Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/picnews.asp?id=155
DOI: 10.54113/j.sust.2022.000011

***ORIGINAL ARTICLE***

# An innovative digital workflow to design, build and manage bamboo structures

**Leonel Mimendi[a,*], Rodolfo Lorenzo[b], Haitao Li[c]**

[a]AKT II Ltd, White Collar Factory 1 Old Street Yard, London, UK, EC1Y 8AF.
[b]University College London, Gower Street, London, UK, WC1E 6BT.
[c]College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China.
[*]Corresponding Author: Leonel Mimendi. Email: leonel.mimendi@akt-uk.com.

**Abstract:** At current rates, the building industry is the major contributor to gas emissions and energy consumption in the world, placing unprecedented pressure to find alternative and sustainable construction materials, particularly in regions where urbanization and population growth are expected to rise. Coincidentally, bamboo culms are a sustainable and abundant resource with the potential to be used as a structural element in those regions, however, their organic nature and inherent incompatibility with modern design and construction procedures have hampered their formal utilization. This article presents the details of an innovative workflow based on the philosophy that the quality and reliability of bamboo structures can be computationally managed through the digitization of individual structural bamboo elements. The workflow relies on reverse-engineering processes that integrate and make bamboo culms compatible with modern data-management platforms such as Building Information Modelling. A case study based on a reconstruction project of bamboo houses in Lombok, Indonesia is presented to illustrate the proposed workflow. This work showed that digitization and management are not just to represent shapes and information regarding bamboo culms through computer software, but can also control the quality, sustainability, and structural behavior of a bamboo structure during its entire service life.

**Keywords:** Bamboo; bamboo structures; digitization; BIM

## 1 Introduction

As the building industry remains the greatest contributor to global energy consumption (35%) and carbon dioxide emissions (39%) [1], bamboo resources are being considered as a potential alternative to highly industrialized construction materials such as steel or concrete. The context for bamboo culms as a structural element is most adequate for the southern hemisphere where the material is endemic as well as most needed due to the high urbanization and population growth expected during the next thirty years [2], which undoubtedly will increase the pressure over non-renewable resources. In response to this challenge, the last three decades have seen an increment in the number of researchers, designers, architects, and engineers around the globe focusing on the utilization of bamboo culms within the construction industry as structural elements due to their lightweight, high-strength, and unparallel environmental properties [3–9].

The mobilization of this natural resource can boost the economic development of local communities through sustainable production and consumption of bamboo culms at a low environmental



Received: 10 February 2022; Received in revised form: 12 March 2022; Accepted: 20 March 2022

cost [10,11]. Statistical data shows that bamboo production, mainly in Asian countries increased in a range of 80 to 400% between 1990 and 2005 [12]. However, only six percent of the culms production was estimated to be utilized in its round nature, from which only a portion was used as structural elements [13]. The volume of bamboo culms used as a structural element is practically negligible when compared to other industrialized construction materials. This is mainly due to multiple technical challenges associated with the organic nature of this resource and the inherent incompatibility of bamboo elements with current design and construction procedures. This is, bamboo culms are produced by nature as opposed to anthropogenic construction materials which heavily rely on industrial manufacturing procedures to ensure their quality and reliability.

A key challenge is the variability found in the geometric, physical, and mechanical properties of bamboo culms [14–18], from which limited experimental data is available in comparison with the large number of species suitable for construction purposes [19]. As a result, bamboo culm structures are generally built using raw material without appropriate quality control and thorough design and construction procedures based on broad and empirical assumptions which overall prevent the quantification and managing of the structural reliability. Although several efforts have been carried out to test, classify, sort, and standardize bamboo culms of common species [20–24], which have pushed forward the development of technical codes of practice [25–27], these processes, when compared with current timber grading and classification procedures, are still in their infancy. In addition, recent studies focusing on measuring bamboo culms of different species to determine characteristic values and analyze their variability, have found weak, or in some cases, no correlation patterns between geometric, physical, and mechanical properties, which suggests that conventional standardization procedures might not be the right approach for this organic material [28,29]. In contrast, alternative and more compatible approaches for bamboo as a natural structural element have been suggested to quantify and guarantee the structural reliability of bamboo structures with the aid of modern digital technologies that help take into account the uniqueness of bamboo poles into design and construction procedures [30–32].

This article presents the details of an innovative workflow based on the philosophy that the quality and reliability of bamboo structures can be computationally managed through the digitization of individual structural bamboo elements using a combination of high-tech, affordable and low-energy digital tools. The workflow relies on reverse-engineering processes that integrate and make bamboo culms compatible with modern data-management platforms such as Building Information Modelling (BIM), from which quality of material, structural design, construction, and maintenance are coordinated, enabling the wider use of bamboo culms as structural elements and their combination with other structural systems. This article also presents a case study as an illustration of the digital workflow as part of a reconstruction project of bamboo houses in Lombok, Indonesia.

## 2 The Digital Workflow

The reason for the workflow to be digital is because the building industry is already living within a digital environment, where every aspect of a construction project from inception to maintenance, or even dismantling, is controlled through digital platforms [33–35]. BIM refers to a digital platform that represents a building, infrastructure, or landscape, as well as its functionality from inception onwards, allowing architects, engineers, and contractors to design, simulate construction and maintain a building [36]. In practice, BIM is a collection of three-dimensional (3D) representations of physical objects (e.g., columns, walls, façade, windows, among others), containing all the relevant data (e.g., spatial relationships, quantities, properties, location, among others) to ensure their correct design, installation, and functioning. The BIM objects are in some cases used as blueprints to fabricate the physical ones in workshops or factories. Subsequently, relevant properties are assigned to those BIM objects as part of the factory product specifications, which are then made available in digital catalogs. Furthermore, BIM allows the simultaneous interaction between stakeholders during the different stages of a project [37], bringing a more efficient and collaborative method of work that ensures quality. Digital platforms have also the capacity to analyze and manage the environmental impact, as well as the performance of buildings even before a contractor sets foot on site.

Conventional structural elements and materials, such as steel profiles, concrete columns, or reinforcement bars, are easily incorporated into BIM as their standard prismatic shapes, materials, or environmental properties are defined prior to their fabrication and certified during quality control procedures. This applies even for bespoke structural elements, such as free-form concrete shells, provided that the geometry can be quantified and the constituent materials of the shell are standard; however, this is not the case for bamboo culms. The organic shape of an individual culm (irregular cross-section and longitudinal spatial curvature) and irregular anatomical arrangement of its constituent materials (parenchyma and sclerenchyma cells) [3,38], increase the complexity for the culm to be represented in a digital environment. Moreover, the variability of geometric, physical, and mechanical properties within culms makes them unique [28,29,39], as opposed to standard, which not just prevents the formal utilization of bamboo culms in the building industry, but also their integration into digital platforms. This gap requires a holistic digital approach that tackles the challenge associated with the organic nature of bamboo culms while integrating them into modern platforms to properly manage the quality and reliability of bamboo structures.

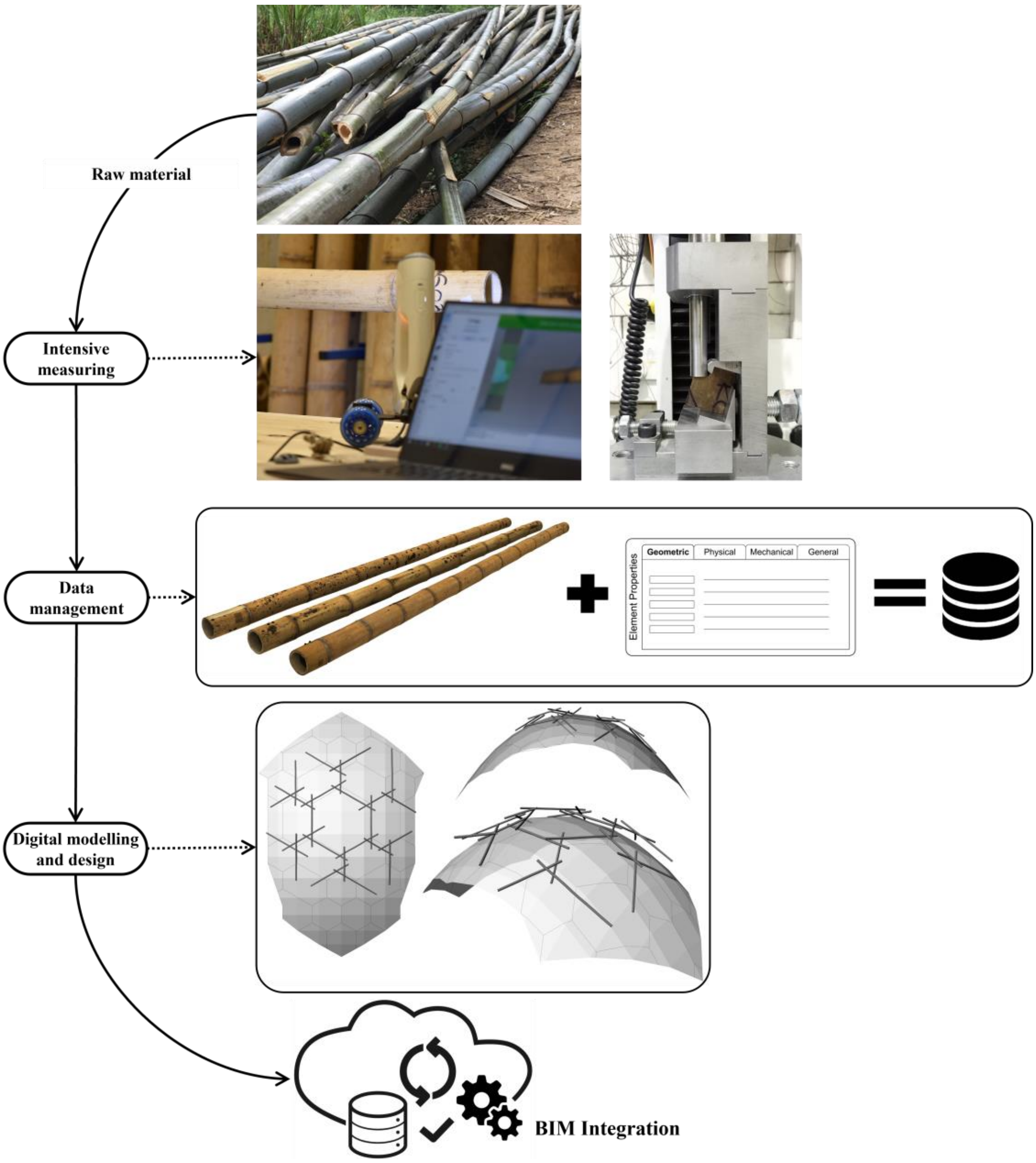


**Fig. 1.** Schematic representation of the digital workflow for bamboo structures

The schematic representation of the proposed digital workflow is shown in Figure 1 which covers all major aspects to digitize bamboo culms and integrate them into a BIM project. The process involves three main steps: i) the intensive measuring of properties for individual bamboo culms; ii) storing and managing the acquired information; iii) and effectively using the bamboo culm data as a catalog for the digital modeling and design of a structure. Each step is described in the following sections and is fundamental for the integration of a bamboo structure into a digital platform such as BIM.

### *2.1 Intensive Measuring as Quality Control*

The backbone of the digital workflow is the efficient and accurate acquisition of geometric, physical, mechanical, and other relevant properties from every single pole. Table 1 shows examples of the properties that can be measured, however, any other relevant property can also be added. The intensive measuring gathers data from different stages of bamboo production such as plantation and growth, harvesting, transportation, and storage, as well as treatment and drying procedures. There is, under the knowledge of the authors, no local producer or institution in bamboo-producing regions that currently gathers all this type of information and keeps a record for research or commercial purposes. The intensive measuring step is best situated within the scope of local bamboo producers which can allow them to not just add value to the raw material, but also better control the quality of the bamboo culms as structural products. Moreover, local producers can share the data of available stock with distributors and other stakeholders within the industry so that only an optimized selection of culms matching the structural requirements of a particular project make it to the site.

**Table 1**. Bamboo culm data gathered through an intensive measuring approach

| Intensive measuring | | | |
|---|---|---|---|
| Production data | | Technical data | |
| Plantation | • Species<br>• Sprout date<br>• Location<br>• Weather condition<br>• Altitude<br>• Soil properties<br>• Identification number | Geometry | • 3D model<br>• Length*<br>• Equivalent diameter*<br>• Equivalent thickness*<br>• Straightness*<br>• Diameter taper*<br>• Thickness taper*<br>• Volume<br>• Discrete geometry** |
| Harvesting | • Harvesting date<br>• Harvesting method | | |
| Transportation | • Type of transport<br>• Distance<br>• Other resources<br>• Energy consumption<br>• Gas emissions | Mechanical | • Compressive strength<br>• Compressive MOE<br>• Shear strength<br>• Transverse strength<br>• Transverse modulus |
| Treatment | • Type and method<br>• Treatment effect<br>• Energy consumption<br>• Gas emissions<br>• Recycling details | Physical | • Moisture content<br>• Density<br>• Fibre content |

*Assuming average values per bamboo culm

**Geometric properties of discrete cross-sections along the culm

The key data to gather from the plantation site is the species and the date the bamboo shoot sprouted. Also, each bamboo culm at the plantation site is assigned with a unique identification number (UIN) which is the direct link to its digital representation and corresponding data during its entire service life. Other data related to the location, temperature, altitude, and soil properties, as well as weather conditions throughout the growth of the culm, can help producers to increase their efficiency (e.g., yielding) and relate these properties to the quality and performance of bamboo culms as structural elements. This type of data can be acquired using low-cost digital equipment installed and managed on-site. Data related to harvesting, transportation, and treatment fill out the basic product specifications of a bamboo culm (e.g., to describe quality, durability, and recycling details) but can also help to keep track of energy consumption and gases emitted during these processes and estimate the embodied carbon for each element.

As a structural element, technical data related to the geometric, physical, and mechanical properties are required. According to the International Standard Organization (ISO), the cross-section of bamboo culms can be represented by average diameter and thickness resembling a hollow circular tube [26]. This assumption can be adopted for preliminary desk studies, however, the unique organic geometry of each culm becomes an important constraint for the fabrication and construction procedures and can only be acquired using more advanced geometric acquisition methods [30]. Moreover, the variation of the geometry has a significant effect on the behavior and capacity of structural elements [16,40,41], thus its accurate quantification is essential. Similarly, the physical and mechanical properties of bamboo culms can be measured individually, rather than assuming characteristic values highly punished by the variability found within a batch of species [29]. This provides data to estimate the capacity of a specific culm, but can also play an important role by gradually gathering experimental data of multiple bamboo species for scientific use, thus helping to improve the general understanding of the material.

The intensive geometry measurement relies on 3D scanning technology, to rapidly digitize the irregular shape of individual culms, combined with computational processing that automatically extracts cross-section properties at given intervals [28,39,42]. This digitization procedure (Figure 1) has been validated (in terms of model accuracy) and further used in research to help understand the structural behavior of bamboo culms [40–42]. The physical and mechanical properties are measured with an innovative non-destructive method that extracts and tests small coupons (similar to clear wood samples) from the ends of the culm through the use of 3D modeling, robotic fabrication, and small testing machines (Figure 1) [29]. Research has shown that although some bamboo species tend to be more appropriate for structural purposes, the high range of geometric, physical, and mechanical properties of one species overlaps with others [28,29,43]. This effectively reduces any effect of the species and thus, the intensive measuring method is equally applied to any bamboo species.

The intensive quantification of bamboo culm properties is an alternative to conventional quality control procedures for industrialized construction materials and structural elements and gives bamboo producers control over the quality of structural elements they distribute. An intensive measuring process would be impractical and inefficient if applied using conventional measuring tools and manual record of data, however, a semi-industrial low-cost and low-energy setting using the proposed digital tools enables a streamlined process that ensures the specifications required for the design, construction, and management of a bamboo structure are available within a digital environment.

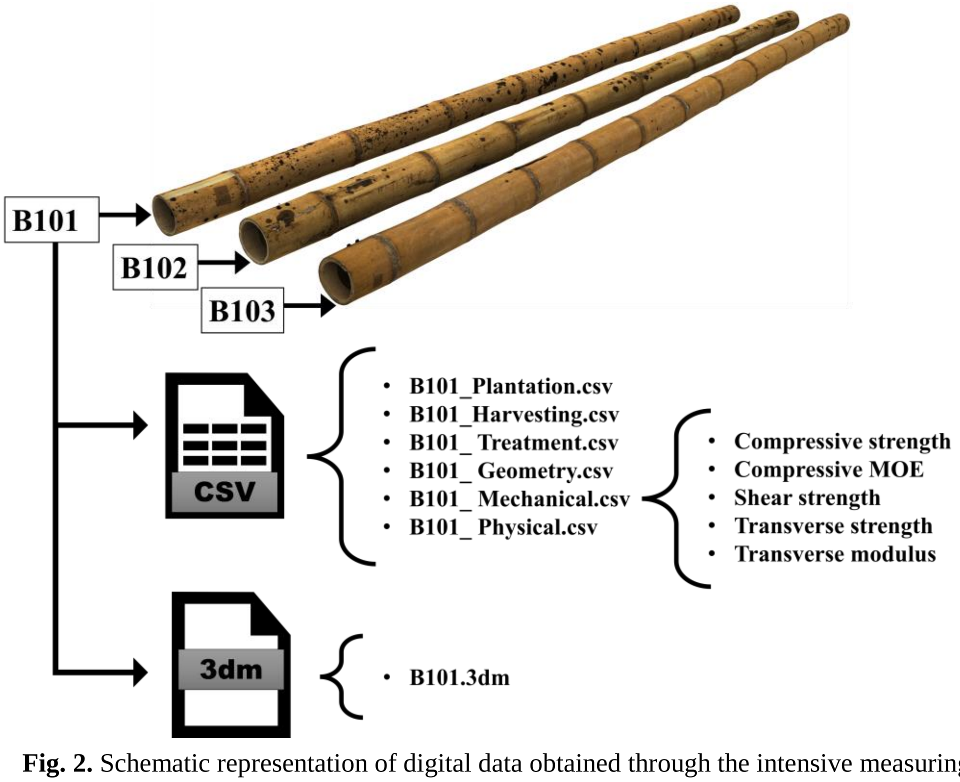


**Fig. 2.** Schematic representation of digital data obtained through the intensive measuring

### *2.2 Data management*

This step focuses on the management and organization of the data acquired so it can be queried or updated during the design, construction, and management processes. This step aims to define a simple data management approach that can be quickly adopted by local manufacturers and made available in universal data formats. Following a clear and standard approach across different producers and regions will simplify the integration of digitized bamboo culms into design and construction procedures. The main challenge is that the intensive measuring generates two types of data intrinsically correlated as shown in Figure 1: i) text-based data; and ii) a Non-Uniform Rational B-spline (NURBs) [44] 3D surface model of the bamboo culm [42]. Data gathered during the different production stages is stored in tabulated files, most known as comma-separated value (.csv) files [45], from which each file follows the same naming convention linked to the UIN of every culm. The tabulated information stored in CSV files should follow a parameter-value format as this becomes useful when creating BIM objects on a later step. Tabulated files are then stored together with the 3D model of the bamboo culm which format is a .3dm – an open-source format that allows geometry interoperability between applications [46]. Figure 2 shows a schematic representation of the data management, noting that other relevant information can be added by following the same approach.

Industrial producers of construction materials and structural elements commonly used database management systems (DBMS) to create, manage and update information about their products. Developing a product-specific database where information about natural bamboo culms is available as a product catalog has the following benefits: i) data can be added, queried, or updated for any bamboo culm at any point during production or later stages by using a unique identification number; ii) producers can have a dynamic tool for inventory control and tracking system; and iii) the database can be shared across digital platforms with costumers and distributors. However, interacting with DBMS is not a standard procedure within architectural or structural design software which commonly uses pre-loaded object libraries or import product or structural element specifications from CSV files. Therefore, although a more sophisticated data management approach can be used, it is favorable to keep data stored into flat, sequential tabulated files such as CSV. A drawback of CSV files is that the data is static, this means that in case the data needs to be updated (e.g., a bamboo culm is cut in half during the design procedure, then the data for the single culm should be replaced by two new sets of data with their corresponding UIN), the file needs to be overwritten completely, making the process less efficient and reliable when compared with DBMS.

### *2.3 Digital Modelling and Design*

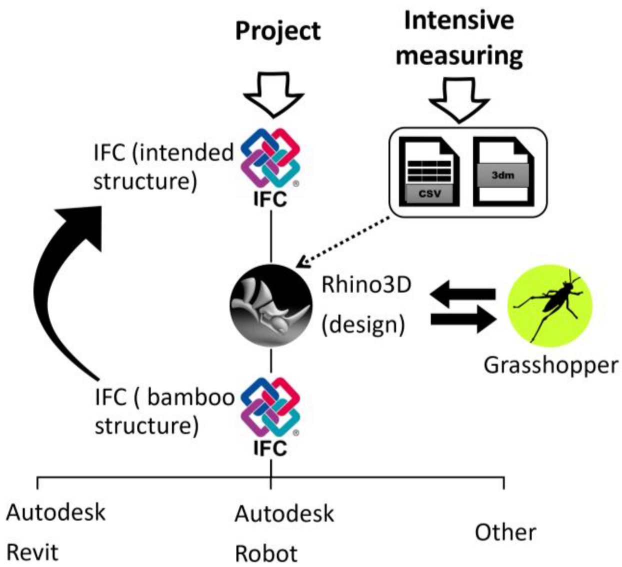


**Fig. 3.** Developing and representing the bamboo structure using IFC format

Once all relevant data has been measured and stored, the digital modeling and design of the bamboo structure can take place (Figure 1). Since every bamboo culm is unique and its properties are readily available in a digital catalog, the design is performed following a bottom-up design paradigm [47]. Researchers have started to apply this design approach for bamboo structures, where the properties of bamboo culms (e.g., geometry) are first defined, and then an optimization procedure is performed to select or assign poles to the structure based on best-matching criteria [30,31,43].

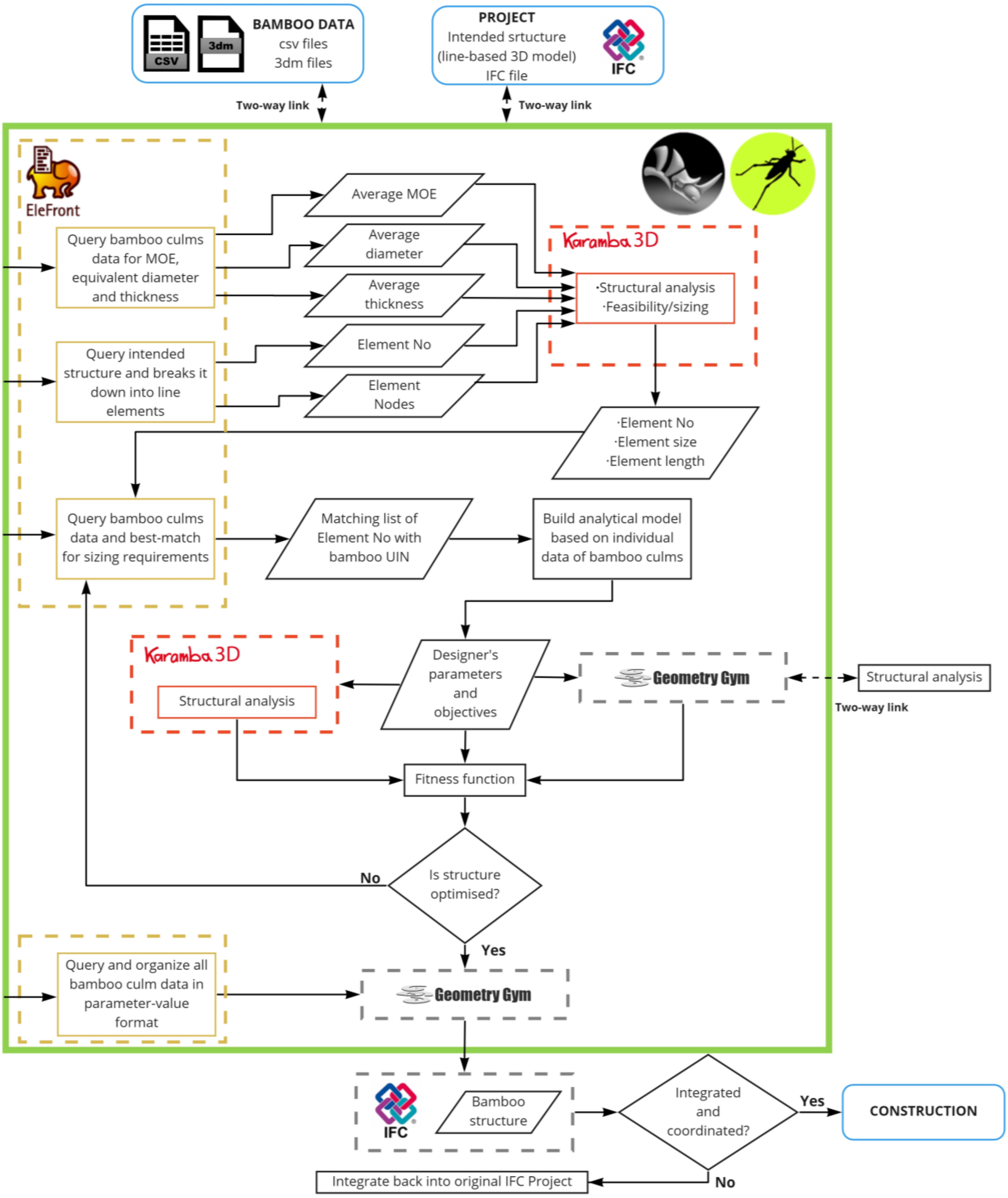


**Fig. 4. Bamboo structure design process within parametric software**

The digital modeling and design step require two inputs: i) digitized data of bamboo culms (CSV and 3dm files); and ii) a line-based 3D model where the intended structure is defined. The former derives from the data management step, whereas the latter can come from multiple sources in different file formats, therefore, the 3D model of the structure should be converted into an open-source and neutral data exchange format for BIM known as Industry Foundation Classes (IFC) [48]. The advantage of IFC is that it is a BIM format certified by ISO [49] and thus the majority of the software (proprietary and open-source) within the Architecture, Engineering, and Construction (AEC) industry are compatible with this format.

Figure 3 shows a diagram where both inputs are used to create digital information of the bamboo structure in IFC format, which can be then imported into any proprietary or open-source software, for example, Autodesk® Revit® (project visualization and coordination) and Autodesk® Robot® (finite element analysis and design) [50]. The main design software used in the digital workflow is Rhinoceros 3D [46] together with its visual programming toolkit for parametric design Grasshopper 3D [51].

Figure 4 shows the details of the bamboo structure design process which takes place within Rhinoceros 3D and Grasshopper 3D, with the aid of three further plugins Elefront [52], Karamba [53], and GeometryGym [54] to manage data, perform structural analysis and apply interoperability utilities. The process comprises five stages:

i) Feasibility/sizing study to estimate the required bamboo culm sizes for each structural element based on average properties found in the bamboo culm catalog.

ii) Matching of the size and length requirements with the available bamboo culms. An extra iterative step can be added when the available bamboo culms cannot meet the initial size criteria and therefore, the structure should be adjusted. Although this is possible, the adjustment of the structure should be based on the material at hand resulting in an entire process by itself which should be looked at separately.

iii) Building an analytical model including all relevant parameters derived from the project such as loads, service limits, constraints, or connectivity.

iv) Based on the aforementioned parameters, a fitness function is defined. The fitness function assesses (through the results of structural analysis either within Grasshopper 3D or externally) how optimal a structural configuration is based on single or multiple objectives such as minimizing deformation, volume, and/or weight, or maximizing utilization of elements. The structural configuration can change based on input parameters defined by the designer, such as the arrangement of bamboo elements, position, or orientation. These parameters, all related to geometry, can play a major role in optimizing the structure as previous research has shown that the geometric irregularity of bamboo culms significantly impacts their structural behavior [16,40,41]. Determining the design strength for each bamboo pole is independent of the present workflow and is open to the designer's criteria to define an appropriate design code such as ISO 22156 [25].

v) Importing all available data of each bamboo culm to generate the corresponding BIM objects of the culms to be used in the structure. The BIM objects are subsequently used to build the IFC file of the bamboo structure which is finally shared for project coordination.

### *2.4 Integration and Coordination*

Digital platforms are already being exploited by architects and engineers as explorative, effective, and collaborating tools. The coordination can be simply defined as the sharing of design information from different disciplines regarding a specific project so that all stakeholders can view, revise, comment, modify or approve any component of the building within the same platform (BIM). Coordinating the bamboo structure is as fundamental and required as any other component, yet this is commonly dismissed for bamboo structural projects as the BIM model is unavailable.

As shown in Figure 1, the final step of the proposed workflow is the integration of the bamboo structure IFC file into the main BIM project (from which the intended geometry of the structure was extracted), where the bamboo structure interacts with other structural and non-structural systems. Any updates in the original project or clashes will induce an iterative process where the bamboo structure is adapted accordingly through the design stage (Figure 4) until coordination is finished and the building is ready for construction. Once the structure is integrated and coordinated, the BIM model of the bamboo structure can be further used to manage its maintenance. Maintenance is an inherent process for all structures, however, for bamboo culms, it becomes paramount due to its organic nature.

## 3 Case study

The chosen case study illustrates the potential of the proposed digital workflow to ensure high-quality and reliable bamboo structures through the digitization of bamboo elements and subsequent integration of bamboo structures into the modern building industry. This case study is based on a reconstruction project in Lombok (Sajang village), Indonesia funded by Ramboll Foundation in partnership with Grenzeloos Milieu in 2019 following the 2018 earthquake which damaged more than one hundred thousand homes [55]. Figures 5 and 6 show the structural model and completed structure which is a simple triangulated frame structure. Columns are connected to the ground slab through short steel tubes where the bamboos are inserted and fixed with bolts. The connectivity between columns, beams, and bracing is through a combination of bolts and traditional lacing.

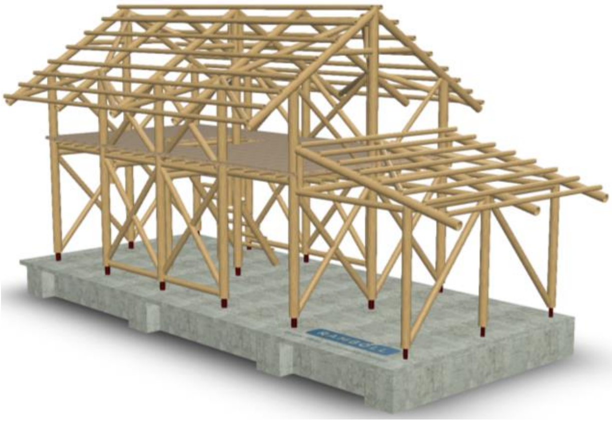

**Fig. 5.** Structural model of bamboo house developed by Ramboll. [55]

**Fig. 6.** Bamboo template house during and after construction (image extracted from [56])

**Fig. 7.** Bamboo culms on-site, Lombok, Indonesia. **Fig. 8.** Digitization of bamboo culms in Lombok, Indonesia

Traditionally, bamboo culms for any project are procured following a basic semi-empirical grading system on the raw material (Figure 7) lacking the maturity of that used for timber. This research postulates that an alternative approach to characterize bamboo poles can be based on the intensive but efficient measurement of their individual properties. Thus, engineers can use the bamboo data to design bamboo structures through modern digital tools, while providing builders with graded material to support their activities on-site.

The focus of this study is on the typical planar frame of the structure, comprised of three columns, one beam, two rafters, and six bracing elements (thirteen elements in total). The bamboo species was Dendrocalamus Asper (Petung) for columns and beams, and Gigantochloa Apus (Tali)for the remaining elements.

### *3.1 Measuring and digitizing*

Figure 8 shows the geometric digitization of the bamboo culms during the site visit to Lombok. The equipment utilized was a structured light Artec Eva 3D scanner [57], capable of capturing two million points per second with a resolution of 0.5 mm at a maximum frame rate of 16 fps. The geometric data captured by the scanner was processed by a laptop Dell XPS 15 equipped with an Intel i7-6700HQ CPU @ 2.66 GHz, 16 GB of memory, and a video card Nvidia GTX GeForce 960. The thirteen bamboo culms were scanned by the simultaneous rotation and translation of the culm along and about its main axis, making sure that the cross-section and a portion of the internal wall at each end were scanned. The post-processing of the scanning raw data (3D mesh), and its further conversion into a NURBs surface model followed the detailed procedure presented in [42,43]. Figure 9 shows the surface model of one of the bamboo culms scanned (Figure 9a) from which discrete cross-section properties are extracted to numerically describe the bamboo culm's irregular geometry (Figure 9b) [28]. The numerical description of the geometry comprises a collection of centroids along the axis of the bamboo, which when joined by straight lines form linear discrete elements that represent the bamboo culm's centroidal line. Actual cross-section properties of the culm are estimated at the mid-point of, and perpendicular to each discrete line. These properties are useful to estimate average values for preliminary structural analysis (first step of proposed design process) but play an important part to estimate and optimize the structural behavior of the structure at later steps. Figure 9b also shows an average centroidal line, which is an imaginary best-fit line that minimizes the out-of-straightness deviations of the culm and helps as a reference during the design process.

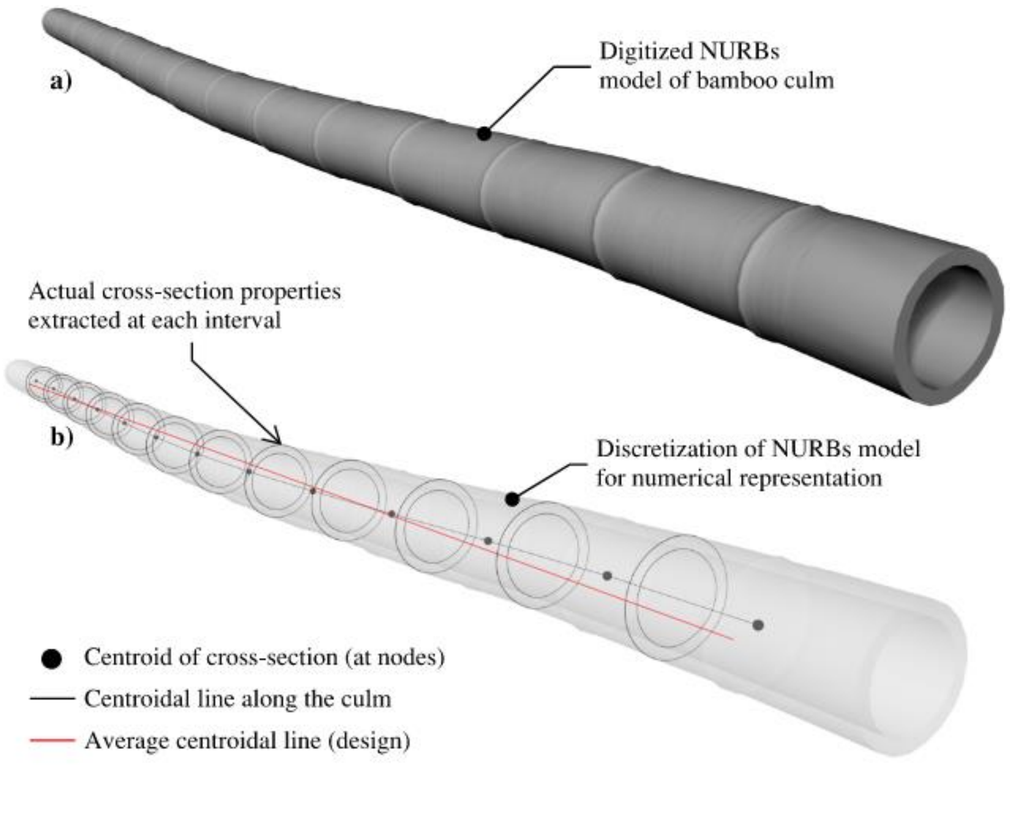


**Fig. 9.** Digitized NURBs model (a) and discrete cross-section properties (b) of a bamboo culm

Prior to the geometric digitization, small portions from the ends of the thirteen selected bamboo culms were cut and collected to produce small bamboo clear samples and perform the testing of physical and mechanical properties. The fabrication and testing of the clear bamboo samples took place at UCL at Here East laboratory, where a streamlined process combining affordable scanning and automated fabrication equipment was used to produce the samples, adapting the fabrication toolpath to the organic shape of the culm to ensure the quality of the specimens. Figure 10 shows a snap of the fabrication process where the portions of the thirteen bamboo culms were first clamped to a working table and scanned using a Structure 3D scanner [58] to acquire the bamboo culm's outer geometric surface and thus produce a toolpath adapted to the shape of the bamboo. The samples were then produced using a Kress 1050 FME-1 milling motor attached to a small industrial robotic arm Kuka Agilus KR 10 R1100 [59]. This semi-automated fabrication method to produce clear bamboo specimens was adopted from [29,43]. The testing procedure was performed according to the Chinese standard JG/T 199-2007 [60] whereas the sampling method follows a method adopted in [29]. The sampling method is based on a minimum of four clear bamboo samples per mechanical or physical property to maintain the integrity of the entire piece of bamboo culms, whichever its standard or commercial length. Although this sampling and testing procedure has been shown to give a good approximation of the mechanical properties of full-size bamboo culms [61], the low number of samples poses a statistical disadvantage to estimating characteristic values per individual pole. Instead, this sampling and testing method can be further used as a sorting approach to manage the variability of bamboo poles and estimate characteristic values [43]. The refinement of the sampling and testing method is out of the scope of this research, however, the concept of intensive measuring and digitization paves the way for further research.

Figure 10 shows the clear bamboo samples, their fabrication, and the testing process for the thirteen bamboo culms. The geometric, physical, and mechanical properties obtained during the intensive measuring were stored in separate CSV files, following the corresponding naming convention according to the bamboo culms' UIN.


**Fig. 10.** Extraction, fabrication, and testing of clear bamboo samples.

### *3.2 Design process and BIM integration*

Figure 11 shows a summary of the design process (Figure 4). The first step was to import the IFC model and data of the bamboo culms into Rhinoceros 3D/Grasshopper (Figure 11a), from which one of the structural frames was isolated to extract a line-based model of the intended structure (Figure 11b).

As the number of bamboo culms was equal to the number of elements required, the preliminary analysis was not run, instead, bamboo culms were matched to each structural element based on two parameters: i) length of the culm; and ii) average cross-sectional area (Figure 11c). The largest cross-section areas were used for columns and beams, making sure that the length was sufficient. The following step was to query all relevant data of each bamboo culm using its UIN (e.g., actual cross-section properties, MOE, among others) so that the line-based intended structure was replaced by discretized bamboo culm elements (Figure 11d). To position the discrete bamboo culms, the best-fit line reference (shown in Figure 9b) of the culms was aligned with the line-based intended structure.

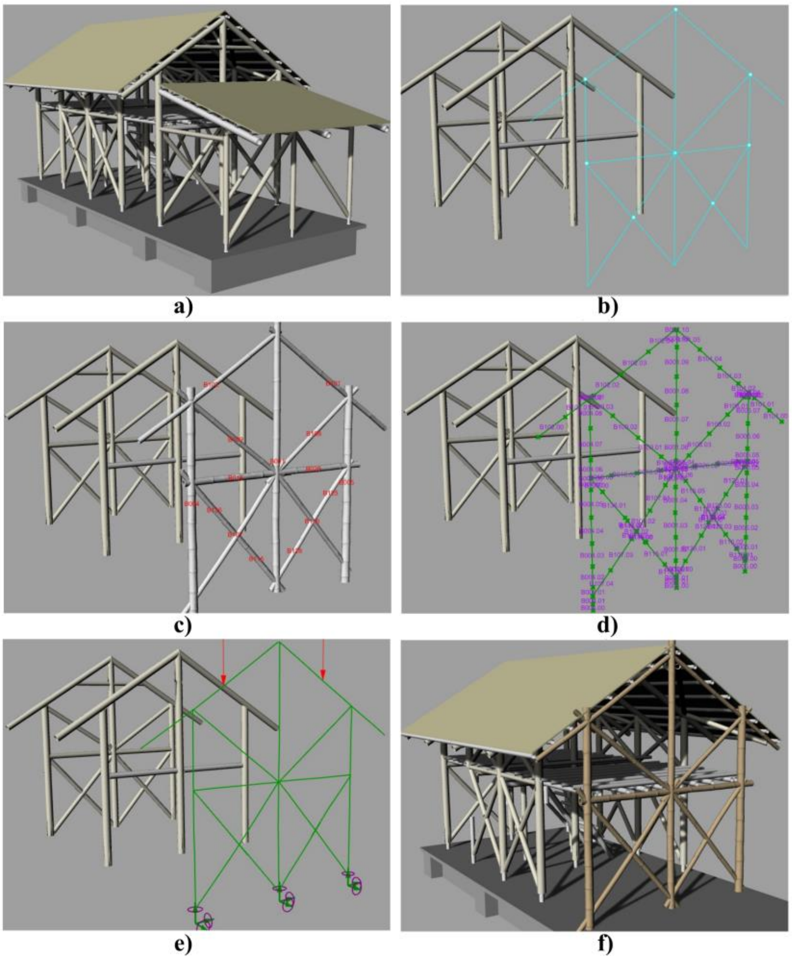


**Fig. 11.** Structural design process. a) Original IFC template house. b) Line-based model of intended structure (blue). c) Matched bamboo culms and intended structure based on geometric parameters. d) Discretized bamboo culms on the frame. e) Analytical model of bamboo culms. f) Preview of 3D bamboo culm frame

Subsequently, the analytical model was built within Grasshopper, defining the required supports, loading, and connectivity parameters (Figure 11e). It is important to notice that due to the spatial curvature of the culms, their centroidal lines did not intersect (i.e, each bamboo culm was technically considered as a separate structure). The approach taken to connect the analytical model was to define short links located at the closest points between two connecting elements. Another approach could be to “force” centroidal lines to intersect as the bamboo elements are being “placed” in the model. The advantage of the proposed workflow is that allows the designer to control the modeling and design criteria, as well as the behavior of the structure based on the constraints of the project. In addition, stiffness, constraints, and capacity of the connections have to be considered by the designer’s criteria. This case study assumed the connecting links as rigid and significantly stiffer than the bamboo. Once the analytical model was built, the structural analysis was performed within Grasshopper. The orientation of the bamboo culms was used to minimize the vertical and lateral displacements of the frame.

Finally, a preview of the surface representation for each bamboo culm was 3D modeled together with the original template of the Lombok house (Figure 11f). This was the final step before creating an IFC file of the bamboo structure.

Figure 12 shows the integration of the IFC bamboo structural model into the BIM model of the Lombok house template. All data related to each of the thirteen bamboo culm elements was successfully incorporated and can be explored or reviewed using any BIM viewer. As shown in Figure 12, clashes with other existing elements within the template house can be checked by designers and engineers. This is a major advantage of the proposed digital workflow and demonstrates that bamboo culms can become part of modern design, construction, and management workflows just like any other conventional structural element.

A direct comparison of the digital workflow presented in this article with a traditional or analog approach to designing and building a bamboo structure cannot be easily applied. In the first place, the tools adopted in this article are different, and therefore, offer a different range of outcomes (e.g., estimating the diameter of a bamboo culm following ISO 22157-1 using a Vernier caliper against the measurement of the entire bamboo surface using a 3D scanner). A digital environment also offers storage and rapid access to all kinds of data related to a bamboo culm, which drives the design procedure towards a semi-automated process. This approach is not possible when single material properties (e.g., diameter, thickness, modulus of elasticity, among others) are assumed in the traditional design of bamboo structures.

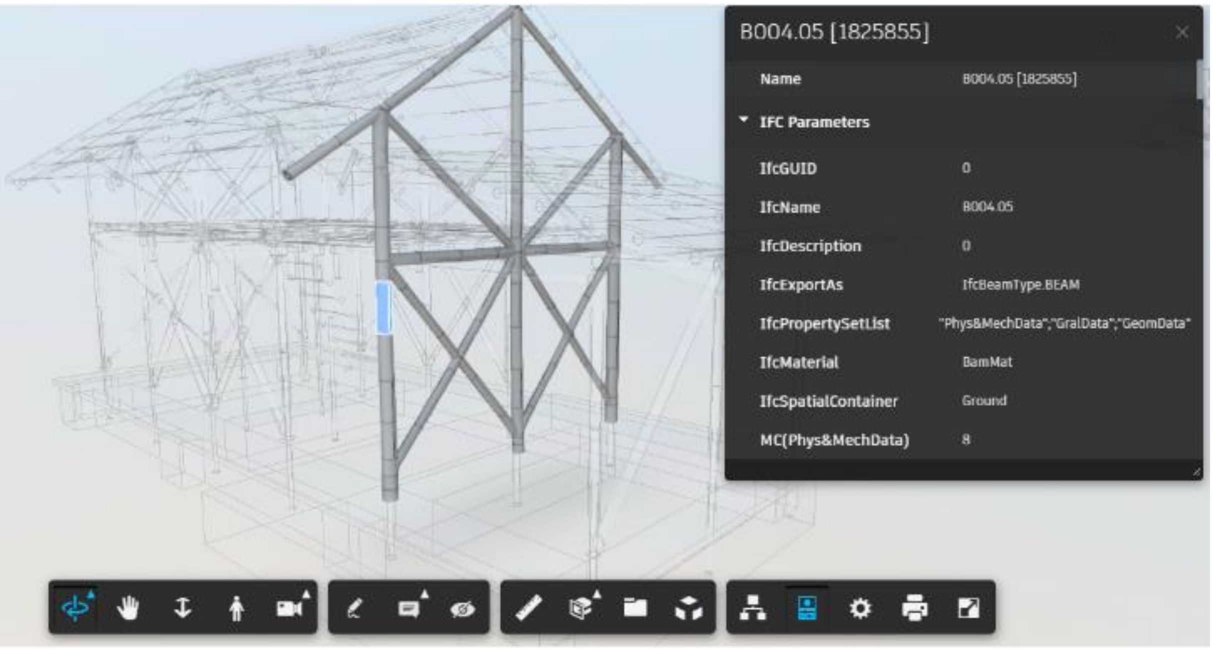


**Fig. 12.** Coordination view of bamboo culm structure and corresponding IFC data

## 4 Conclusions and future work

This article shows how bamboo culms can be fully integrated into the digital era that the AEC industry is already immersed in. Digitization and management are not just to represent shapes and information regarding bamboo culms through computer software, but can also control the quality, sustainability, and structural behavior of a bamboo structure during its entire service life. The proposed workflow has the potential to increase design efficiency by using catalogs of available stock, optimizing the structure, and reducing material waste. It has also the potential to anticipate issues during construction by inspecting the BIM model. Finally, the outcome of the proposed workflow allows the development of alternative methods to tackle other challenges faced by designers and engineers when dealing with bamboo structures such as fire resistance and durability. For example, durability by design can be achieved through the management of bamboo culm data and structural connections that allow the gradual replacement of structural elements, thus extending the life of a structure as opposed to relying on the working life of individual elements. The following summarizes key points where future development can focus:

- Implement a dynamic data system such as DBMS, to allow for a more efficient workflow
- Refine the intensive measuring method. More specifically to the fabrication and testing of physical and mechanical properties and their use to sort and characterize a stock of bamboo culms
- Assess the economic and market impact of digitizing bamboo culms by adding value to raw material without implementing energy-intensive and polluting processes
- Perform a thorough validation and calibration of the workflow, from the inception to the construction of a bamboo structure, including full-size experimental tests
- Define specific structural, fire, and durability design processes based on digital data of bamboo culms

This work also showcases the need to continue the development and implementation of standard procedures to ensure the quality of bamboo culms as irregular and organic structural elements. This requires the serious contribution of researchers and local producers, as well as designers and stakeholders, so that bamboo culms do not become an option only for self-build housing and humanitarian relief in isolated communities, but a reliable structural material that supports the development of sustainable and affordable infrastructure within the modern AEC industry.

## Acknowledgments

The authors would like to thank Marcin Dawydzik and Simon Banfield (Ramboll UK Ltd) for their support during this research. Equally, the authors would like to thank Cong Wang for the technical support. This work was carried out during the first author's doctoral training at University College London.

## Funding Statement

This work was supported by the Knowledge Exchange and Innovation Funding (KEIF) program [grant number: EP/R511638/1 | received by R.L. | URL:
https://www.ucl.ac.uk/enterprise/staff/access-funding/knowledge-exchange-and-innovation-funding].

## Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study. This publication is independent of Autodesk, Inc., Rhinoceros 3D, Grasshopper, or any other software mentioned and is not authorized by, endorsed by, sponsored by, affiliated with, or otherwise approved by Autodesk, Inc, Rhinoceros 3D, Grasshopper, or any other software mentioned.

## References

[1] GABC. Global status report for buildings and construction- Towards a zero-emissions, efficient and resilient buildings and construction sector. Nairobi, Kenya: 2020.

[2] OWD. Future Population Growth - Our World in Data 2020. https://ourworldindata.org/future-population-growth [accessed December 10, 2020].

[3] Janssen J. Designing and Building with Bamboo. 2000.

[4] Zea Escamilla E, Habert G. Environmental impacts of bamboo-based construction materials representing global production diversity. Journal of Cleaner Production 2014; 69: 117–127. https://doi.org/10.1016/j.jclepro.2014.01.067.

[5] Van der Lugt P, Van den Dobbelsteen AAJF, Janssen J. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Construction and Building Materials 2006; 20(9): 648–656. https://doi.org/10.1016/j.conbuildmat.2005.02.023.

[6] VTN. Vo Trong Nghia Architects 2016. https://www.vtnarchitects.net/du-an-tre-cpe1.html [accessed July 20, 2020].

[7] Dezeen. Penda's bamboo pavilion is a sustainable modular housing system 2015. https://www.dezeen.com/2015/10/01/penda-rising-canes-bamboo-pavilion-prototype-modular-housing-beijing-design-week/ [accessed July 20, 2020].

[8] INBAR. The INBAR garden - Holticulture expo 2019. https://www.inbar.int/inbar-pavilion-architect-mauricio-cardenas-laverde/ [accessed July 20, 2020].

[9] Zeri pavilion - Expo Hannover 2000 2013. http://www.zeri.org/ZERI/Bamboo.html [accessed July 20, 2020].

[10] Hunter IR. Bamboo — solution to problems. Journal of Bamboo and Rattan 2002; 1(2): 101–107. https://

doi.org/10.1163/156915902760181577.
[11] INBAR. Bamboo and sustainable consumption: seminar on SDG 12- INBAR 2017. https://www.inbar.int/bamboo-and-sustainable-comsumption-seminar-on-sdg-12/ [accessed August 22, 2019].
[12] Lobovikov M, Paudel S, Piazza M, Ren H, Wu J. World bamboo resources. A thematic study prepared in the framework of the Global Forest Resources Assessment 2005. Rome: 2007.
[13] INBAR. An overview 2016: Bamboo and Rattan Products in the International Market. 2016.
[14] Nugroho N, Bahtiar ET. Bamboo taper effect on center point bending test. Journal of Physical Science and Application 2012; 2(9): 386–391.
[15] Bahtiar ET, Nugroho N, Surjokusum S, Karlinasar L. Eccentricity Effect on Bamboo's Flexural Properties. Journal of Biological Sciences 2013; 13(2): 82–87. https://doi.org/10.3923/jbs.2013.82.87.
[16] Harries KA, Bumstead J, Richard M, Trujillo D. Geometric and material effects on bamboo buckling behaviour. Proceedings of the Institution of Civil Engineers - Structures and Buildings 2017; 170(4): 236–249. https://doi.org/10.1680/jstbu.16.00018.
[17] Ghavami K, Moreira LE. The influence of initial imperfections on the buckling of bamboo columns. Asian Journal of Civil Engineering (Buillding and Housing) 2002; 3(3 & 4): 1–16.
[18] Akinbade Y, Harries KA, Flower C V., Nettleship I, Papadopoulos C, Platt S. Through-culm wall mechanical behaviour of bamboo. Construction and Building Materials 2019. https://doi.org/10.1016/j.conbuildmat.2019.04.214.
[19] Kaminski S, Lawrence A, Trujillo D. Structural use of bamboo Part 1 : Introduction to bamboo. The Structural Engineer 2016(August): 40–43.
[20] Nurmadina, Nugroho N, Bahtiar ET. Structural grading of Gigantochloa apus bamboo based on its flexural properties. Construction and Building Materials 2017; 157: 1173–1189. https://doi.org/10.1016/j.conbuildmat.2017.09.170.
[21] Bahtiar ET, Imanullah AP, Hermawan D, Nugroho N, Abdurachman. Structural grading of three sympodial bamboo culms (Hitam, Andong, and Tali) subjected to axial compressive load. Engineering Structures 2019; 181: 233–245. https://doi.org/10.1016/j.engstruct.2018.12.026.
[22] Trujillo D, Jangra S, Gibson JM. Flexural properties as a basis for bamboo strength grading. Proceedings of the Institution of Civil Engineers - Structures and Buildings 2017; 170(SB4): 284–294. https://doi.org/10.1680/jstbu.16.00084.
[23] Sá Ribeiro RA, Sá Ribeiro MG, Miranda IPA. Bending strength and nondestructive evaluation of structural bamboo. Construction and Building Materials 2017. https://doi.org/10.1016/j.conbuildmat.2017.04.074.
[24] Chung KF, Yu WK. Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering Structures 2002; 24(4): 429–442. https://doi.org/10.1016/S0141-0296(01)00110-9.
[25] ISO 22156. International Standard Organization ISO 22156. Bamboo - Structural design 2021.
[26] ISO 22157-1. International Standard Organization ISO 22157-1. Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods 2019: 25.
[27] BSI ISO 19624. British adoption for International Standard Organization ISO 19624 : 2018 Bamboo structures — Grading of bamboo culms — Basic principles and procedures 2018.
[28] Lorenzo R, Mimendi L, Godina M, Li H. Digital analysis of the geometric variability of Guadua, Moso and Oldhamii bamboo. Construction and Building Materials 2020; 236: 117535. https://doi.org/10.1016/j.conbuildmat.2019.117535.
[29] Lorenzo R, Godina M, Mimendi L, Li H. Determination of the physical and mechanical properties of moso, guadua and oldhamii bamboo assisted by robotic fabrication. Journal of Wood Science 2020; 66(1): 20. https://doi.org/10.1186/s10086-020-01869-0.
[30] Wang TH, Espinosa Trujillo O, Chang WS, Deng B. Encoding bamboo's nature for freeform structure design. International Journal of Architectural Computing 2017; 15(2): 169–182. https://doi.org/10.1177/1478077117714943.
[31] Hang Wu N, Dimopoulou M, Hsun Hsieh H, Chatzakis C. Rawbot: A digital system for AR fabrication of bamboo structures through the discrete digitization of bamboo. Education and research in Computer Aided Architectural Design in Europe, 2019. https://doi.org/10.5151/proceedings-ecaadesigradi2019_538.
[32] Lorenzo R, Lee C, Oliva-Salinas JG, Ontiveros-Hernandez MJ. BIM Bamboo: a digital design framework for bamboo culms. Proceedings of the Institution of Civil Engineers - Structures and Buildings 2017; 170(4): 295–302. https://doi.org/10.1680/jstbu.16.00091.
[33] Tetik M, Peltokorpi A, Seppänen O, Holmström J. Direct digital construction: Technology-based operations management practice for continuous improvement of construction industry performance. Automation in Construction 2019; 107(July): 102910. https://doi.org/10.1016/j.autcon.2019.102910.
[34] Ding Z, Liu S, Liao L, Zhang L. A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects. Automation in Construction 2019;

102(January): 45–58. https://doi.org/10.1016/j.autcon.2019.02.012.
[35] Sweet K, Sweet T. A Reconceived Digital Workflow: A Case Study. Innovative Production and Construction, WORLD SCIENTIFIC; 2019. https://doi.org/10.1142/9789813272491_0012.
[36] Kubba S. Building Information Modeling (BIM). Handbook of Green Building Design and Construction, Elsevier; 2017. https://doi.org/10.1016/b978-0-12-810433-0.00005-8.
[37] Sinclair D. RIBA Plan of Work 2020 - Overview 2020.
[38] Liese W. The anatomy of bamboo poles. Beijing, China: International Network for Bamboo and Rattan; 1998.
[39] Lorenzo R, Mimendi L. Digital workflow for the accurate computation of the geometric properties of bamboo culms for structural applications. ACEM2018 and SBMS1, vol. 275, 2019. https://doi.org/10.1051/matecconf/201927501024.
[40] Lorenzo R, Mimendi L, Li H. Digital analysis of the geometric variability of bamboo poles in bending. MATEC Web of Conferences 2019; 275: 01007. https://doi.org/10.1051/matecconf/201927501007.
[41] Lorenzo R, Mimendi L, Yang D, Li H, Mouka T, Dimitrakopoulos EG. Non-linear behaviour and failure mechanism of bamboo poles in bending. Construction and Building Materials 2021; 305. https://doi.org/10.1016/j.conbuildmat.2021.124747.
[42] Lorenzo R, Mimendi L. Digitisation of bamboo culms for structural applications. Journal of Building Engineering 2020; 29: 101193. https://doi.org/10.1016/j.jobe.2020.101193.
[43] Mimendi L. Digital workflow for the design, construction and management of natural bamboo pole structures. University College London, 2021.
[44] Farin GE. NURBS: From projective geometry to practical use. Natick, MA, USA: A.K. Peters, Ltd; 1999.
[45] Wikipedia. Comma-separated values 2021. https://en.wikipedia.org/wiki/Comma-separated_values [accessed December 8, 2021].
[46] RMNA. Robert McNeel & Associates- Rhinoceros 3D. Software Version 5.0 2015.
[47] Wikipedia. Top-down and bottom-up design 2020. https://en.wikipedia.org/wiki/Top-down_and_bottom-up_design [accessed May 3, 2020].
[48] buildingSMART- Industry Foundation Classes Version 4, addendum 2 2019. http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [accessed January 24, 2019].
[49] BS EN 16739-1. British adoption of European Standard BS EN 16739-1:2020. Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries. Data schema 2020.
[50] Autodesk. Autodesk | 3D Design, Engineering & Entertainment Software. https://www.autodesk.co.uk/ [accessed February 9, 2022].
[51] Grasshopper. Grasshopper 2021. https://www.grasshopper3d.com/ [accessed July 24, 2021].
[52] Elefront. Elefront Plugin. http://www.elefront.info/ [accessed February 9, 2022].
[53] Karamba3D. Karamba3D – parametric engineering 2020. https://www.karamba3d.com/#projects [accessed July 24, 2020].
[54] GeometryGym 2019. https://geometrygym.wordpress.com/ [accessed January 24, 2019].
[55] Ramboll. Bamboo – a sustainable solution to Lombok's housing needs - Ramboll Group 2019. https://ramboll.com/projects/ruk/lombok_bamboo_housing [accessed June 10, 2020].
[56] Ramboll. Lombok bamboo housing - completed home 2019. https://uk.ramboll.com/-/media/images/ruk/3_projects/jkl/lombok_bamboo_housing/completed-house/1360x765_completed-house.jpg [accessed December 15, 2021].
[57] Artec 3D 2021. https://www.artec3d.com/ [accessed February 17, 2021].
[58] Occipital 2019. https://occipital.com/ [accessed January 24, 2022].
[59] Kuka 2019. https://www.kuka.com/en-gb [accessed August 20, 2021].
[60] MCBI. Ministry of Construction and Building Industry. MCBI: JG/t 199: 2007. Testing methods for the physical and mechanical properties of bamboo materials used in construction industry 2007: 1–47.
[61] Lorenzo R, Mimendi L, Li H, Yang D. Bimodulus bending model for bamboo poles. Construction and Building Materials 2020; 262: 120876. https://doi.org/10.1016/j.conbuildmat.2020.120876.