamental in addressing bamboo's durability concerns and structural limitations. The monitoring system integrates sensors and data analytics to continuously evaluate the condition of bamboo structures. Additionally, remote accessibility enables engineers and maintenance teams to access real-time data and insights from anywhere, facilitating proactive decision-making and timely interventions to address structural concerns. Furthermore, predictive maintenance could be enabled through historical data analysis and trend prediction, optimizing maintenance schedules to prevent deterioration and extend the structure's life. The VR/AR/MR app enhances understanding, visualization, and decision-making regarding bamboo structures through immersive experiences. Users can visualize the internal and external features of the bamboo structure, including nodes, joints, and load-bearing components. Simulations of stress and load distribution help identify potential areas of weakness and optimize structural design. Collectively, these high-performance aspects of the monitoring system and VR/AR/MR app contribute to addressing bamboo's durability concerns and structural limitations by enabling proactive monitoring, predictive maintenance, informed decision-making, and enhanced understanding of bamboo structures.

5. Conclusion

The research conducted represents a significant advancement in structural engineering, particularly in the field of bamboo structures, by integrating advanced technologies for detection and analysis. Focused on a specific case in China, the approach involved meticulous data collection via drones, processing using specialized software, joint analysis with advanced algorithms, and the implementation of a virtual, augmented, and mixed reality app for visualization and interpretation of results. While the findings are promising, the study has its limitations, such as the dependence on weather conditions during drone surveying and potential challenges in the temporal comparison methodology due to facility layout changes over time. However, these limitations serve as avenues for future research developments and improvements. Looking ahead, optimizing algorithms for enhanced efficiency, validating 3D models through physical measurements, refining detection algorithms to address varying light conditions, and improving app interactivity for real-time access to structural information are crucial areas of focus. These advancements not only contribute to the reliability and suitability of bamboo structures but also have broader implications for structural engineering as a whole.

Practically, the research offers tangible benefits by enabling continuous monitoring, analysis, and knowledge expansion of bamboo as a construction material. By improving advanced technologies, structural engineers can optimize maintenance strategies, improve structural integrity, and ensure the safety and sustainability of infrastructure projects.

Without doubt, this research highlights the transformative potential of integrating advanced technologies in structural engineering, offering practical solutions to real-world challenges, and paving the way for safer, more resilient, and environmentally friendly construction practices. It underscores the importance of ongoing research and innovation in advancing the field and addressing the evolving needs of modern infrastructure development. This approach highlights the advances in the field of bamboo structures, since through continuous monitoring it is possible to carry out analyzes and above all it allows the expansion of knowledge of this extremely useful material from an engineering point of view, further studies and analyzes must be carried out to allow complete reliability, suitability for any type of structure and real-time availability.

CRediT authorship contribution statement

Vincenzo Barrile: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Emanuela Genovese:** Writing – original draft, Visualization, Validation, Software, Investigation, Data curation.

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

Data will be made available on request.

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