



A 3D printed bio-composite removable connection system for bamboo spatial structures

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ABSTRACT

A 3D printed bio-composite removable connection system for bamboo space structures is introduced in this paper. The system consists of a removable clipping connection for raw bamboo structures, adapted to the European market. The use of parametric design and 3D printing enables to have both design and production processes adapted to the non-uniform bamboo culm dimensions, while being standardisable. The resulting design possibilities are very large due to the high adaptability of the whole process. The efficiency of the introduced connection system has been validated experimentally. Standardized specimens of the bio-composite material, a connection detail (clip), and a structural component were examined experimentally to validate the design. A pyramidal structure made of bamboo culms of 30 mm of diameter and 4 mm in thickness was able to sustain a load of 7 kN in compression, proving the relevance of the proposed connection system. A finite element model was developed to model the clip behaviour and successfully compared to the experimental results.

1. Introduction

In 2017, the building sector was responsible for 39% of energy-related carbon dioxide (CO₂) emissions, from which 11% are directly related to the construction industry [1]. Therefore, actors of the construction sector should try to reduce the environmental impact of their designs, without altering their quality. One way to contribute to this is by using organic building materials, such as bamboo.

Bamboo usually offers better mechanical properties than wood [2] and a natural circular hollow section fitted for structural use. Among the, ca., one thousand bamboo species, the highest can attain 30 m height and can reach a diameter of 200 mm [3]. Bamboo can be used as a construction material in its natural shape, and therefore the only amount of energy needed for its use is the amount needed for the harvesting, preservation process and transportation. Consequently, if the bamboo is produced locally, it offers a very sustainable solution. Moreover, it can be harvested on average after 3–5 years compared to 20–40 years needed for timber [4], hence, on the same land surface, a larger quantity of bamboo than wood can be produced per year: 78.3 ton/(ha*year) for the bamboo compared to 17.5 ton/(ha*year) for timber [5]. A life cycle analysis of the use of bamboo as a construction material showed that bamboo proves more than 20 times as sus-

tainable as timber in several applications, if produced locally and used in its natural state [5].

Some bamboo species can be cultivated in European climates, such as *Phyllostachys nigra* Boryana, originated from Japan, which can attain 15 m of height and a diameter of 75 mm [6]. Plantations of bamboos adapted for structural applications in Europe are today very rare but that could change if the European demand for structural bamboo grows. Last years, several initiatives began to work on the creation of bamboo plantations in Europe for other purposes than garden decoration, such as OnlyMoso [7] and BambooLogic [8].

The thin-walled bamboo culms are particularly vulnerable to exterior influences such as fire, insects, or fungus, and must be protected for structural use. Attention should be put during the design of the structures on the protection of the culms from rain, humidity, and direct-sun light. In addition to these, the culms must be treated against insects. This is usually done with Boron [9].

Bamboo is used as a construction material since a long time especially in Asia, Africa and Latin America [10]. Today, bamboo is rarely used in European building structures and when this happens is mostly for temporary structures. Nevertheless, thanks to its ecological interest, bamboo is more and more used in Europe today for non-structural applications, such as laminated bamboo for flooring or small

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objects such as toothbrushes, chopped bamboo fibres for toilet paper, etc. [11]. The main reason is the reduced interest for using Bamboo and lack of knowledge about this material in Europe [5] mainly due to the lack of cultivation sites in Europe. Without standards and codes on the structural design with bamboo, the use of bamboo as a structural material is very difficult to be approved by authorities and end users. Moreover, there is a lack of skilled workers in Europe, necessitating the deployment of foreign trained personnel; a quite complicated and costly procedure. Otherwise, structures can be prefabricated outside Europe at the highest possible degree to ease mounting, however increasing the complexity and the transportation costs [5]. Nowadays, norms for bamboo structures have been derived, usually based on relevant documents for timber. Nevertheless, security demand can differ in European and other countries [12].

The most important focus considering bamboo structures is the connection system. Bamboo connection systems should avoid stresses perpendicularly to the fibres, as the resistance in traction perpendicular to the fibres is around 1/50 of its resistance in tension parallel to the fibres. Splitting can then easily appear and propagate due to a small imperfection in the culms, or during the cutting of the culm. Another difficulty with bamboo connections is that raw bamboo culms do not have a standard size, which implies the need to have flexible connection systems in terms of bamboo culms' geometry, which can make the connection system complex to design, produce and assemble.

Traditional bamboo constructions usually use lashed connections. This technique permits a connection without holes in the bamboo, decreasing the risk of splitting and facilitating the connection process. However, the resulting connection is not stiff and does not permit utilizing the entire bearing capacity of the bamboo culms [5].

Today, several new types of connection systems have been developed in order to improve the structural properties of the connection, the durability and the aesthetic result. Many of these modern systems use bolted connections, with the bolts passing through two or more bamboo culms. Additional filling of the culms was proposed in several cases to protect them from the problems arise due to drilling. For instance, [13] analysed the structural capacity of bolted joints with or without concrete-mortar infill, categorized as 'Engineered Conventional Bamboo Constructions'. The results showed a higher resistance with than without concrete infill, but concrete infill induces an increase in weight as well as the impossibility to demount the connection. [14] proposes a low-cost and easy to produce solution for bamboo truss connections using wooden plates and bolts. The experimental results were conclusive, but the visible wooden plates alter the aesthetic of the finish product, and the connection system only works for 2D connections.

Bolted connections induce high pressure concentration in the culms due to the small bolts' diameter, and do not permit to have complex 3D nodes connections. Therefore, research has been carried out to find innovative solutions for 3D nodes connections for free-formed bamboo structures. [15] proposes a steel clamp connection system. This technique allows very flexible in terms of used bamboo diameter or node geometry, but the connection is complicated to manufacture due to its complex shape and the fact that it is made of steel.

The most similar connections system to the one developed in this paper found is a 3D printed connection system for free-formed structures, described in [16]. The shape of a node is modelled by parametric design, and then individually 3D printed. It enables to have very flexible design and production processes, adapted to the use of a natural material varying in shape. The structural geometries can be very complex, and their assembly is relatively easy. On the other hand, the 3D printing of these complex nodes induces some difficulties due to the lack of flat surfaces, and the glued connections, which does not permit to easily dismantle the connection system. According to published reviews [17], the 3D printing global market is growing at a very fast pace and is projected to expand even further in the next few years. Additive manufacturing techniques, are emerging in indus-

trial and household settings, including bio-composite materials [18], allowing the derivation of parts in small scales with limited waste [19,20], minimal energy consumption [21], and without the need for expensive tools [22,23]. 3D printing facilitates as well the rapid production of parts with complex shape, whose production is either very difficult or/and very expensive through standard manufacturing procedures [24,25].

To increase the use of bamboo as a structural material in Europe, the main aspect to work on is the development of a new connection system which can respond to all the challenges explained above. The literature review showed that no one of the existing connection systems is versatile and sustainable to meet the global challenge of significantly reducing the ecological footprint of bamboo structures and be standardisable to facilitate batch production processes.

A new, sustainable and multipurpose connection system that fulfils the requirements set above is presented in this work. The bamboo structural connection system developed in this work is designed parametrically. This way, the geometry of the connection can easily be adapted to the size of the bamboo culm. In addition, the parametric model allows various node geometries with different angles for complex free-formed nodes to be easily produced. The parametric model has been conceived with *Grasshopper*, a plug-in for the computer-aided design software *Rhinoceros 3D 6.0* (Robert McNeel & Associates, 2018). Fused deposition modelling (FDM) 3D printing has been chosen as a production process for the connection due to its high flexibility. It enables to individually produce the pieces individually modelled. The efficiency of the introduced connection system has been validated experimentally. Standardized specimens of the bio-composite material, a connection detail, and finally a structural component was examined experimentally to validate the design.

2. Structural concept

The proposed connection system enables to easily connect several bamboo culms together through a clipping system to make bamboo structures. The clips are composed of a base, two curved branches and a button at the end of each branch. The branches are bent for the connection to be entered in (or taken out from) the bamboo culm and then the buttons enter in circular holes drilled in the culms. The buttons' role is to take up tension forces from the culm, while the compression forces are transferred through the base and the node core (see Fig. 2). The base also permits to avoid rotation of the culms at its base.

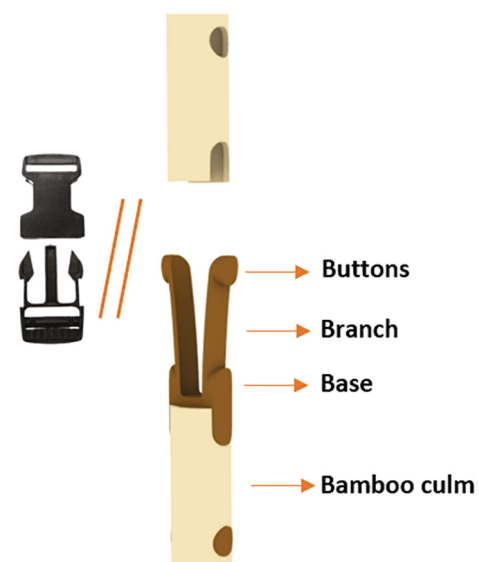


Fig. 1. Clipping compliant mechanism.

The system is therefore suited for most load cases and is at the same time easily removable thanks to the ease of use of the clipping compliant mechanism. The clipping compliant mechanism is schematically shown in Fig. 1.

In a structure made with this connection system, each bamboo culm end has a corresponding clip, adapted to the dimensions of that culm end. All the clips composing a node are connected by a tooth shaped mechanism (no need of glue, see Fig. 2) to the node core adapted to the specific geometry of that node. This kit-of-parts system is therefore very easy to use and standardised while the resulting structures can have complex geometries. Fig. 3 shows the design process of two different complex nodes.

The system is sustainable as the processing of the raw bamboo is limited to drilling the holes for the buttons and treating against exterior environmental influences such as water and insects. Moreover, the connections can be made of biopolymers such as PLA (usually made out from corn). The polymer can be reinforced with fibres, which can also be naturally sourced, such as flax fibres.

This clip-based connection system could be used for a large variety of applications, such as temporary structures, e.g., furniture, shadow devices, trusses, scaffoldings shown in Fig. 4. The system is optimal for exterior bamboo culms' diameter comprised within 30–60 mm

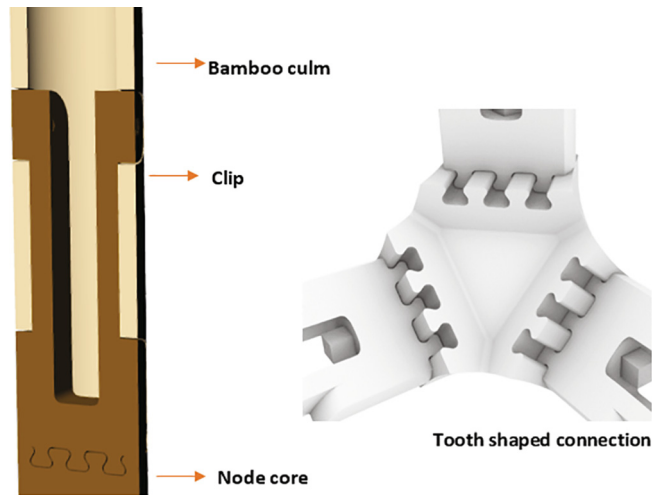


Fig. 2. Cut view of the system and detail of the tooth shaped connection.

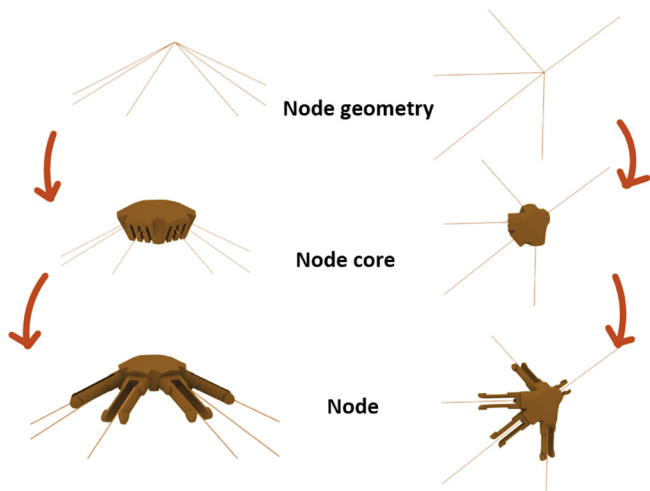


Fig. 3. Flexible design process.

Temporary structures



Furniture



Fig. 4. Examples of applications.

with a thickness of around 10–15% of that diameter. If the culm is smaller, it would become vulnerable to splitting because of the small wall thickness. A larger culm would result in larger connections that are more complex to be 3D printed and that require a higher force to be clipped-in in the culm. Also, larger bamboo species are more complicate to be produced in Europe. Moreover, if the culm's thickness is more than 15% of the diameter, the clip would be too large to be inserted in the culm, as the buttons of the clip would be larger and the interior radius smaller. Finally, if the thickness is less than 10% of the culm diameter, the culm may have to be very large to have the wanted structural capacity/section area.

3. Design and production process

The design process, illustrated in Fig. 5, is based on an algorithm programmed in Grasshopper (RhinoCeros plug-in), which designs a node in function of two parameters: the dimension of the culms which have to be connected and the geometry of the node.

It is a parametric design process, which is divided in two main steps, illustrated in Fig. 6. Firstly, the clips are modelled in function of the dimension of their relative culm end, which has been measured and entered in a database which feeds the parametric design algorithm. The measurement can be done automatically with a laser scanner. However, it may be simpler to have structures with the same dimension for all the clips, which is possible as the system has around 3 mm of tolerance in terms of interior radius of the culms. Therefore, a range of culm interior radii can be defined for a specific structure. Secondly, the node core is designed based on the basic node geometry defined by the centre lines of the culms intersecting at that node, and the culms dimensions.

Features can be added to the model, such as identification codes on each clip to easily match the culms with their relative clip during the

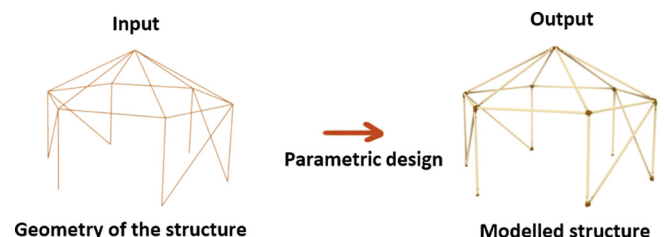


Fig. 5. Simplified design process.

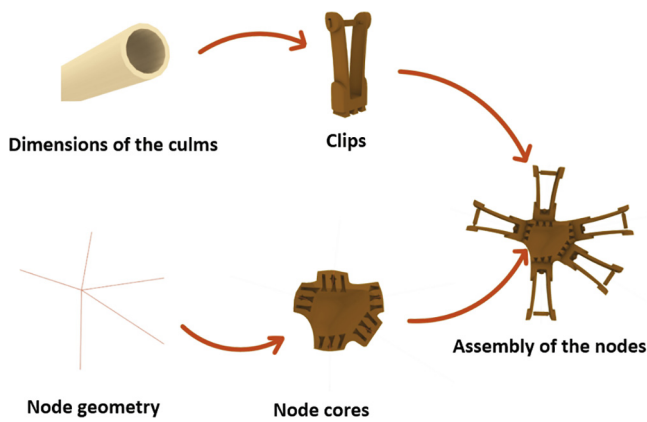


Fig. 6. Main steps of the design process.

assembly of the structure. Another optional feature are the holes which can be modelled in the node core for future screwing of plates or other coverings.

Tolerance spaces are foreseen between the clips and the culms to allow some imperfection in the drilling process (around 0.4 mm) as well as between the 3D printed parts (around 0.2 mm). They depend on the precision of the specific tools used.

The production process, illustrated in Fig. 7, is as flexible as the design process. All the parts of the node designed by the algorithm are 3D printed and then connected with a tooth shape mechanism (shown in Fig. 2), without any need of glue. Translation is avoided by the addition of a pine which passes through both the clip and the node core.

Fused deposition modelling (FDM) is the most common additive manufacturing process. It consists of a plastic filament heated and then extruded through a moving nozzle. Layer after layer, the 3D object is printed by the nozzle, which follows a defined path [26,27]. Many different types of filaments exist for FDM. They are usually mainly composed of plastics, most commonly PLA or ABS. Other types of filaments exist, with the possibility to obtain a very flexible object, a specific texture, or to increase the mechanical capacities of the object. The latter, which interest us the most, can be obtained by reinforcing the filament with fibres. These fibres can be continuous or chopped. Printing with chopped fibres reinforced filaments (chopped fibres usually ± 0.1 mm) is easier, cheaper and enables more complex geometries, but the mechanical results are way lower than with continuous fibres [26]. Very high resistances can be attained with filaments reinforced with continuous fibres, such as nylon reinforced with continuous carbon fibres, which proved a resistance of more than 400 MPa in tension, following the American Standard Test Model (ASTM) D638-14 type I (Tensile test) [28].

The next step of the production process is to cut the bamboo culms at the appropriate length and drill the holes at the position of the buttons, with the correct corresponding orientation. The process can be

automated as the geometry of the cuttings is calculated by the algorithm.

Finally, the clips are clipped in the culms to assemble the structure, as illustrated in Fig. 8. The whole process from the basic scheme of the structure to its assembly, is very flexible while being standardised and mostly automatable.

4. Structural analysis

This section discusses the structural behaviour of the clipping system, and more precisely the forces anticipated when the bamboo culms are loaded.

4.1. Tension

When a culm is submitted to tension, the tension force is transferred from the culm to the node core through the buttons, then to branches and then to the tooth shaped part connecting the clip to the node core. The different stresses induced are illustrated in Fig. 9. This transfer of force induces compression stress in the culm below the buttons (reaction force from the traction of the culm), as well as shear stress at the interface between the part of the culm in tension and its part in compression. In the connection, the main stresses are the tension stresses in the branches and in the tooth shape part.

Bending will also be induced due to the eccentricity of the force centre in the branches compared to the force centre in the culm. If the bending is too large it may cause unclipping of the connection. To avoid the unclipping, a pine or a screw can be added, as illustrated in Fig. 10. It will be submitted to compression, and therefore apply a force towards the exterior on the branches, which will prevent the bending of the branches.

If the pine or screw to protect from unclipping is added, the failure mode of the system will most probably be the rupture of the branches of the clip submitted to traction.

4.2. Compression

When a culm is submitted to compression, the force is partially transmitted from the culm directly to the node core to which the clip is connected, and partially from the base of the clip to the node core. The resistance will be higher than with the tension load case where all the load must pass through the branches. The actual hypothesis is that the failure mode under compression would be the failure of the node core submitted to compression.

4.3. Bending

Because the moment of inertia of the branches of the clip is higher when bending is applied parallelly to the plane of the branches, resistance to bending should be higher in that direction. In that case, the bending load is mostly transferred through the branches submitted to bending. The resistance in bending of the system is relatively low due to the small diameter of the culms used. Therefore, the nodes



Fig. 7. Production process of a node.

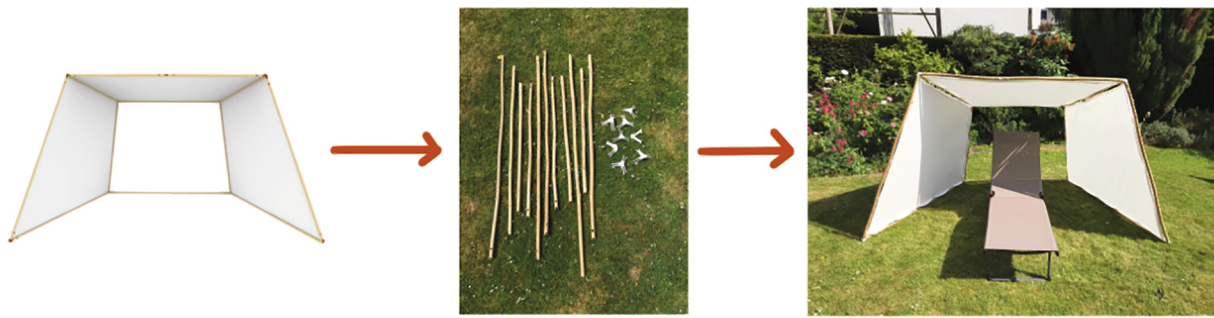


Fig. 8. Assembly of a simple shading structure.

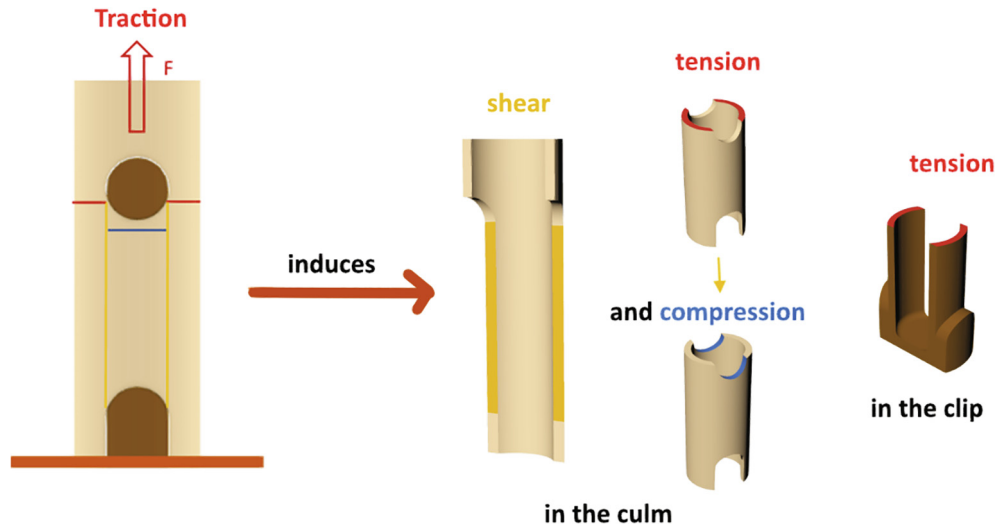


Fig. 9. Structural behaviour in tension.

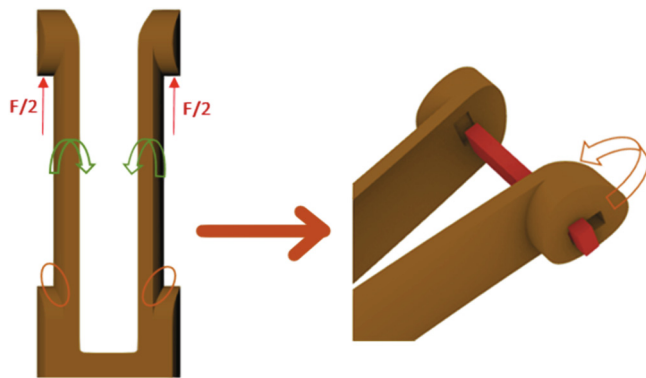


Fig. 10. Pine to protect from unclipping.

made with the connection system should be considered as pinned. However, if used in applications submitted to low loads such as a table, the nodes could be considered as rigid. If used for larger structures, the structures should rather be triangulated or braced. The bracing could be easily done by panelling the areas between the culms.

4.4. Clipping the connection

For connecting the clip in the culm, a force perpendicular to the branches must be applied to make the branches bend enough inwards to be inserted in the culm. A compromise should be found for the

thickness of the branches between the strength of the branches in tension (thicker branches) and the ability to easily insert the clip in the culm (thinner branches). Also, the branches should be long enough to avoid too high bending stresses at their base due to bending the branch inwards when inserting.

5. Experimental investigations

Experiments have been conducted to investigate the structural behaviour of the connection system. The results will also be used to validate the developed finite element model and to indicate which applications are suitable for the developed structural system. The aim is to obtain a digital twin of the system to enable parametric optimisation through finite element modelling of nodes with varying parameters. The latter can easily be carried out thanks to the parametric design process, which enables to quickly design new node with varying parameters.

5.1. Experimental set up

5.1.1. 3D printed material

The filament used to produce the 3D printed piece for the experiments is PLA reinforced with chopped flax fibres. The filament (STAR-FLAX 3D) tested is produced by NANOVA, a French chemical company. The mechanical properties of plastic filaments reinforced with chopped fibres is not well known, therefore the material has been characterised to be able to interpret better the experimental results on the clipping system, and to parametrise the finite element analysis

model. The printing pattern definition was performed by using the Simplify 3D software and the specimens were manufactured by a AON3S SN-1.1–10-61 3D printer at an extrusion temperature of 215 °C, on a bed plate heated at 40 °C. The nozzle diameter was 0.6 mm and the layer thickness was 0.3 mm, the infill was 100%, while no shell was used.

Material experimental investigations were performed based on the ISO 527-1:2019 [29] and ISO 527-4:2009 [30].

The geometry of the 3D printed samples is shown in Fig. 11.

Two specimen configurations were fabricated and tested. One with the fibres aligned along the longitudinal specimen direction, see Fig. 12 (top) and a second one with fibres in the transverse specimen direction, see Fig. 12 (bottom).

Five samples of each configuration were tested under traction, at a constant displacement rate of 5 mm/min using a W + B electromechanic machine of 50-kN capacity, at temperature of 24 ± 2 °C and relative humidity of $38 \pm 5\%$. The force and the strain of the device were recorded, and Digital Image Correlation (DIC) was employed to measure the full field surface displacement in order to facilitate the strain, stiffness and the Poisson ratio estimation and parametrise the finite elements analysis. The testing setup is shown in Fig. 13.

5.1.2. Clip

The same 3D printer was used for the manufacturing of the clips, by using the same parameters. The only difference in this case was the infill of 50% printed in 3 shells with the pattern shown in Fig. 14.

As for the experiments on the printed “dumbbell” specimens, the clips were examined under tension with a continuous displacement of 5 mm/min at the same testing machine. The test setup for the clips is illustrated in Fig. 15.

The experimental matrix is shown in Table 1. In total, 8 specimens were examined to investigate different performance. For these experiments, the piece equivalent to the node core of the system has been manufactured with a shape that eases the clamping of the connection to the machine. This “clamping device” was connected to the clips by the tooth shape mechanism described in Fig. 2. The base line specimens C1 and C2, shown in Fig. 15(a,b), have a screw to prevent unclipping of the buttons. The resistance of bamboo in tension perpendicular to the fibres is very low (1–5 MPa, a few percent of the resistance parallel to the fibres [31]), while tension forces perpendicular to the fibres are present when the system is submitted to traction. In fact, due to the contact surface between the clip and the bamboo which is not perpendicular to the culm at every point, as the shape of the buttons is circular, horizontal components are present in the reaction forces between the culm and the clip at the sides of the buttons. These horizontal components are opposed at each side of the buttons, which induces tension perpendicular to the fibres in the culm under the buttons. To avoid the splitting of the bamboo culms and allow the investigation of the clip performance up to failure without considering the effect of the bamboo preliminary failure, specimens C3–C5 were equipped with a radial clamp. Specimen C6 was without a screw but with a clamp, to investi-

gate the effect of potential unclipping. Specimens C7 had the same configuration as C6, but with the modified clip geometry shown in Fig. 16(b), in which the branches have bigger section area. C8 was equivalent to C3–C5, however also with the modified clip geometry.

5.1.3. Structural component

The last experiment was carried out on a 35 cm side pyramid. The aim was to verify the system’s potential with 3-dimensional nodes, representative of connections in actual truss structures. The modified clip geometry was used in this case, and the bamboo culms have been reinforced with tape wrapped around the culm to avoid splitting. The pyramid was loaded by a W + B table top electromechanic machine of 50-kN capacity at temperature of 22 ± 2 °C and relative humidity of $38 \pm 5\%$ under compression at a constant displacement rate of 5 mm/min at the summit, as shown in Fig. 17. The load and displacement of the machine were recorded. The pyramid was loaded 4 times, letting the structure to recover for approximately 2 min between each loading cycle. The objective of these repetitive loading cycles was to investigate the structural performance and the system elasticity.

5.2. Results and discussion

5.2.1. 3D printed material

Five samples were tested for both configurations, with relatively stable results. The resulting strength for the specimens printed in the longitudinal direction was 42.4 ± 0.81 MPa, and the stiffness was 2.3 ± 0.10 GPa, and 28.2 ± 0.51 MPa with a stiffness of 1.7 ± 0.07 GPa for sample printed perpendicularly to the load. The Poisson’s ratio was 0.32 ± 0.02 and 0.28 ± 0.03 accordingly. These values are slightly lower than others obtained in previous studies on the mechanical properties of 3D printed PLA, e.g., [32], where 3D printed PLA was submitted to traction parallel to the printing direction and resisted ca. 45–50 MPa. This may be explained by the printing conditions and parameters which may have not be optimal in the case examined in this work.

The experimental results were very consistent showing very small scatter between the specimens tested with coefficient of variation between 1 and 6% for all cases. A clear elastic deformation segment and second part of plastic deformation for can be distinguished in the stress–strain curves of all specimens shown in Fig. 18.

During the loading, the full surface strain was measured by a 3D digital image correlation system (3D DIC). As shown in Fig. 19(a–c) the strain field was homogeneous along the surface, except before failure when a localized strain was measured. Strain field photos shown in Fig. 19(a–c) have been taken at the points indicated in Fig. 18 from one longitudinally printed specimen. All specimens failed without the presence of any necking as shown in Fig. 19(d).

5.2.2. Clip

The failure modes for the clip experiments are shown in Fig. 20. For C1 and C2, bamboo splitting was observed (Fig. 20(a)) prior to the clip

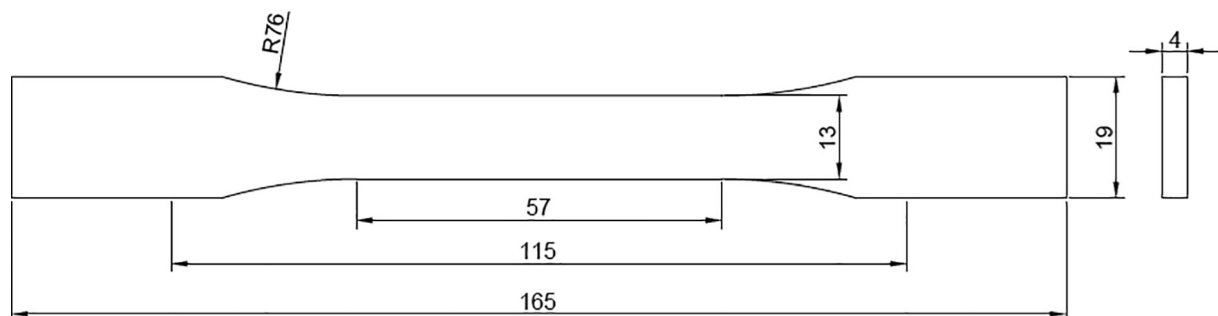


Fig. 11. “Dumbbell” shape of the specimen (dimension in [mm]).

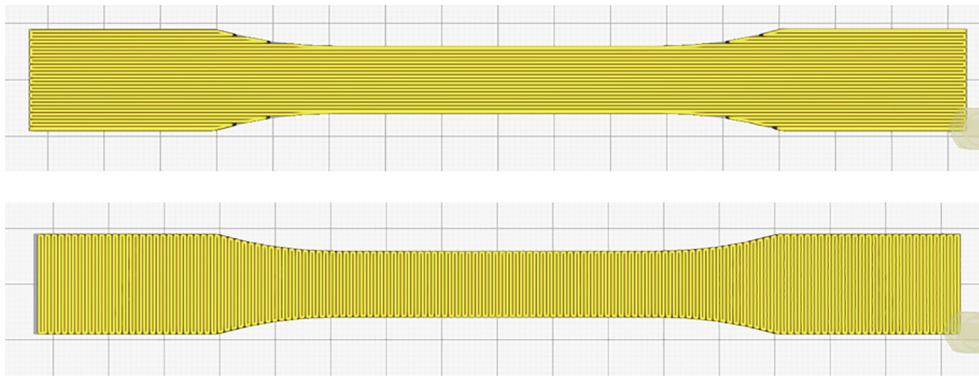


Fig. 12. Tensile 3D printed bio-composite specimens. Printing longitudinal (top) and transverse (bottom) to tension.



Fig. 13. Testing setup for the PLA reinforced with chopped flax fibres (a), Mounted specimen (b).

failure (Fig. 20(b)). C3-C5 were confined by a clamp, and therefore no split of the bamboo occurred. The clips failed in the branches for specimens C3 and C5 (Fig. 20(b)) with similar resulting resistance to that reached by the C1 and C2 specimens, meaning that the splitting strength of the bamboo and that of the clip branch were similar. Specimen C4 failed due to the disassembly of the clamping device from the clip base (Fig. 20(d)), maybe due to a lower printing quality of this specific piece, causing lower resistance of its tooth shaped connection. In the case of C6, which was not reinforced with a screw to avoid unclipping of the buttons, the clip branches were deformed significantly (see Fig. 20(c)) leading to unclipping at about half the loading attained by the previous specimens. This result is interesting to evaluate the capacity of the simpler system (without screw), for small scale applications. Specimens C7 and C8 had the same configuration as respectively C6 and C3-C5 while using the modified clip geometry, which aims to increase the resistance of the system thanks to a larger branches section area. C7 exhibited the same failure mode as C6, although reached around 25% higher load. C8 failed due to the clamping device disassembly, as C4 did. However, in this case the load to failure was much higher, probably reaching the maximum capacity of the tooth shaped mechanism.

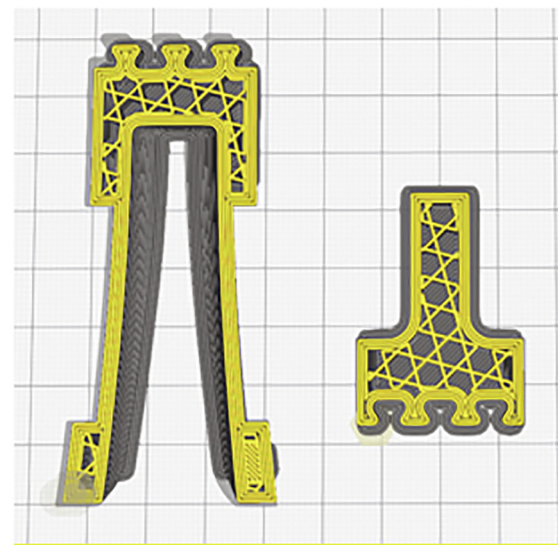


Fig. 14. Clip printing.

The two-step failure of C1 and C2 specimens is visible in the load displacement curves shown in Fig. 21; the first drop on these curves is due to the splitting of the culm, while the final failure of the system is due to the breaking of the clip branches. The load-displacement curves of specimens C3-C5 show similar behavior until ca. 0.75 kN when the clamping device of specimen C4 starting disassembling resulting to a lower stiffness of C4 and therefore a lower slope of the corresponding load/displacement curve. The absence of the screw (specimens C6 and C7) obviously does not allow attaining high loads, since the clip branches deform and are pulled out for loads below 0.75 kN for the initial clip geometry (C6) and less than 1 kN for the modified clip geometry (C7). Nevertheless, it is clear that the modified clip geometry has a positive impact in terms of rigidity, in addition to the increase of strength when a screw is used (C8).

5.2.3. Structural component

The pyramid resisted 7kN during the first test (see Fig. 22, curve 1), with a failure due to the disassembly of the tooth shaped pattern of the clips submitted to tension in the bottom nodes (shown in the red ellipse in Fig. 23), showing the same failure mode as that shown by the C8 specimen with the same configuration of the clip as was described in the previous section.

Subsequent loading, applied on the pyramid keeping the same clips, led to similar failure (tooth disassembly) however at a lower load

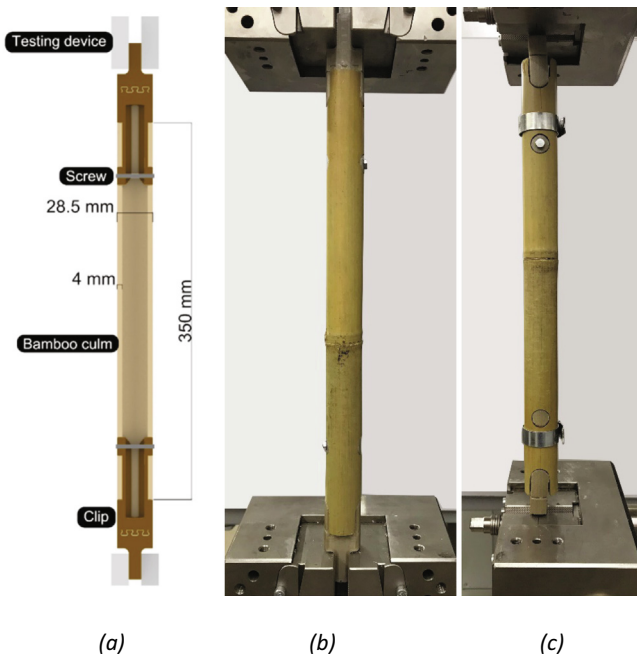


Fig. 15. Testing setup for the clip under traction: with a screw and without clamp (a,b), with both (c).

Table 1
Experimental matrix describing the clip experiments.

ID	Configuration	Max. Load (kN)	Failure mode
C1	Screw/no clamp (Fig. 14 (a,b))	1.61	Bamboo split, then branches break
C2	Screw/no clamp	1.49	Bamboo split, then branches break
C3	Screw/clamp (Fig. 14(c))	1.60	Branches break
C4	Screw/clamp	1.23	Tooth shaped mechanism disassembly
C5	Screw/clamp	1.48	Branches break
C6	No screw/clamp	0.79	Branches bend (plastic) and buttons get out of the hole
C7	Modified clip (Fig. 15(b))/no screw/clamp	0.99	Branches bend (elastic) and buttons get out of the hole
C8	Modified clip/screw/clamp	1.91	Tooth shaped mechanism disassembly

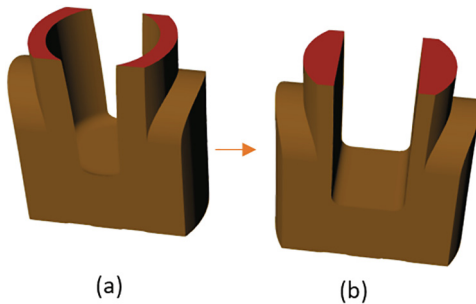


Fig. 16. Section view of the basic (a) and modified clip (b) geometry.

level and with reduced structural rigidity of the pyramid as shown in Fig. 22.

The tooth shaped pattern, although largely deformed during each loading, recovered nearly totally during the recovery phase between each loading cycle. The maximum load achieved at each loading cycle



Fig. 17. Testing setup of the pyramidal structure under compression.

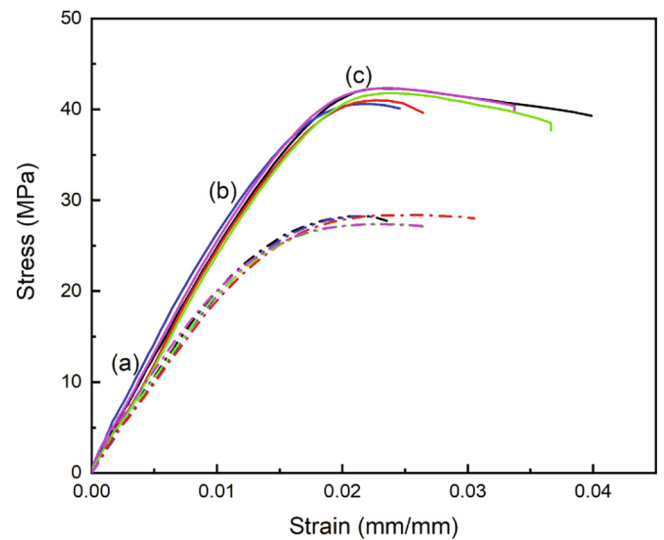


Fig. 18. Evolution of the stress with the deformation parallel to loading for the samples. The continuous line represents the specimens printed in the longitudinal direction, the dotted lines represent the specimens printed perpendicular to the load.

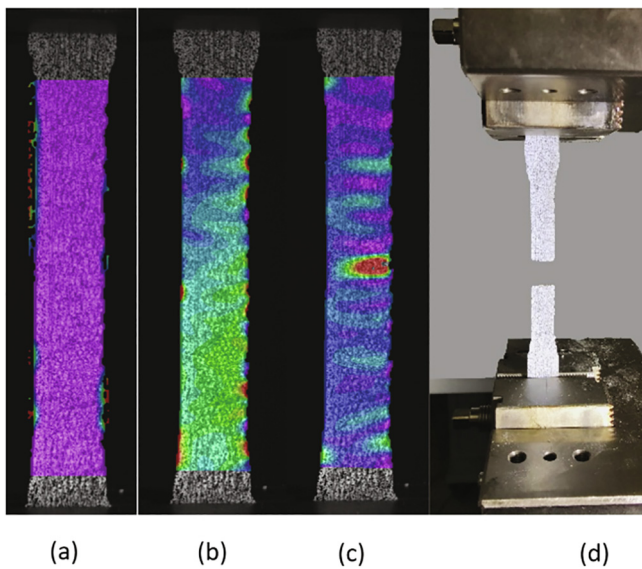


Fig. 19. Homogeneous strain distribution (a,b) localised strain before failure (c) and broken longitudinal specimen (d).

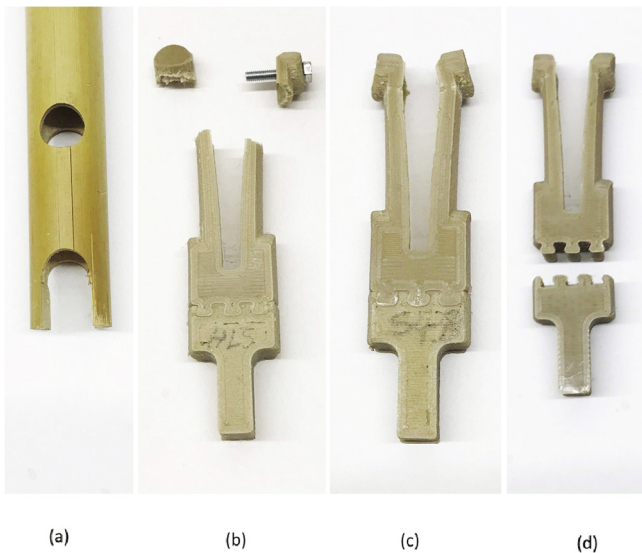


Fig. 20. Failure modes of the system submitted to tension: (a) splitting of the culm (b) breaking of the branches (c) bending of the branches (d) disassembly of the tooth shape mechanism.

was decreased by ca. 3.5%, while the structural rigidity (the slope of the linear part of each curve) showed a similar trend with decreasing rigidity which was around 30% between the first and the second loading cycle, however was less than 10% for both subsequent loading cycles. This means that the system shows an almost elastic behaviour which is an interesting feature for certain applications.

6. Finite element analysis

To ease future optimisation of the system, a finite element model has been developed using the commercial finite element analysis (FEA) software ABAQUS 6.14–1 under academic license. The experiment on the clip sample C7 (modified clip/no screw/clamp) submitted to traction has been chosen for the validation of the finite element model. Therefore, the same experiment has been carried out with

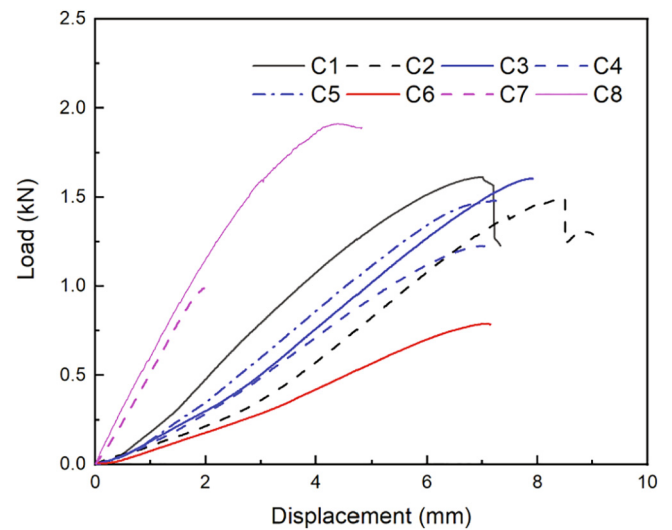


Fig. 21. Evolution of the load with the displacement of the device for the system under traction.

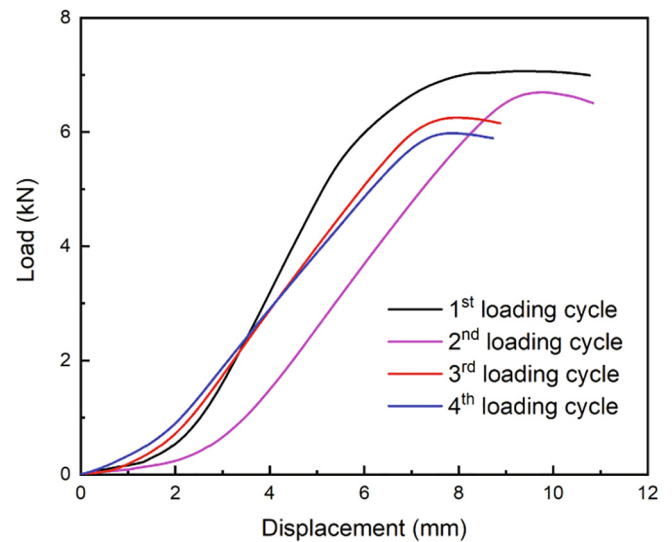


Fig. 22. Evolution of the load with the displacement of the device for the pyramidal structure under compression.

the developed finite element model, and it will be compared with the results obtained with the test on the sample C7.

For the clip, the mechanical properties have been defined based on the results from the tests of the material (Table 2, see Section 5.1). The material has been considered as isotropic since it would be too complicated to specify the direction of printing at every location of the clip, and as the main stresses resulting to the load in the clip develop in the direction of printing. Therefore, the fact that the less stiff and resistant behaviour of the material in the direction perpendicular to the printing is not considered in the FE model, does not influence significantly the result of the analysis. For the bamboo, mechanical properties have been defined based on [33], as shown in Table 3.

To simplify the model, only half of it has been modelled in two directions, as it is symmetric. The Abaqus model is type static, general. The mesh approximate global size is 3 mm, resulting in 36,312 elements and 69,656 nodes in the model. The C3D10 solid element (A10 node quadratic tetrahedron) was used due to the complex geometry of the structural element. The interaction properties are “hard

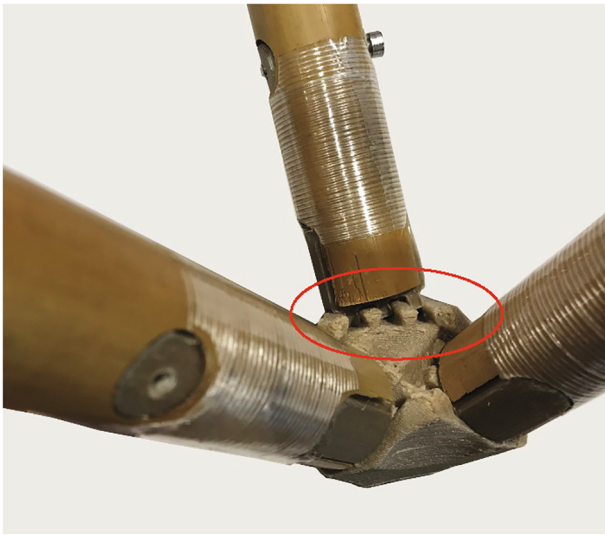


Fig. 23. Disassembly of the tooth shaped pattern of the clip.

Table 2

PLA-flax mechanical properties for the FEA (Section 5.1).

Young's modulus	2300 MPa
Poisson's ratio	0.32
Tensile strength (then plastic deformation)	42.4 MPa

Table 3

Bamboo mechanical properties for the FEA [33].

Young's modulus X direction	15,000 MPa
Young's modulus Y/Z direction	500 MPa
Poisson's ratio	0.3
Shear modulus XY/XZ	250 MPa
Shear modulus YZ	8000 MPa
Tensile strength	150 MPa
Compressive strength	80 MPa

contact" for the normal behaviour and a friction coefficient of 0.3 for the tangential behaviour, with general contact in the model.

For the boundary condition of the system, as shown in Fig. 24, the base part is blocked to simulate the clamping (red), the cuttings are locked in the direction perpendicular to the cuttings to simulate the symmetry of the model (blue), and a ramped displacement is induced at the top of the bamboo culm to load the system (green).

6.1. Simulation results

The resulting displacement-strain curve is corroborated very well by the experimental data until the breaking point (see Fig. 25) confirming the selection of the material properties.

The reason why the buttons went out of their hole sooner with the experiment may be because the bamboo did not perfectly fit the clip, thus the horizontal displacement of the buttons needed for unclipping was smaller than the one needed in the Abaqus simulation. It could also come from the coefficient of friction between PLA and bamboo, which has been guessed to be 0.3 but may be smaller in reality. That could explain a larger displacement of the buttons as they would slip more easily against the edges of the holes in the bamboo.

Fig. 26 confirms that the behaviour of the clip in the simulation and in the experiment are similar, with the deformation of the end of the branches towards the interior of the culm in both cases.

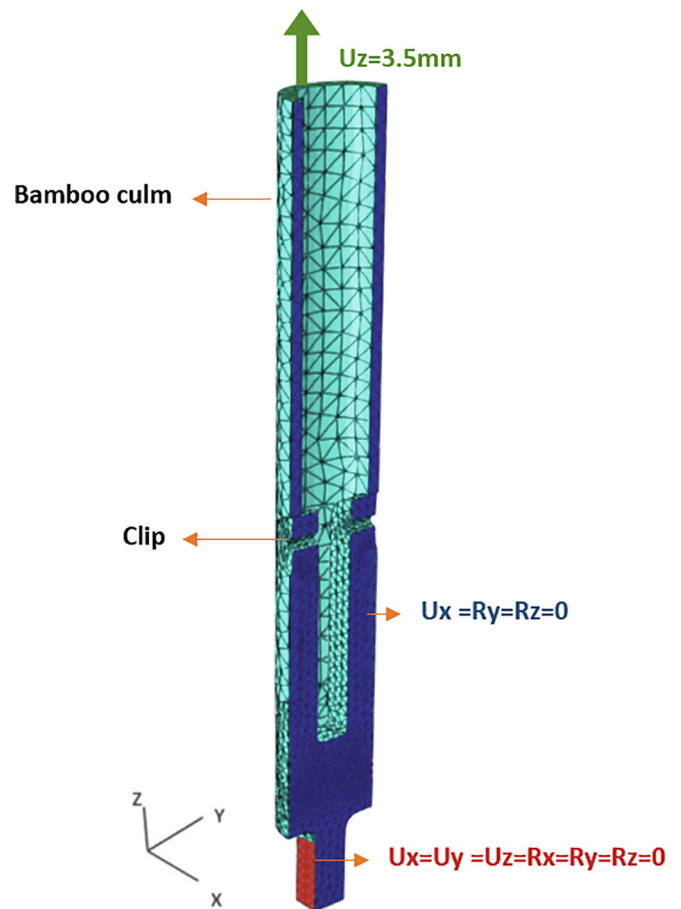


Fig. 24. Boundary conditions in the FE model.

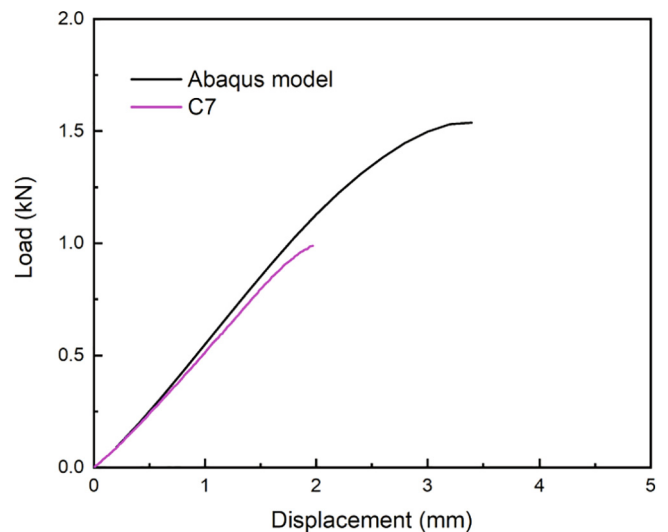


Fig. 25. Evolution of the load with the displacement of the device for the clipping system under tension, without screw to prevent unclipping.

7. Conclusions

A new 3D printed bio-composite connection system for bamboo structures that could help reducing the ecological footprint of the construction and furniture sectors has been introduced in this work. The new concept allows the use of bamboo, an incredibly sustainable

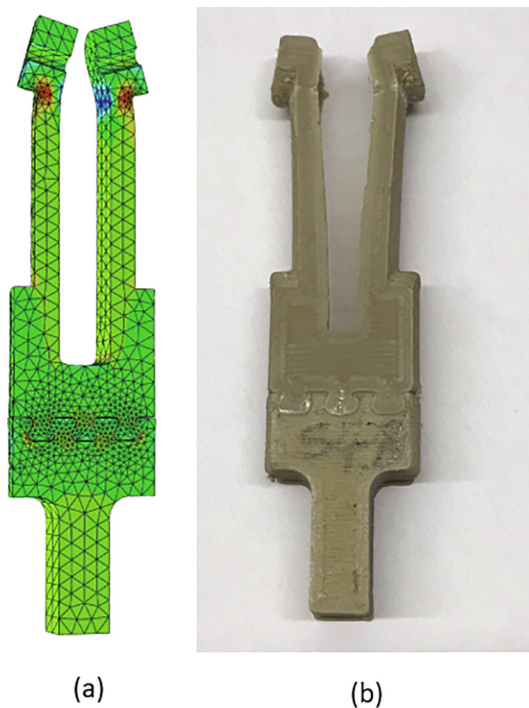


Fig. 26. Comparison of the clip after failure: Abaqus (a) vs experiment (b).

and strong natural material, as a structural element for a wide range of applications. The difficulty of standardizing a procedure due to the variety of the natural dimensions of bamboo culms is overcome by using the design and production flexibility of parametric design and 3D printing. A feasibility study has been performed and showed that the structural resistance of the system resulting from the different experiments performed herein is convincing. The values of the resisted forces attained, considering the bamboo size tested, are high enough to grant credibility to the developed connection system. The following conclusions were drawn from this work:

- The 3D printed bio-composite material exhibits very low scatter both in the longitudinal and the transverse directions.
- The preliminary experimental investigation performed in the frame of this work proved the potential of the proposed connection system, but more work needs to be carried out to precisely define the applications for which the system can be used.
- The combination of the parametric design process and the 3D printing allows the derivation of a standardisable system and to automate the design and production processes, increasing the creative potential for free-formed structures, without any large decrease of the process efficiency.
- Further experimental results are needed to confirm the rigidity of the connection system proving that the flexibility offered by the introduced connection system permits to use it for temporary structures and small-scale applications, offering good opportunities for the introduction of bamboo structures in the European construction market.

Preliminary results are presented in this work (only tension, one bamboo size/type) and more efforts should be allocated to use the system in real applications. The FE model can estimate the behaviour under more loading cases (compression and bending) and resistance values for other bamboo sizes could also be predicted using finite element analysis. The durability (long term and fatigue performance) of the connection system should be evaluated in the future and modifications/optimizations can be suggested.

CRedit authorship contribution statement

Romain van Wassenhove: Conceptualization, Investigation, Visualization, Writing - original draft, Data curation. **Lars De Laet:** Conceptualization, Supervision, Writing - review & editing. **Anastasios P. Vassilopoulos:** Conceptualization, Supervision, Writing - review & editing.

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.

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References

- [1] Agency, International Energy, and United Nations Environment Programme. "2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector." Tech. rep., Global Alliance for Buildings and Construction, 2018.
- [2] Awalluddin D, Ariffin MA, Hanim Osman M, Hussin M, Ismail M, Lee H-S, et al. Mechanical properties of different bamboo species. *MATEC Web Conf* 2017:138.
- [3] Kaminski S, Lawrence A, Trujillo D, Feltham I, López L. Structural use of bamboo: Part 3: Design values. *Struct Eng* 2016;94.
- [4] Wang JS, Demartino C, Xiao Y, Li YY. Thermal insulation performance of bamboo and wood-based shear walls in light-frame buildings. *Energy Build Elsevier B.V.* 2018;168:167–79.
- [5] Van Der Lugt P, Van Der Dobbelssteen A, Abrahams R. Bamboo as a building material alternative for Western Europe? A study of the environmental performance, costs and bottlenecks of the use of bamboo (products) in Western Europe. *J Bamboo Rattan* 2003;2(3):205–23.
- [6] Depuydt DEC, Billington L, Fuentes C, Sweygens N, Dupont C, Appels L, et al. European bamboo fibres for composites applications, study on the seasonal influence. *Ind Crops Prod* 2019;133:304–16.
- [7] OnlyMoso. 2014. www.onlymoso.fr.
- [8] BambooLogic Europe. www.bamboologic.eu.
- [9] Kaminski S, Lawrence A, Trujillo D, King C. Structural use of bamboo: Part 2: Durability and preservation. *Struct Eng* 2016;94:38.
- [10] Lobovikov M, Paudel S, Piazza M, Ren H, Wu J. World bamboo resources. Edited by INBAR. Food and agriculture organization of the United Nations, 2007.
- [11] Van Der Lugt P. Booming bamboo : the (re)discovery of a sustainable material with endless possibilities, Naarden : Materia, 2017.
- [12] Gatoo A, Sharma B, Bock M, Mulligan H, Ramage M. Sustainable structures: Bamboo standards and building codes. *Proc ICE Eng Sustain*, 2014; 167: 189–196.
- [13] Phanratnamala S, The Study of Design and Structural Potential of Bamboo Practical Joints and Frame Truss System. Master thesis at Graduate School of Human Environment Studies, Department of Architecture, 2014.
- [14] Sassu M, Andreini M, De Falco A, Giresini L. An innovative low cost solution for bamboo trusses with high-ductility connections. *Adv Mater Res* 2014;875–877:406–10.
- [15] Vahanvati M. The challenge of connecting bamboo. *World Bamboo Congress* 2015.
- [16] Raspall F, Amsberg F, Banon C. 3D Printed Space Frames. 2018.
- [17] Mazzanti V, Malagutti L, Mollica F. FDM 3D Printing of polymers containing natural fillers: A review of their mechanical properties. *Polymers* 2019;11:1094.
- [18] Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos Part B* 2018;143:172–96.
- [19] Wahab MS, Wagiman A, Ibrahim M. Development of wood-based composites material for 3D printing process. *App Mech Mat* 2013;315:987–91.
- [20] Tisserat B, Liu Z, Finkenshtadt V, Lewandowski B, Ott S, Reifschneider L. 3D printing biocomposites. *J Plast Res Online SPE* 2015:1–3.
- [21] Vaidya AA, Collet C, Gaugler M, Lloyd-Jones G. Integrating softwood biorefinery lignin into polyhydroxybutyrate composites and application in 3D printing. *Mater Today Commun* 2019;19:286–96.
- [22] Filgueira D, Holmen S, Melbø JK, Moldes D, Echtermeyer AT, Chinga-Carrasco G. 3D Printable filaments made of biobased polyethylene biocomposites. *Polymers* 2018;10:314.
- [23] Kuo CC, Liu LC, Teng WF, Chang HY, Chien FM, Liao SJ, et al. Preparation of starch/acrylonitrile-butadiene-styrene copolymers (ABS) biomass alloys and their feasible evaluation for 3D printing application. *Compos Part B* 2016;86:36–9.

- [24] Pitt K, Lopez-Botello O, Laerty A.D, Todd I, Mumtaz K, Investigation into the material properties of wooden composite structures with in-situ fibre reinforcement using additive manufacturing. *Compos Sci Technol* 2017, 138, 32–39.
- [25] Tarrés Q, Melbø JK, Delgado-Aguilar M, Espinach FX, Mutjé P, Chinga-Carrasco G. Bio-polyethylene reinforced with thermomechanical pulp fibers: Mechanical and micromechanical characterization and its application in 3D-printing by fused deposition modelling. *Compos Part B* 2018;153:70–7.
- [26] Parandoush P, Lin D. A review on additive manufacturing of polymer-fiber composites. *Compos Struct* 2017;182:36–53.
- [27] Daminabo SC, Goel S, Grammatikos SA, Nezhad HY, Thakur VK. Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems. *Mater Today Chem* 2020;16:100248.
- [28] Mohammadizadeh M, Imeri A, Fidan I, Elkelany M. 3D printed fiber reinforced polymer composites - Structural analysis. *Compos Part B Eng*, 2019; 175.
- [29] ISO. [Plastics — Determination of tensile properties —Part 1: General principles. ISO 2019.](#)
- [30] ISO. “Plastics — Determination of tensile properties —Part 4 : test conditions for isotropic and orthotropic fibre-reinforced plastic composites.” ISO, 1997.
- [31] Trujillo D, López L. Bamboo material characterisation. 2016: 365–389.
- [32] Kandasamy J. A case study of 3D printed PLA and its mechanical properties. 2018.
- [33] Mishra DP, Khattry R. Finite element analysis of bamboo and joints using steel members under various loading conditions for design study. *Ind Inst Technol Kanpur* 2013.