2
Literature review

2.1. General introduction to bamboo

Bamboo is a gradient natural composite material of which its native species originates from most of the tropical countries. The composition of its fibres which are distributed at different proportions across the bamboo culm and imbedded in a lignin matrix make it suitable as a gradient composite material. The maximum mechanical properties of the fibres are in tension, which are aligned along the bamboo length [37]. Bamboo is one of the natural materials that has the highest mechanical properties (as presented in this study) and therefore can be applied in construction, the energy field (structural parts of wind turbine blades), the automotive field (car structures and panels) and for aviation (small aircraft). Few authors have investigated bamboo and its relevance in the use of composite materials. However, its use as an application in construction for concrete reinforcement has been reported by Ghavami [38]. Reinforcement of wood beams using laminated bamboo is reported by Lima and Dias [39]. Ghavami and Rodrigues [40] using digital image processing (DIP) methodology were able to establish the variation of the volume fraction of fibres of *Dendrocalamus giganteus* bamboo across its wall's thickness, proving that the Bamboo's diameter, thickness, and internodal length have a macroscopically gradient architecture. The bamboo wall is not provided with knots, giving a better distribution of stresses throughout its length [41].

Bamboo is unique as it is an invasive species and a fast-growing resource in comparison with other strong natural fibres. Bamboo is therefore a great alternative to engineering composite materials while it is produced sustainably. Around the world more than 1200 bamboo species have been identified [42], but only a few bamboo species are useful for engineering purpose.

2.2. Bamboo Chemical Composition

The main constituents of bamboo culms are cellulose, hemi-cellulose and lignin, which amount to over 90% of the total mass [43]. "In practically all cases, cellulose is the main component of vegetable fibres. The elementary unit of a cellulose macromolecule is anhydro-d-glucose, which contains three hydroxyl (-OH) groups. These hydroxyl groups form hydrogen bonds inside the macromolecule itself (intramolecular) and between other cellulose macromolecules (intermolecular) as well as with hydroxyl groups from moist air. Therefore, all vegetable fibres are hydrophilic in nature and their air dry moisture content can reach about 3-13%" [44].

Bamboo´s resins, tannins, waxes and inorganic salts are the minor constituents of bamboo chemical composition. Bamboo has higher alkaline extractives, ash and silica content than wood [45,46]. In addition to cellulose and lignin Bamboo contains other organic materials in its composition. It contains about 2-6% starch, 2% deoxidized saccharide, 2-4% fat, and 0.8-6% protein. The ash content of bamboo is made up of inorganic minerals, primarily silica, calcium, and potassium. Manganese and magnesium are two other common minerals. Silica content is the highest in the epidermis, with very little in the nodes and is absent in the internodes [43].

2.3. Properties of Bamboo

2.3.1. Anatomical structure

The bamboo culm consists of a functional gradient distribution of vascular bundles and xylem, where the vascular bundle includes sheaths of fibres and sieve tubes (Figure 2.1). As can be observed in the Figure 2.1 the vascular bundles change their geometrical characteristics and quantities of sieve tubes and sheaths of fibres. This distribution and the mechanical resistance of the fibres provide a functional gradient of elastic modulus for the bamboo cross section.

The sheaths of fibres are the most important component that determines the mechanical properties of bamboo, and the xylem can transfer loads and take on the role of a composite matrix. Therefore, in view of its macro-mechanical behaviour, bamboo is typically a unidirectional fibre reinforced bio-composite. Its unique direction, length of bamboo fibres and its microstructure characteristics, such as the volume fraction and the distribution of sheaths fibres optimize its mechanical properties as a composite material structure [47].

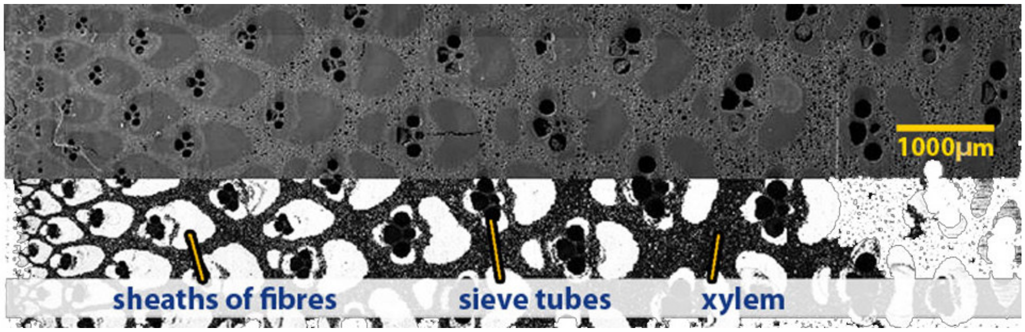

Figure 2.1- Transverse section of *Dendrocalamus giganteus (DG)* bamboo showing a decreasing distribution density of vascular bundles from the outer layer to inner layer of the culm wall

2.3.2. Physical and Mechanical Properties

The density or specific gravity (SG) and moisture content (MC) of the bamboo varies in function depending upon its species, age and the position of the material along the culm length and cross section. The bamboo SG varies between 0.4 to 0.8 approximately and its MC varies from 155% to 70% from the innermost layers to the peripheral layers in some species. The vertical variation is comparatively less [48]. Li (2004) [43] studied the MC of a green and three year old Bamboo along the longitudinal direction, reporting an average MC of 60% for the green bamboo and a significant variation for the three year old bamboo as shown in Figure 2.2.

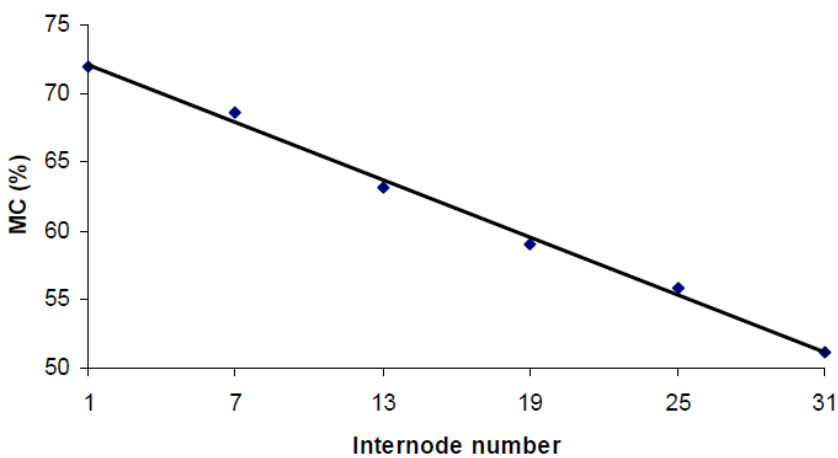

Figure 2.2- Moisture content of three years old bamboo of different internodes [43]

Bamboo fibres length compared with those hardwoods (approximately 1.5 mm) are much longer (variation within species is between 1.6mm to 3.2mm) [49] contributing to the high resistance of the bamboo. Bamboo strength properties experience variation with age (40% to 50%) [50, 51], reaching maximum values at 3-6 years old. The variation in the mechanical properties of bamboo also depend on the position along the bamboo length and it can be more than 100% [52].

Li (2004) [43], studied the longitudinal and tangential compressive strength and its correspondent Young´s modulus for one, three and five year old bamboo at bottom, middle and top position. The results show that the one year old bamboo had in average the lowest compressive strength (16.1MPa) and the five year old bamboo had the highest average compressive strength (34.3MPa). Also the influence of height position is significant when comparing the bottom with the top. The compressive strength as shown in Table 2.1 presents little difference for three and five year old bamboo.

Table 2.1- Compression strength of bamboo [43]

			Longitudinal		**Tangential**	
Year	**Height**	**SG**	***fc* (MPa)**	***Ec* (MPa)**	***fc* (MPa)**	***Ec* (MPa)**
One	Bottom	0.49	47.0 (2.4)	2067 (339)	14.8 (1.1)	277 (61)
	Middle	0.53	50.9 (3.1)	2776 (362)	16.0 (1.2)	254 (71)
	Top	0.54	55.7 (3.8)	3658 (464)	17.4 (0.5)	359 (75)
Three	Bottom	0.70	86.8 (1.8)	4426 (491)	33.0 (1.5)	535 (101)
	Middle	0.71	83.9 (2.8)	4428 (305)	29.8 (3.2)	456 (98)
	Top	0.72	84.0 (3.3)	4660 (451)	33.8 (1.2)	606 (80)
	Bottom	0.75	93.6 (3.6)	4896	34.1 (2.0)	533 (98)

Five				(116)		
	Middle	0.78	86.6 (3.5)	4980 (262)	33.6 (3.0)	527(55)
	Top	0.76	85.8 (5.3)	5185 (330)	35.3 (2.1)	552 (81)

The tensile strength of *Dendrocalamus giganteus* and *Guadgua angustifolia* bamboo considering the tensile specimen with node and without node was reported for Acha (2002) [35] as 135.11 MPa (E=20.76 GPa), 73.17 MPa (E=11.09 GPa) and 245.56 MPa (E=25.37 GPa), 90.78 MPa (E=18.09 GPa)respectively. Dunkelberg (1985) [53] reported that tensile strength of bamboo could reach 370 MPa in some species. The mean longitudinal modulus of elasticity and tensile strength for Moso bamboo were found to be 8.9 GPa to 27.4 GPa and 115.3 MPa to 309.3 MPa respectively [43]. Relative density, Modulus of elasticity and tensile strength were found to increase from the inner layer of the culm to the outer layer and with increasing longitudinal distance from the base [54].

A transversely isotropic equation has been developed by Torres et al., (2007) [55] to predict the circumferential modulus of elasticity for bamboo, by finding a relationship between load and deformation. it was found that for Moso bamboo the circumferential modulus was 1.7 GPa and that the modulus was mostly independent of the longitudinal position along the specimen.

Gibson and Ashby (1999) [7] showed that one of the great benefit of bamboo over steel, apart from ecological advantages, is in its strength to weight ratio (six times greater than that of steel, Figure 2.3).

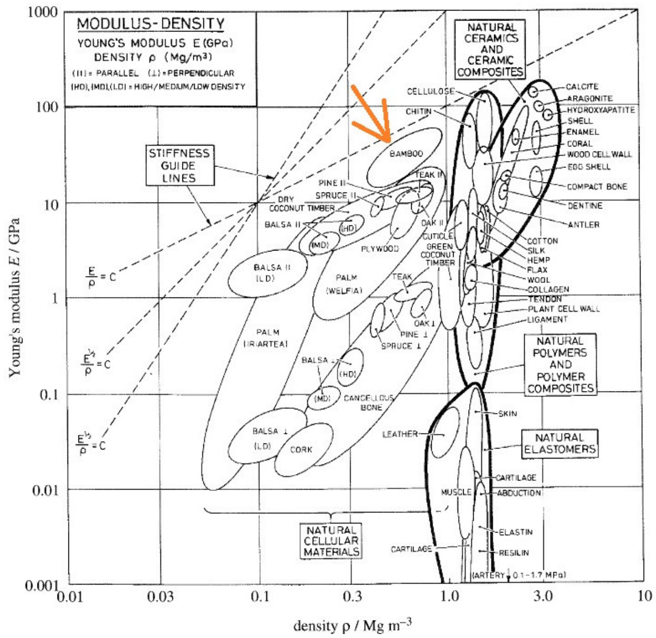

Figure 2.3- A material property chart for natural materials, plotting Young's modulus against density [7]

2.4. Bamboo as concrete reinforcement

Since the beginning of the last century the first intention of using bamboo as concrete reinforcement has been reported by H.K. Chow [30] in 1914 at the Institute of Technology in Massachusetts. Although the study was for concrete reinforcement it never happened, limiting the research on the water's absorption of bamboo.

The United States Naval Civil Engineering Laboratory (1966, 2000) [56] studied the use of bamboo as concrete reinforcement for prefabricated structural elements. Their obsession for wars made them to study the use of bamboo in concrete without any treatment so it could be useful for temporary structures. This was a basic mistake when using natural materials with concrete. After several tests they have reported that green bamboo and un-waterproofed bamboo cannot be used for concrete reinforcement. Recently, as other researchers they have suggested the use of concrete mix, which is the same as that used with steel, with a slump as low as workability will allow and the use of bamboo reinforcement in a proportion of 3-4% of the concrete's cross-sectional area.

Culzoni & Ghavami (1986) [31], studding concrete beams reinforced with bamboo, applied two surface treatments: Negrolin + Sand and Negrolin + Sand + Wire wrapped. The results slightly improved the bonding between both materials (Table 2.2).

The first investigation of bamboo shuttering concrete slabs was performed by Ghavami and Zielinski (1988) [57]. The slabs were manufactured using *Dendrocalamus giganteus* bamboo. It was found that there were three factors in producing an effective bonding and impermeability treatment to bamboo: Adhesion of the substance to both the bamboo and the concrete; Roughness of the bamboo surface and water resistance of the substance.

Masani (1977) [58] encouraged the use of bamboo from an environmental, economical and mechanical points of view. His studies present discussions on waterproofing, concrete design and structural elements design. After considering what the average bamboo tensile strength was, he concluded that the area for reinforcement in concrete should be five times the normal steel reinforcement. He also highlighted the risk of insect attacks for untreated bamboo and fire for dried bamboo.

Ghavami (1995) [59], reported that the highest strength of the bamboo culm is in tension and the compression strength is much lower. The culm tangential strength is low and cannot be considered. Comparing the young modulus between steel and bamboo the second is 1/15 times lower. More bonding between the bamboo and concrete is required. When using bamboo for concrete reinforcement in a beam the last ultimate load increased almost 400% if compared with an un-reinforced concrete beam.

Achá (2002) [35], recommend the use of epoxy resin for bamboo surface treatment to improve bonding between bamboo/concrete and waterproof of bamboo (SIKADUR 32 is an epoxy resin developed for bonding steel to concrete and new concrete with old concrete). This treatment improves significantly the bond stress (Table 2.2).

Table 2.2- Bamboo-concrete push-out test results, presented by Culzoni (1986)[31] and obtained result using SIKADUR 32 Gel (Achá, 2002)[35]

Bamboo surface treatment	**Bonding stress (MPa)**
Sem tratamento	0.52
Negrolin + Areia	0.73
Negrolin + Areia +Arame enrolado	0.97
Sikadur 32 Gel	2.75

The variables which Acha sought to investigate were the type of shear connector, bonding agent between the bamboo and concrete and the type of bamboo used. Two species of bamboo were used, *Dendrocalamus giganticus* and *Guadua angustifolia*. The slab dimensions were 3500mm × 650mm × 110mm and a layer of the bonding agent Sikadur-32 was applied to the bamboo immediately prior to pouring the concrete (Figure 2.4). Material properties for both bamboo and concrete were found. The values are shown in Table 2.3. The nomenclature for the results is as follows:

BT Bending test
DG *Dendrocalamus giganticus*

GA *Guadua angustifolia*

HD Half Diaphragm Connectors

FD Full Diaphragm Connectors

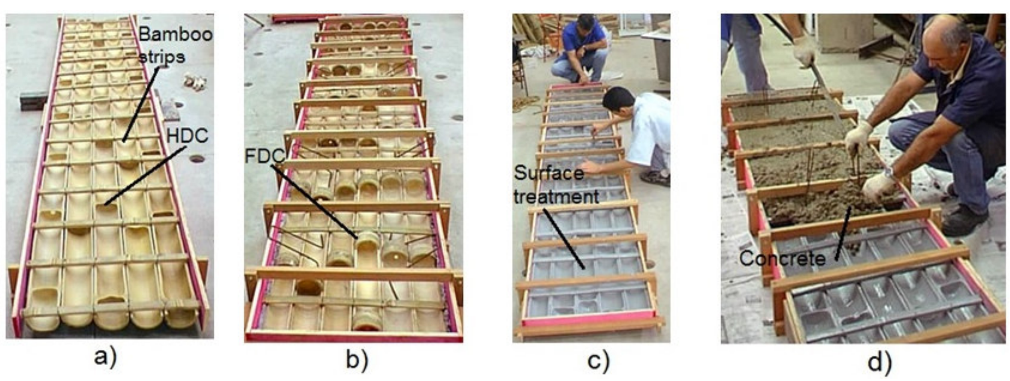

Figure 2.4- (a) formwork of BTDG-HDC (b) formwork of BTDG-FDC (c) epoxy resin treatment [35]

Table 2.3- Materials properties [35]

Slab	**Concrete**				**Bamboo**		
	Slump (mm)	f_c (MPa)	f_t (MPa)	E_c (GPa)		σ_t (MPa)	E_b (MPa)
BTDG - HD	85	29.34	3.37	34.76	With Node	135.11	20760
BTDG - FD	85	28.71	3.41	34.40	Without Node	245.56	25370
BTGA - HD	80	30.3	3.7	36.12	With Node	73.17	11090
					Without Node	90.78	18090

These results concur with those found by Lima et al (1996) [13] where the tensile strength was found to be significantly lower at nodal points. The slabs were subjected to a four point bending test. Linear variable differential transformers (LVDT) were used to measure deflection at five points along the top of the slabs. Strain was also recorded in five points in the concrete and bamboo at the same longitudinal position. Any differential movements and therefore sliding between the concrete and bamboo were recorded by transducers at both ends of the slab. The slab was unloaded at various loads to determine the magnitude of residual deflections. There were some small residual deflections following each loading cycle, these were nominal in comparison to the overall deflection. The results showed that for half diaphragms the *Dendrocalamus giganticus* had a higher collapse load but both showed similar deflection up to the point of collapse of the *Guadua angustifolia*. The full diaphragm had lower deflections loads and achieved a collapse load of about 100kN, 20kN greater than the half diaphragm shuttering of the same species, clearly displaying the influence of the diaphragms on the overall stiffness of the slab.

No sliding was recorded between the bamboo and concrete; it is unclear whether this was due to an effective bond being provided by the bonding agent Sikadur-32 as it was used for all slabs tested. In general, the slabs showed little cracking prior to ultimate load capacity, with larger cracks starting to appear at greater than 90% of the collapse load. The cracks seemed to propagate at points where the bamboo culms had been fixed with transverse bars. For the slab with full diaphragm shear connectors, cracks initiated from the top of the connectors. Collapse occurred by failure in the centre of the slab for the half diaphragms and close to the load points for the full diaphragms, suggesting that the half diaphragms failed in bending and the full diaphragms failed in shear. It should be noted that a greater depth of concrete was used for the full diaphragm slab to provide sufficient cover to the bamboo.

All slabs were found to comply with the limits of maximum deflection, outlined in the Brazilian codes at a loading of 5kN/m^2. The full diaphragm slab suffered deflection of 1.92 times less than that of the equivalent half diaphragm slab. These results will have been influenced to a certain degree by the greater depth of concrete used in the entire diaphragm slab in order to provide sufficient cover to the bamboo. Table 2.4 below shows a summary of the calculated stresses and strains at the centre of the slab for both the concrete and the bamboo.

Table 2.4- Analytical results (Acha, 2002) [35]

Slab	**Service Load (5kN/m^2)**			**State limit of Use (L/500)**			**Ultimate limit State**		
	M (kNm/m)	**ε_c (‰)**	**σ_c (MPa)**	**M (kNm/m)**	**ε_c (‰)**	**σ_c (MPa)**	**M (kNm/m)**	**ε_c (‰)**	**σ_c (MPa)**
BTDG - HD	7.66	0.06	1.74	15.00	0.29	7.68	71.90	2.99	24.34
BTDG - FD	7.66	0.13	3.72	12.50	0.38	9.88	44.30	3.47	21.82
BTGA - HD	7.66	0.04	1.16	20.00	0.30	7.82	108.77	3.27	22.37
	Bamboo			**Bamboo**			**Bamboo**		
	M (kNm/m)	**ε_b (‰)**	**σ_b(MPa)**	**M (kNm/m)**	**ε_b (‰)**	**σ_b(MPa)**	**M (kNm/m)**	**ε_b (‰)**	**σ_b(MPa)**
BTDG - HD	7.66	0.08	1.66	15.00	0.35	7.74	71.90	2.89	60.00

BTDG - FD	7.66	0.03	0.33	12.50	0.06	0.71	44.30	0.34	3.77
BTGA - HD	7.66	0.05	1.04	20.00	0.34	7.05	108.77	3.29	68.30

Acha concluded that using the entire diaphragm contributed efficiently to the composite nature of bamboo-concrete composite slabs and both the experimental and analytical results showed that the ultimate limit state is in concrete crushing.

Although there has been notable progress made in this field since Ghavami's inaugural paper on bamboo concrete composites, his concluding remarks remain relevant. He states the importance of energy saving through technical knowledge, which can be applied to component design alongside non technical issues such as economic and social sustainability. From the data obtained, he concludes that bamboo can substitute for steel satisfactorily as long as the durability and bond are compliant. He also highlights the need to establish characteristic strength tables through rigorous statistical analysis to allow the incorporation of bamboo in structural design to be more accessible.

2.5. Punching shear strength

The theoretical punching shear strength as per the specifications of the British Code of Practice BS 8110 [36] is estimated to be made up of the following: (i) concrete section alone and (ii) both concrete section and tension reinforcement.

$$v = \frac{V}{b_v \, d} \quad \textbf{(2.1)}$$

v not exceed $0.8\,(f_{cu})^{0.5}$ or 0.5 N/mm^2

Where,

v Shear stress

V Design shear force due to design ultimate loads on width of slab equal to the centre distance between ribs

b_v Is the average width of the ribs

d Is the effective depth

2.6. Final considerations

Many of the sources referenced in this section have highlighted how it is necessary for bamboo to be treated for better bonding with concrete. The improved bonding between bamboo and concrete discovered by Acha (2002) [35] which used epoxy resin on the surface of bamboo culms could also be explored further by considering alternative procedures and applications. As bamboo shuttering concrete slab composite standardisation is a necessity, experimental tests where the collapse is reached for failure on the bamboo is also needed to establish limits and analyse the best represented Push-out test specimen and test procedure. The application of bamboo strips as concrete reinforcement provides another alternative material for use in civil engineering, and its production, treatments and application need to be considered also. The fact is that there are limitations in the tensile strength, compression strength, tension stiffness and other physical and mechanical properties of bamboo culm for some applications in engineering. It is a challenge in engineering to find alternative procedures in the ways to use, enhance or improve the bamboo material.

This study is a continuation of the previous studies made by Acha (2002) [35] which used epoxy resin as a bamboo surface treatment (Figure 2.5). Experimental tests on bamboo shuttering concrete slabs will be carried out; inducing the collapse of the slabs to the failure of bamboo connectors to determinate this limit. Alternative bamboo surface treatment and procedures will be considered and tests made to establish mechanical properties. Using the treatment which has better mechanical results, a full scale two-way concrete slab reinforced with bamboo strips will be constructed and tested applying a concentre load (Figure 2.6), and then analysed. In order to produce bamboo bars or strips with better properties than what is found in just plain bamboo culm, layers of the bamboo culm wall with high fibre volume factor will be characterized on its physical and mechanical properties by using a tensile and compression test on the specimens at different moisture and temperature conditions.

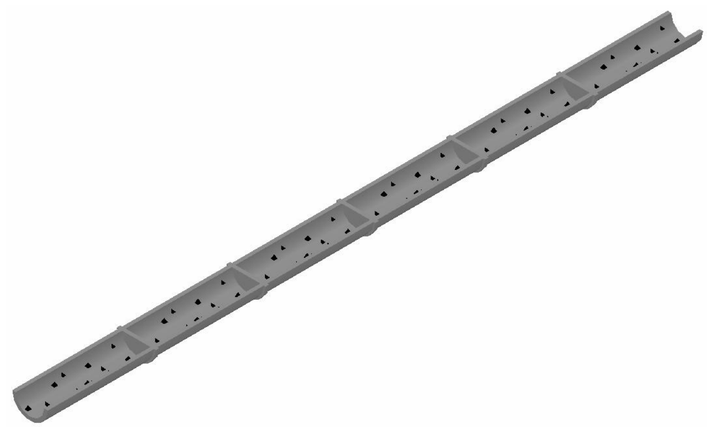

Figure 2.5 - SIKADUR 32 GEL+Brita Surface treatment scheme

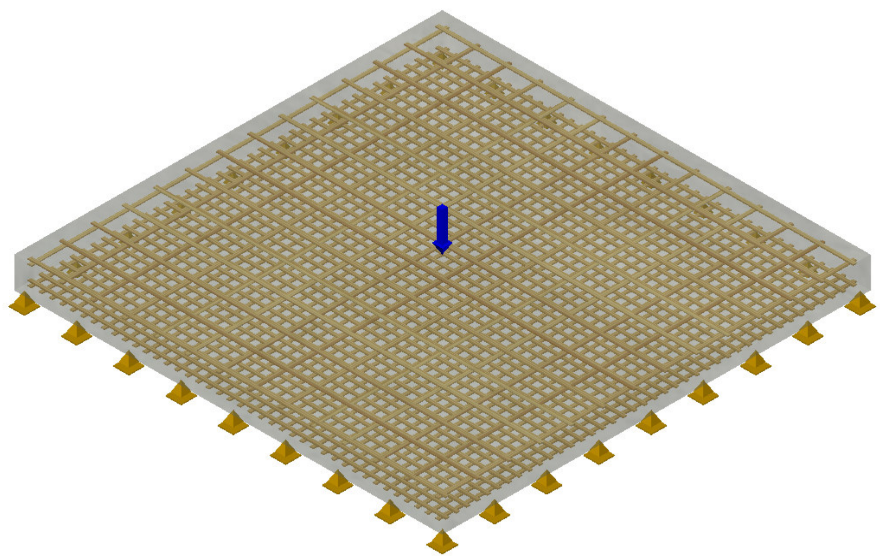

Figure 2.6 - Full scale two-way concrete slab reinforced with bamboo strips scheme