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MEETING REPORT

"Bamboo: A Very Sustainable Construction Material" - 2021 International Online Seminar summary report

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Abstract: 2021 International Online Seminar - Bamboo: A Very Sustainable Construction Material was held in November 2021. This was led by INBAR and co-organised by other 16 national and international institutions. Nineteen senior experts from 10 countries delivered presentations and shared the latest research and development on bamboo construction to approximately 900 participants from 74 countries. The seminar called upon global architects, engineers and landscape designers to rethink time-tested traditional bamboo architectural forms and related technologies, and use innovative ideas to reshape the global built environment. This paper summarizes the findings of this Seminar, highlighting that while bamboo is growingly accepted as a construction material, considerable efforts are needed to promote bamboo as a mainstream material. The state-of-practice is summarized and means of moving the state-of-the-art forward are discussed. Architects and engineers using bamboo all over the world should work together to contribute to the basic work of bamboo architecture research, standardization and industry development.

Keywords: Bamboo architecture; bamboo structure; national strategy; capacity building of professionals; business model; standardization

1 Introduction

1.1 Overall information of the seminar

In November 2021, the International Bamboo and Rattan Organisation (INBAR), INBAR Bamboo Construction Task Force (INBAR TFC), International Union of Architects (UIA), School of Civil Engineering of Tsinghua University, School of Architecture of Tsinghua University, and Architecture Design & Research Institute of Tsinghua University (THAD), with additional support from 12 national and international institutions, co-organized the *2021 International Online Seminar - Bamboo: A Very Sustainable Construction Material* (the 2021 seminar). The online seminar series, initiated by INBAR and INBAR TFC in 2020, aims to form a new international information exchange platform during and after the pandemic, for communicating to global stakeholders the latest information on bamboo

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construction. Based on the great success of INBAR's first online seminar in 2020 and feedback from global audiences through questionnaires, the 2021 seminar explored five themed sessions: 1) Bamboo architecture; 2) Technologies and recent development of contemporary bamboo structures in China; 3) Global bamboo construction business models; 4) Mechanisms for capacity building of professionals; 5) Standardisation of round-pole bamboo structures. See Appendix A for a listing of all presentations and their recorded video links.

1.2 Analysis of registered international participants

Approximately 900 registered participants from 74 countries attended the 2021 Seminar (Fig. 1). Participants from China and India accounted for 31% and 15% of the total, respectively. The remaining 'top ten' participating countries were: Ethiopia (7%), Ecuador (6%), Colombia (5%), Kenya (4%), the Philippines (4%), Cameroon (3%), Uganda (1%) and the UK (1%) (Fig. 1). All but the UK are INBAR member countries. China hosts INBAR Headquarters, while INBAR regional offices are located in India, Ethiopia, Ecuador and Cameroon. Participants from 31 non-INBAR member countries also attended the seminar, nearly half from European countries. Growing interest in Europe on usage of bamboo as a construction material is exemplified by the President of the European Commission, Ursula von der Leyen, who identifying bamboo construction in her op-ed article for a new European Bauhaus movement to boost a European Green Deal [1].

Based on registration data, more than 230 architects, structural engineers or landscape architects joined the seminar. Over 50 participants were from different companies associated with timber, green agricultural industry and bamboo products' industry, and 8% of the participants were officials from international organizations and national government agencies. More than 160 students from 18 countries participated in the seminar, 50% of which were from Chongqing University. Due to participation of world-renowned designers and architects, the School of Architecture and Urban Planning of Chongqing University incorporated the seminar into their course of study. Each student was requested to attend at least three sessions of the seminar. This is one approach to capacity building of global professionals in the future.

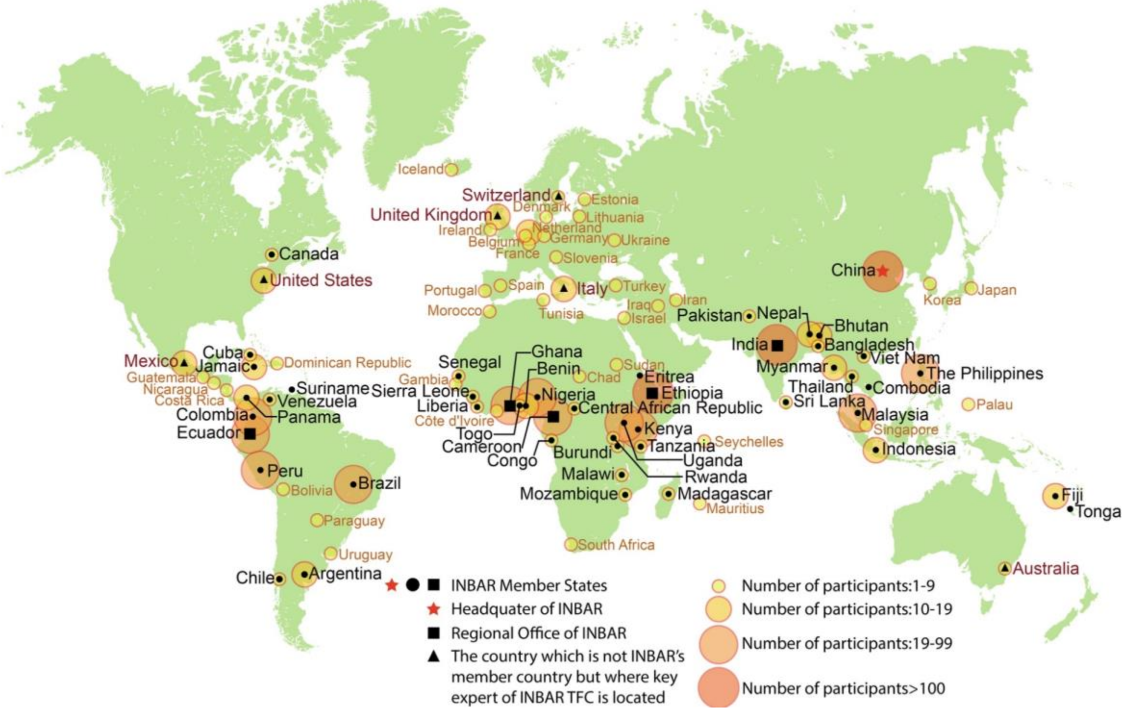


Fig. 1. Geographic distribution of participants in different countries. (*Source: INBAR*)

2 Why use bamboo as a construction material?

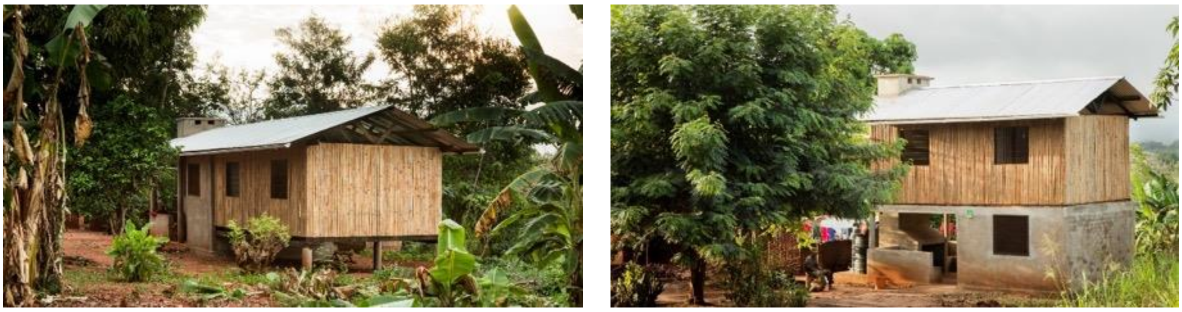
Bamboo has excellent physical and mechanical properties, and has been used as a structural material since ancient times. Due to wide geographic distribution of bamboo forest resources in Asia, Latin America and Africa, bamboo construction can provide a nature-based solution to mitigate the effects of natural disasters, global housing shortages, sustainable livelihood development, climate change mitigation and adaptation, and the goal of carbon neutrality. During the opening of the seminar (see Appendix A – Opening words) [2], representatives from five co-organisers called upon global architects, engineers and landscape designers to rethink the time-tested traditional bamboo architectural forms and related technologies, and use innovative ideas to reshape the global built environment. At the same time, the UIA-INBAR side event 'Built Environment Professionals Towards the Bio-based Design Implementation Process' was held at COP 26 in Glasgow, UK. The event also deliberated on bio-based design, and how architects and engineers can integrate carbon neutrality into the built environment by using bamboo as a construction material [3]. An innovative engineered timber-bamboo gridshell demonstrated at the INBAR-Napier booth showcased the great potential of bamboo to be used in large-span roof structures [4]. As there is not much time left for countries to limit global warming to 1.5 degrees Celsius, natural sustainable building materials, such as bamboo, timber, etc., need to be explored for their potentials to affect carbon neutrality in the construction sector.

3 Architectural uses of bamboo

In the face of various threats such as environmental pollution, resource scarcity and global warming, architects worldwide have been carrying out a series of studies to make architecture a mechanism to serve people better. As a biomaterial, bamboo plays a unique role in the field of architecture. Creating healthy and natural spaces using natural bamboo materials to achieve specific architectural function is a trend for the development of the global bamboo construction sector in the future.

3.1 Healthy residential bamboo houses [2]

According to the report of the World Meteorological Organization, the rate of temperature increase averaged across Africa is greater than the global average [5]. Estimated malaria cases and consequent deaths globally in 2017 was around 219 million and 435,000 respectively, with 90% of the deaths occurring in sub-Saharan Africa [6]. With the global climate change, the range of disease-carrying mosquitoes is increasing [7]. Jakob Brandtberg Knudsen, Dean of the Royal Danish Academy of Fine Arts, School of Architecture introduced his approach for using bamboo to reduce infectious diseases in sub-Saharan Africa (see Appendix A - Topic 1). Knudsen analyses the effect of design on the indoor climate and relates these factors to health, notably the risk of mosquito-borne infectious diseases such as malaria [8]. Bamboo is locally available, lightweight and can be utilized to assure easy ventilation. Knudsen, based on his findings and a detailed understanding of local building styles and preferences, adopted local bamboo to create healthy residential houses (Fig. 2) in sub-Saharan Africa, enhancing comfort for local residents while greatly reducing mosquito infestations.



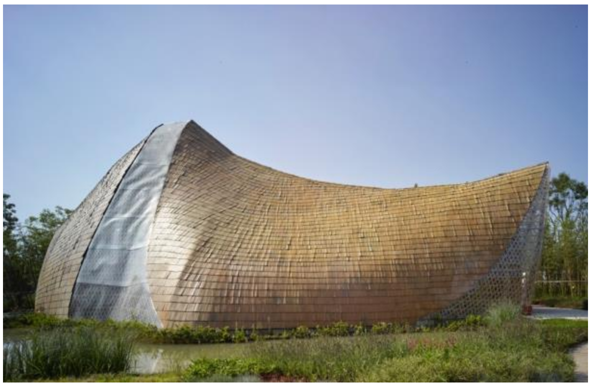
(a) Single-storey house with bamboo cladding. (b) Two-storey house with bamboo cladding.

Fig. 2. Healthy bamboo residential houses in sub-Saharan Africa. [9]

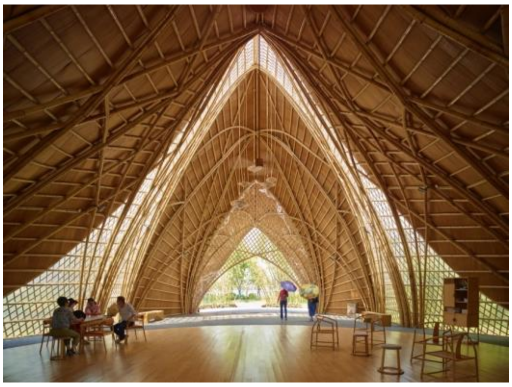
3.2 Bionic bamboo architecture [2]

Asia has the most bamboo species suitable for construction in the world. Asian architects have a preference for curved natural forms to create various bionic buildings to demonstrate the power and beauty of nature. Two cases show applications of architectural and structural bionics respectively.

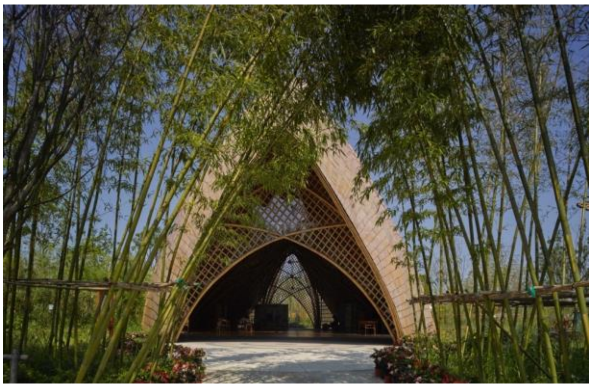
Song Yehao, Co-founder and Principal of SUP Atelier of Architectural Design Research Institute of Tsinghua University, is the leading architect of INBAR Fish-Shaped Bamboo Pavilion (see Appendix A - Topic 2). This is a fish-shaped bionic building, built for the INBAR Garden at the 2021 Yangzhou Horticultural Expo. Song mentioned that the design was inspired by the beautiful Chinese phrase: "Celebrating with gold and jade". The structure creatively uses the minimum amount of round bamboo poles to create a semi open space with as large span as possible. At the same time, the structure is light and beautiful and integrates Chinese culture. "*The Pavilion is symmetrical along the centre of the ridge, resembling a fish with an arched back* (Fig. 3a). *A series of bamboo arches of different heights and spans change with the shape of the roof ridge, which shape the characteristic indoor space* (Fig. 3b) *with great rhythm. The main entrance* (Fig. 3c), *at the head of the fish is larger to the west, and the scale of the secondary entrance at the tail towards the East is slightly smaller. The middle of the pavilion, a "lighting belt", combines the highest roof ridge, and a section of full-height windows yielding rich light and shadow changes to the room. The internal structure of round pole bamboo structure* (Fig. 3b, 3d) *is magnificent, and fully demonstrates the characteristics and charm of natural curved bamboo in modern architectural design*" [10].



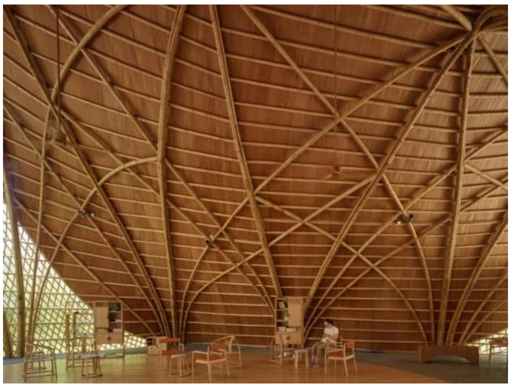
(a) Exterior of Fish-Shaped Bamboo Pavilion.



(b) Interior of function hall.



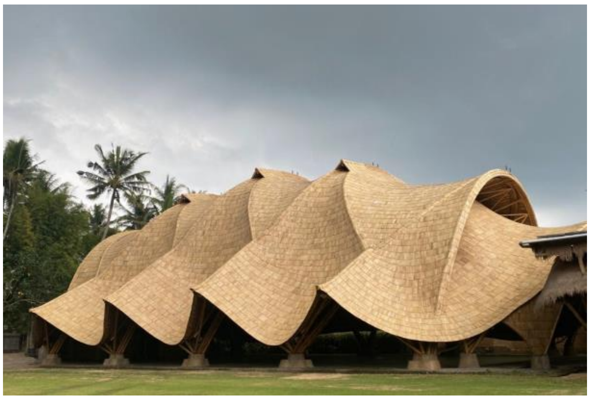
(c) Main entrance.



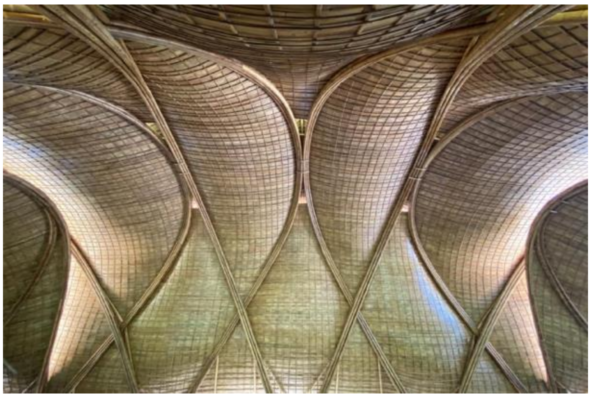
(d) Woven full-culm bamboo structure.

Fig. 3. INBAR Fish-shaped Pavilion in China. (*Credit: Chu Yingnan*).

The Arc Gymnasium (Fig. 4), located in the world-renowned Green School in Bali, Indonesia, is another remarkable structural bionic bamboo building completed in 2021. Neil Thomas, an engineer andthe founder of Atelier One, a UK based structural design company, showcased how he and his team used natural forms of bamboo to achieve buildings of both beauty and strength (see Appendix A - Topic 3). In collaboration with local architecture studio IBUKU, this newest education architecture – the Arc – features a vast and intricate double-curved roof made entirely of bamboo. The Arc continues the local architectural vernacular of the Green School with organic design, fully realising the power and beauty of natural bamboo with the flexible geometry it can form. The structure comprises a series of intersecting bamboo arches which are interconnected by a curved bamboo gridshell [11]. Another participating designer, German carpentry specialist Jörg Stamm described: "The Arc operates like the ribs of a mammal's chest, stabilised by tensile membranes analogous to tendons and muscles between ribs. Biologically, these highly tensile microscopic tendons transfer forces from bone to bone. In the Arc, bamboo splits transfer forces from arch to arch." [11].



(a) Exterior of the Arc Gymnasium.

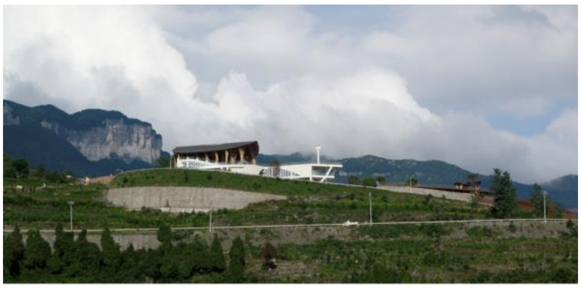


(b) Interior of the Arc Gymnasium.

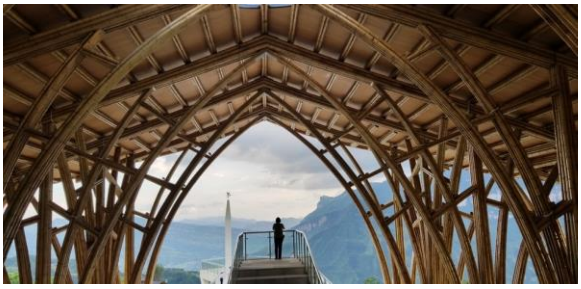
Fig. 4. Arc Gymnasium in Indonesia. (*Credit: Tommaso Riva*)

3.3 Open large-space bamboo landscape architecture integrated into built environment [12]

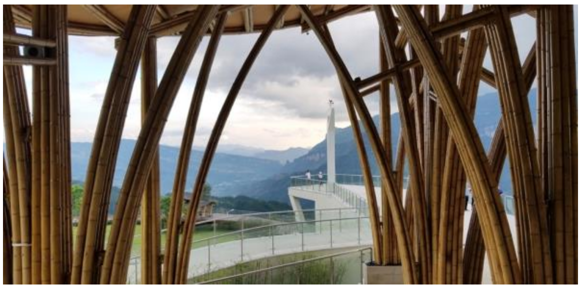
Using natural materials to reduce the impact of buildings on the environment is one of the main reasons architects choose bamboo. Combined with bamboo's excellent mechanical properties, such as light-weight and good ductility, large open spaces can be easily created with good performances of resisting earthquake while the architecture can be fully integrated into the environment. Qin Lin, Associate Professor of the School of Architecture and Urban Planning of Chongqing University introduced her design for such a structure, the Baizhishan Tourist Reception Centre, in Guizhou, China (see Appendix A - topic 5). This large-space bamboo building (Fig. 5) is located on a concrete platform, echoing the distant mountains. The architectural design gives full play to the natural properties of bamboo. The building is composed of six full-culm bamboo arches (each arch has 3 spans of 6 m, 12 m and 6 m, respectively) in the middle and two spans of 12 m at the front and the back of the building [10]. Bamboo is not only for structural load-bearing, but also plays the role of enhancing the natural atmosphere. People can see the surrounding environment through the building, and the building itself becomes a part of the natural landscape.



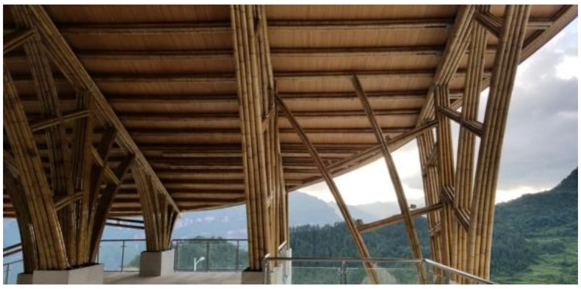
(a) With distant mountains.



(b) Viewing platform and bamboo building.



(c) Looking at the scenery through bamboo building.



(d) Detail of the structure.

Fig. 5. Baizhishan Tourist Reception Centre. (*Credit: Yang Yuzhen & Qin Lin*)

4 Structural uses of bamboo

Natural bamboo features a straight hollow tube with diaphragms at nodal regions. Due to its naturally optimised structural form and distribution of longitudinally-oriented fibres, bamboo has high uniaxial strength and stiffness [13],[14]. Appropriate load-bearing forms for bamboo take advantage of this natural optimization and are most efficient when implemented as arches, trusses and in tensegrity structures. At the same time, combining bamboo with other materials (such as steel) and making full use of the advantages of different materials can build structures with larger spans.

4.1 Bamboo arch structures

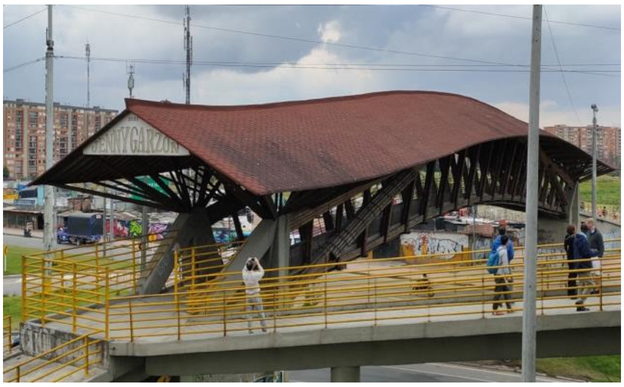
Bamboo, a material with comparative high compression strength, the arch structural form can be an efficient use of its properties, while its curved shape embodies a unique structural beauty. The bamboo arch is usually composed of multiple round bamboos, which can greatly increase the section area, the moment of inertia as well as its stability. Bamboo arch structures are found globally. As described in Section 3.2, the Arc at the Green School in Indonesia was built from a series of intersecting 14 m-tall bamboo arches spanning 19 m, combined with an anticlastic grid shell roof structure [11]. The INBAR Pavilion "Bamboo Eye" (Fig. 6) at the 2019 Beijing International Horticultural Expo [15] is the largest round pole bamboo arch structure in northern China. The main structure is comprised of nine variable cross-section trussed arches spanning 32 m [10]. To reduce the horizontal thrust at the arch bases, steel cable tension ties are used to connect two end of the arch - creating a 'tied arch' structure. An arch and truss hybrid was also used in the design of 45 m long Jenny Garzon bridge in Bogotá, Colombia (Fig. 7). The bridge was completed in 2003 and built with local *Guadua* bamboo. Different from the design of the "Bamboo Eye", two bamboo arches form the main load-bearing structure of the bridge while the trussed roof structure (seen in Fig. 7b) provides lateral stiffness and stability to the bridge.

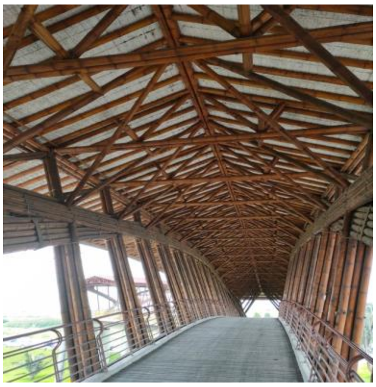
(a) External view to the front façade. (b) Internal view to the roof structure.

Fig. 6. INBAR Pavilion "Bamboo Eye". (*Credit: Liu Kewei*)

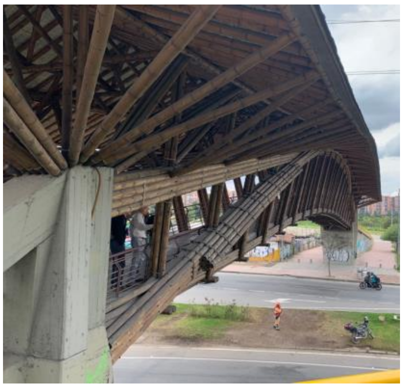
4.2 Tensegrity bamboo structures

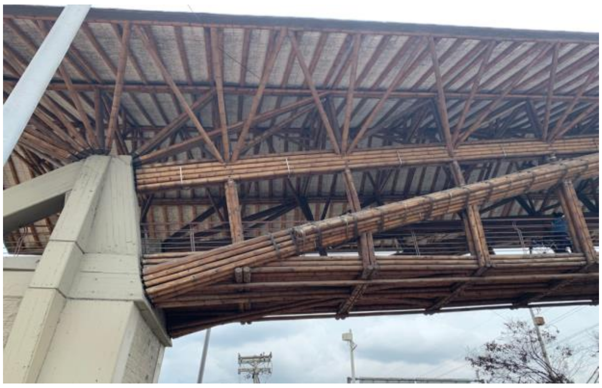
Due to its high longitudinal compression strength, bamboo is well suited to use as compression components for tensegrity structures, while making full use of steel's high-tension strength. Tensegrity is the property demonstrated by a system that employs steel cables and rigidity of other elements (usually steel, wood or bamboo) capable of acting under tension and compression stresses together to form an integrated whole [16]. Andry Widyowijatnoko, Lecturer and Architect at Institut Teknologi Bandung from Indonesia introduced practices of bamboo tensegrity structures in which he trained worldwide students to use different bamboo species and guided them to understand mechanical properties of bamboo (see Appendix A - Topic 11). Fig. 8a shows a tensegrity bamboo structure built in ITB Workshop on Advanced Tensegrity 2017. During the 2018 BFU Garden-making Festival (Fig. 8b), a competition held in China since 2018 for students of landscape architecture, one team used round bamboo culms to create a landscape architecture with flowers in the garden. Currently, tensegrity bamboo structures have only been used in small-scale installations. With the potential for larger structures – such as those realised with steel – only now being explored.





(a) Side view of the bridge. (b) On the bridge.





(c) Side view of bridge. (d) Detail of arch end and abutment.

Fig. 7. Jenny Garzon Bridge in Colombia. (*Credit: Fig.7a, 7b by Liu Kewei, Fig.7c, 7d by Kent Harries*)

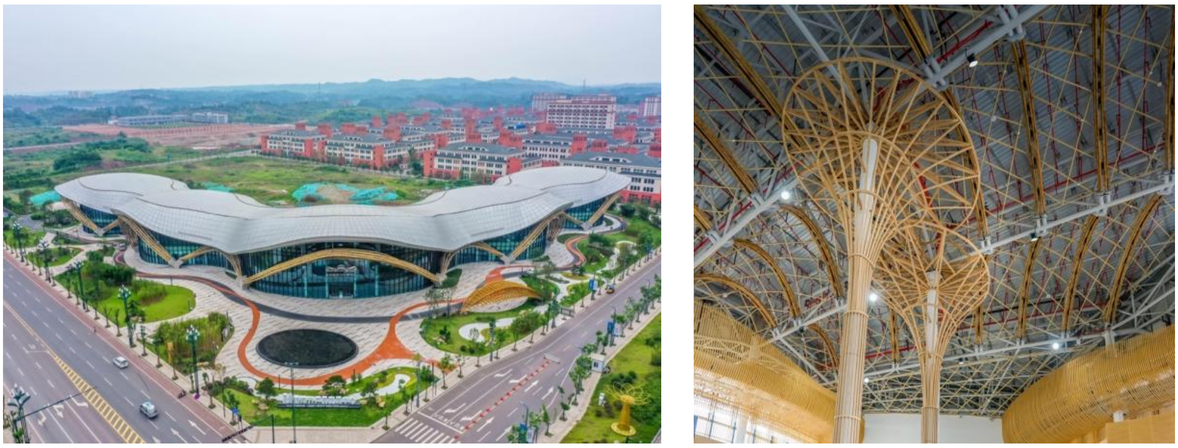
(a) Tensegrity bamboo structure built in ITB Workshop on Advanced Tensegrity 2017. (*Credit: Andry Widyowijatnoko*)

(b) Tensegrity bamboo structure at 2018 BFU Garden-making Festival held in BFU Campus, China. (*Credit: Liu Kewei*)

Fig. 8. Tensegrity bamboo structures.

4.3 Hybrid steel-bamboo structures [12]

Utilising the high compression strength of bamboo, hybrid steel-bamboo truss members have emerged as an alternative for long span structures in China. Peng Baoning, Director of Technology Centre of Xi'an Construction Engineering Green Construction Group Co. Ltd, introduced the design and construction of the largest steel-round bamboo hybrid structure in the world: the "Yibin International Bamboo Products Trading Centre" (Fig. 9a) (see Appendix A - Topic 6). The roof-supporting structure uses a steel-bamboo hybrid truss roof system (Fig. 9b). The top chord of the arched truss is steel while the bottom chord is bamboo. With a maximum span of 20 m, the bamboo arch contributes about 60% of the load-bearing of the composite truss. Sprinkler fire protection measures were required in order to meet strict local requirements [10]. Several tests of fire-resistance performance demonstrated that sprinklers were effective in cooling the bamboo arch, helping to extinguish fire and isolating fire sources. The aesthetics of the bamboo and long-span space combine to result in a flexible and vital space, fully displaying the charm of the combination of Chinese craftsmanship and modern design, ultimately promoting the application of large-scale bamboo structures in China.



(a) Aerial view. (b) Interior space with steel-bamboo hybrid truss roof.

Fig. 9. Yibin International Bamboo Products Trading Centre. (*Credit: Xi'an Construction Engineering Green Construction Group Co., Ltd*)

4.4 Engineered bamboo structures [17]

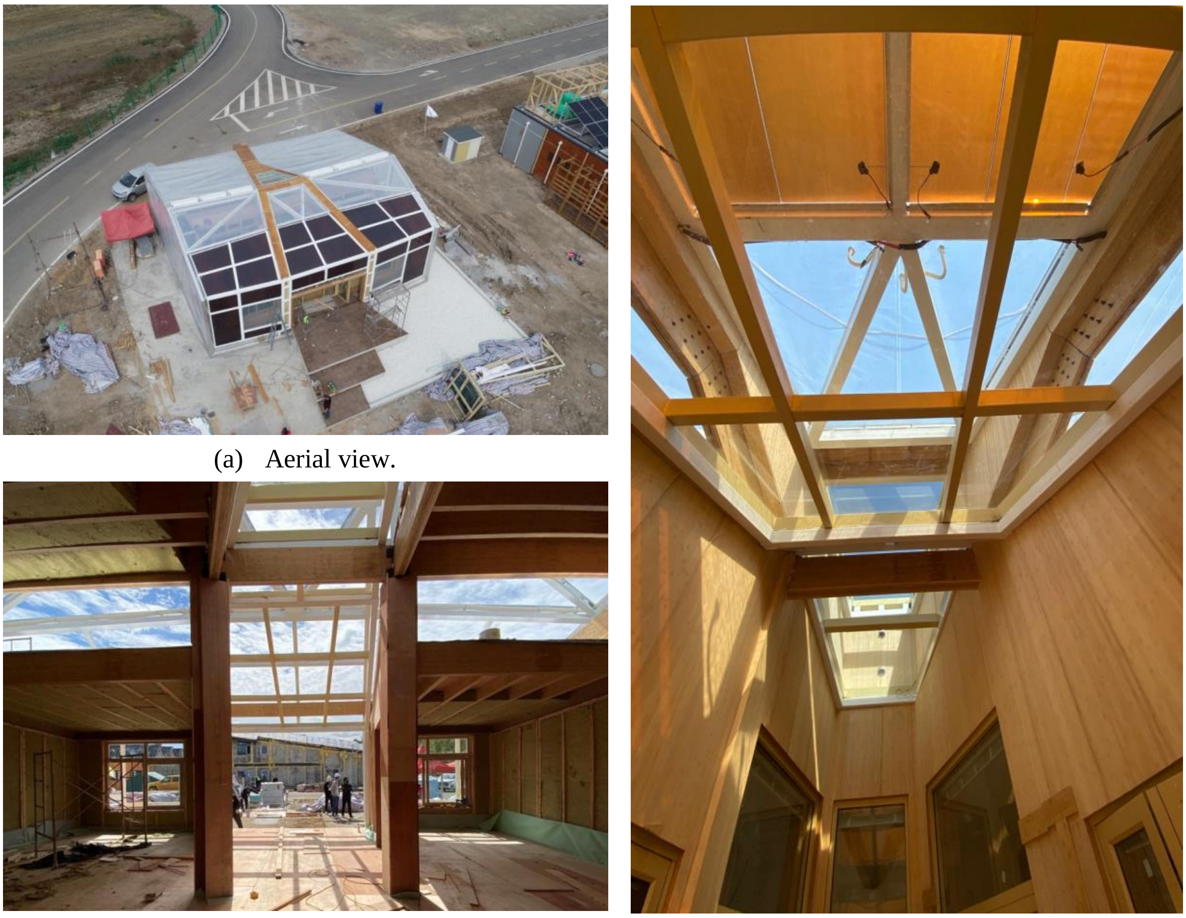
Due to improved material uniformity and dimensional stability, engineered bamboo construction is gradually gaining commercial importance in China. Combining structural bamboo materials with clean solar energy is a promising approach for sustainable housing projects, that can greatly help China's goal of Carbon Neutrality by 2060. Marco Cimillo, Associate Dean of Learning and Teaching of the Design School of Xi'an Jiaotong-Liverpool University introduced the Y-project from the 2021 Solar Decathlon China, a worldwide international student competition for solar housing (See Appendix A, Topic 12). Y-project (Fig. 10) aims at integrating design strategies and state-of-the-art technologies to develop an advanced prototype, able to demonstrate the highest achievable standards in architectural and environmental quality, energy efficiency, and economic viability [18]. The structural system of the project uses locally-available biomass materials, such as bamboo and straw, to construct an innovative climate-smart and energy-saving building. The structural components and interior decoration of the building adopt a large number of engineered bamboo components, which improves long-term carbon-storage in the building and reduces the uses of carbon-intensive construction materials, such as concrete and steel.

5 Business models for the global bamboo construction sector

A discussion of business models from the bamboo construction sector from different countries can promote further development and attract new investment to the sector. Three successful entrepreneurs, managing three companies related to bamboo construction from Spain, China and Colombia, respectively, reported their experiences. Due to different natural bamboo resource distribution, technology development, and import and export trade models, business models and management philosophies differ. Their valuable experience based on product customization, design-driven innovation and technology cooperation with advanced countries are summarised in the following sections.

5.1 Product customization based on import business [19]

Bamboo products in Europe are based on imports from other countries. According to the latest INBAR statistics, the EU-27 was the largest importer of bamboo products in 2019, accounting for 30% of the world's total bamboo imports [20]. Francesco Intrieri is the Director of Projects of Bambusa, located in Spain delivered the presentation on how they applied new bamboo materials in the field of architecture and furniture, Bambusa, established in 2009, started selecting round bamboo materials for garden terrace construction (Fig. 11a). Bambusa gradually grew incorporating round bamboo architectural design (Fig. 11b, 11c &11d) and bamboo household product customization in Spain. They import the bamboo materials from all over the world, providing relevant design, production and consulting services for customers in southern Europe. Bambusa believes that bamboo has great potential to contribute to European green circular economy in the future (See Appendix A, Topic 7).



(a) Aerial view.

(b) Internal view under construction.

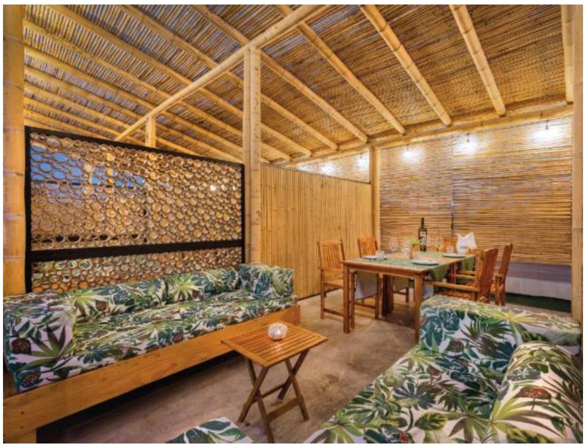
(c) Looking at the roof.

Fig. 10. Y-project of the 2021 Solar Decathlon China. (*Credit: Marco Cimillo*)

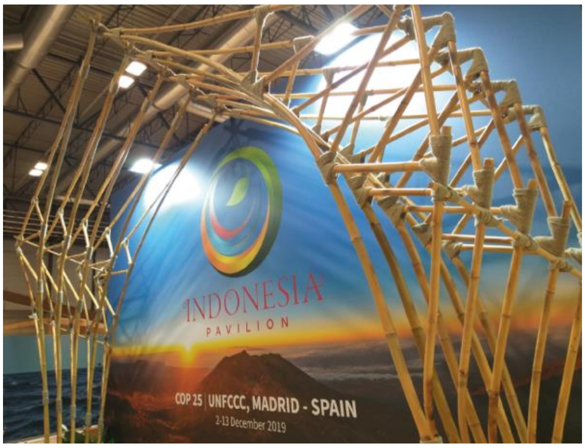
5.2 Design-driven innovation for domestic and international markets [19]

China has always been the world's largest producer and exporter of bamboo products. Xiong Zhenhua, General Manager of Ganzhou Sentai Bamboo & Wood Co., Ltd (Sentai) in China, shared his experience on how his company grew in the commercial market and help his company to stand out from thousands of competitors in China (See Appendix A, Topic 8). Based on its traditional furniture and building decoration materials industry, Sentai focuses on customized production services and promoting research and development of innovative engineered bamboo materials and commercial application of prefabricated engineered bamboo structures. In collaboration with Pritzker award architects and renowned domestic architects, the company cooperates with designers with diversified needs maintaining the core concept of design-driven industry. Projects include the Shanghai Calypso Mediterranean Restaurant of Shangri La Hotel (Fig. 12a), Old Bailey Restaurant of Hong Kong Tai Kwun (Fig. 12b), Tourist Service Room for Tangshan Mine Camp in Nanjing (Fig. 12c) and others. Products have been exported to more than 20 countries. For example, the Ilan and Assaf Ramon International Airport in Israel (Fig. 12d), completed in 2019, uses more than 40,000 square meters of bamboo ceiling and wall decoration – many elements as long as 6 m – which were all manufactured by Sentai to meet the European fire protection B1 Standard [10].

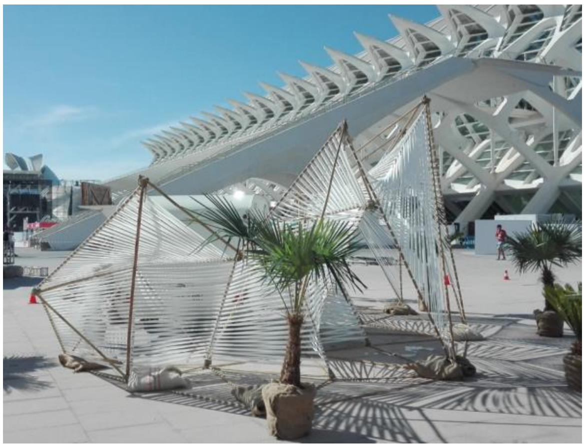
(a) Garden terrace structure in Spain.



(b) Private Lounge of Restaurant in Alicante, Spain.



(c) COP25 Indonesia Bamboo Pavilion in Madrid, Spain.

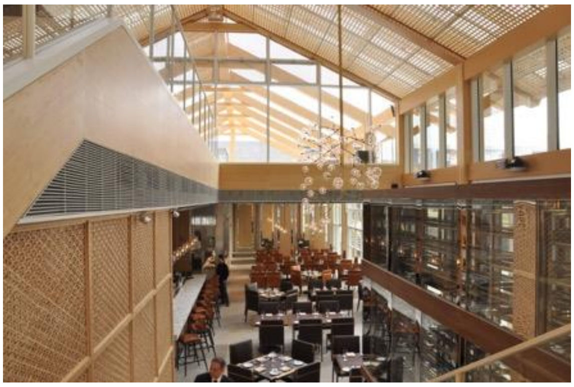


(d) Bamboo Pavilion at Festival de les Arts in Valencia, Spain.

Fig. 11. Bambusa's projects in Spain. (*Credit: Francesco Intrieri*)

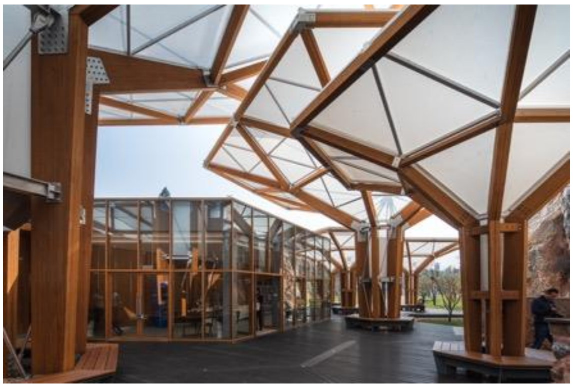
5.3 Cooperation with bamboo technology advanced countries [19]

Since the 1970s, the Colombian bamboo community has focused primarily (and quite successfully) on the development of round pole bamboo structures [10]. In recent years, local entrepreneurs are paying greater attention to engineered bamboo products. Juan Paulo Mayorca is the CEO of Del Bambú, Colombia. He is a chemical engineer who was previously engaged in the business of plastic products. In 2013, he came across bamboo toothpicks and barbecue sticks at China Canton Fair, which inspired his idea of using local *Guadua* bamboo in Colombia to produce relevant products. Upon his return to Colombia, he evaluated local bamboo resources, market, capital and operability. In 2016, he imported equipment from China and established a bamboo toothpick and barbecue stick factory. However, he soon found a problem. Due to the lack of bamboo forest management, local bamboo quality could not be Guaranteed. Additionally, the physical and mechanical properties of Colombian *Guadua* bamboo are different from those of Chinese *Moso* bamboo. Without adjusting, the equipment could not Guarantee production efficiency and quality of finished products. But Mayorca was not discouraged. He continued to cooperate with Chinese research institutions and in 2018, he imported new equipment from China and built a bamboo board processing factory (Fig. 13a). He solved the problem of bamboo supply under the coordination of the Colombian Bamboo Association and ensured equipment, technology and product quality with the help of Chinese research institutions. In 2021, his bamboo boards (Fig. 13b) began to be commercialized and applied to the field of indoor and outdoor decoration (Fig. 13c) and home furnishing (Fig. 13d), which were welcomed by the market. Mayorca believes that the key to his success was his close cooperation with Chinese institutions and firm belief in bamboo (See Appendix A, Topic 9).

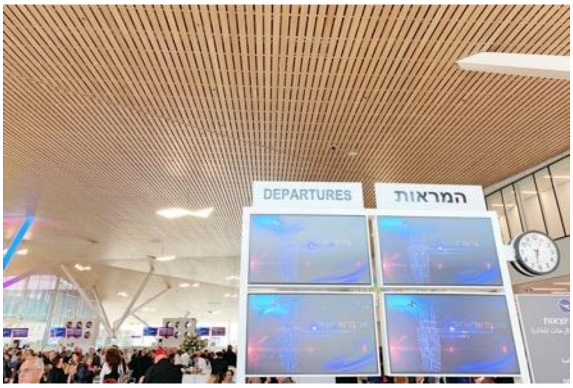


(a) Calypso Mediterranean Restaurant of Shangri La Hotel in Shanghai, China.

(b) Old Bailey Restaurant of Hong Kong Tai Kwun, China.



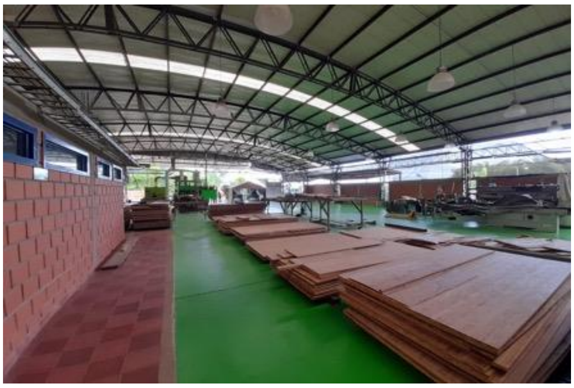
(c) Tourist Service Room for Tangshan Mine Camp in Nanjing, China. (*Photo by Timeraw Studio)*



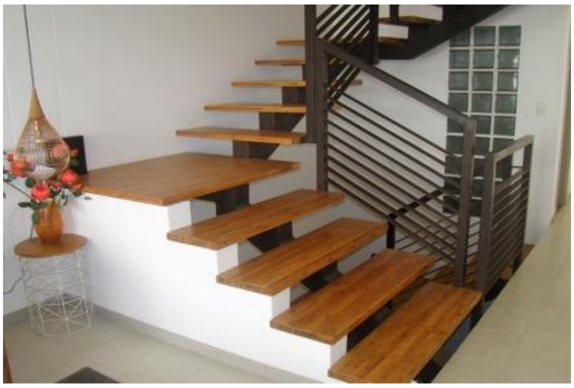
(d) Ilan and Assaf Ramon International Airport in Eilat, Israel.

Fig. 12. Sentai's projects in China and Israel. (*Credit: Fig.12.b, 12.c, 12.d by Sentai*)

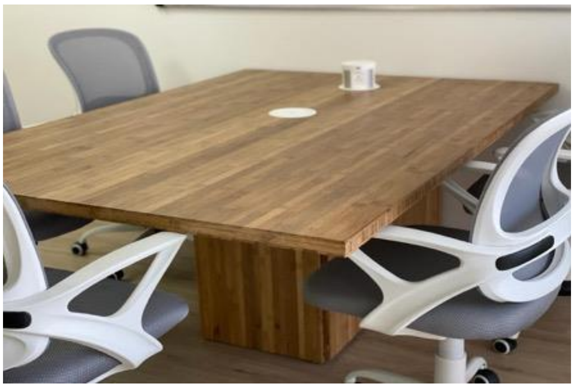
(a) Factory of Del Bambú in Colombia.



(b) Manufacturing bamboo boards.



(c) Bamboo boards for ladder.



(d) Table and kitchen countertops.

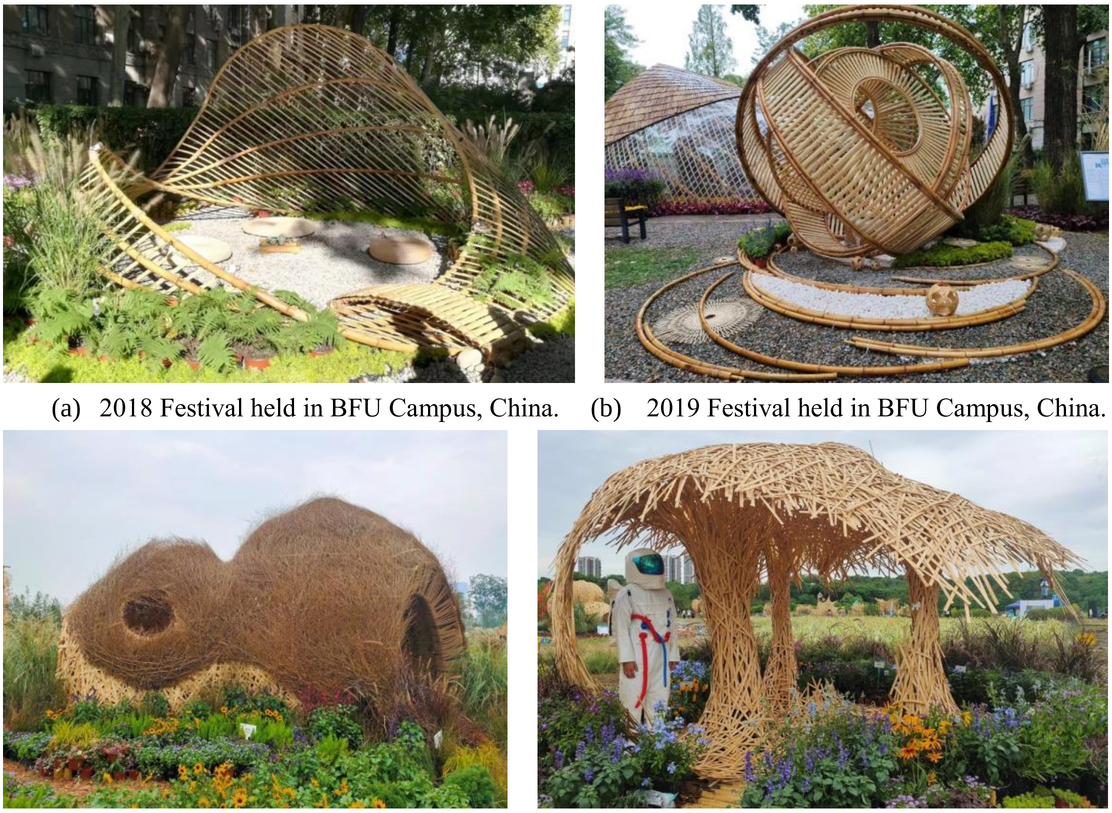
Fig. 13. Del Bambú in Colombia with its products. (*Credit: Juan Paulo Mayorca*)

6 Capacity building of professionals

The development of a global bamboo construction sector requires a large number of professionals. However, the majority of higher education and vocational training institutions across the world, do not provide opportunities for building professionals, such as craftspersons, engineers, architects or designers to 'experience' bamboo [21]. In recent years, the situation has improved as biomass construction materials gradually draw attention from architects and engineers in the context of global climate change. Bamboo-themed competitions related to architecture or landscape architecture become new ways of "Learn by doing" to expose university students to the study of bamboo as a construction material [22],[23]. Although bamboo architecture is still far from becoming an independent discipline, more short-term courses have been set up by universities in several countries, including the UK, China, Indonesia, Colombia etc.

6.1 Competition-driven trainings [17]

The BFU Garden-making Festival is a bamboo-themed landscape architecture competition held in China since 2018. Taking bamboo and flowers as the core design elements, the Festival aims to stimulate the creative enthusiasm of students, improve their design ability and cultivate their practical and innovative talents for the landscape architecture industry. Along the way, the Festival has continuously improved its scale, the number of participating teams and the level of design works. Festival initiators Wang Xiongrong and Zhao Jing are Professors from the School of Landscape Architecture of Beijing Forestry University. They reported that since 2018, the organising committee has received 1,400 submissions from 316 universities and 9,350 applicants, with 93 groups completing field construction (Fig. 14). Nine open activities have been held, attracted online and offline participation of more than 700,000 and 24,000 respectively. The Festival enables more young college students to understand and explore the extensive application of local bamboo material in urban parks, revitalize bamboo in the context of the new era in China, and constantly explore its value and potential in landscape architecture (See Appendix A, Topic 10).



(a) 2018 Festival held in BFU Campus, China. (b) 2019 Festival held in BFU Campus, China.

(c) 2020 Festival held in Chengdu, China. (d) 2021 Festival held in Chengdu, China.

Fig. 14. Field bamboo construction projects of BFU Garden-making Festivals. (*Credit: Liu Kewei*)

6.2 Short-term courses [17]

Andry Widyowijatnoko, Lecturer and Architect at Institut Teknologi Bandung, Indonesia, and John Naylor, Architect of AA School of Architecture, London, introduced their innovative attempts to train students and researchers for design and application of bamboo architecture around the world (See Appendix A, Topic 11). As introduced in Section 4.2, Dr. Widyowijatnoko trained students worldwide to use different bamboo species and guided them to understand mechanical properties of bamboo. Mr. Naylor focused on bamboo architectural design courses at AA School of Architecture, the oldest Architectural College in the UK. From the perspective of architecture and engineering, these courses taught students how to use professional software to design bamboo structures and carry out in-situ tests, so as to further understand and apply local bamboo resources. According to different natural, social and economic conditions in different countries, Widyowijatnoko and Naylor have collaborated with local scholars to carry out many research projects and joint training programmes (Fig. 15). These not only inspire the exploration of local bamboo resources and constructing new bamboo buildings in different regions, but also provide valuable practical experience for training global architects and engineers in bamboo structure design and construction.

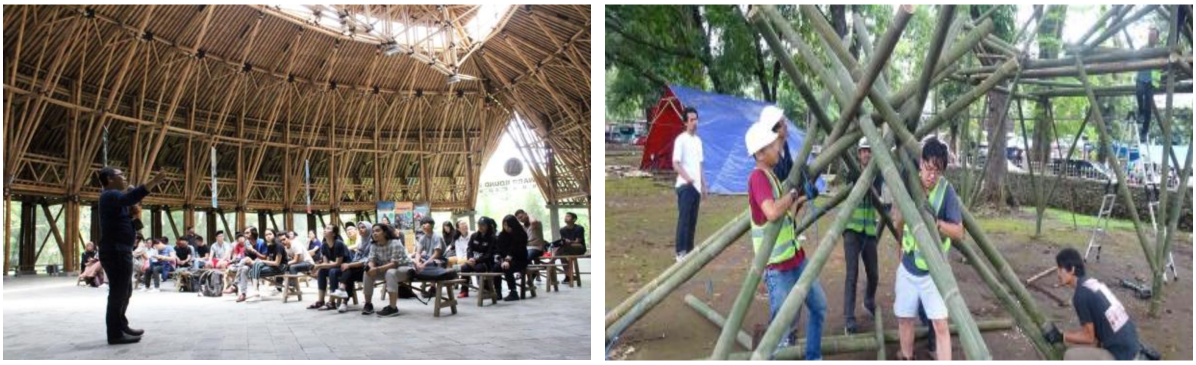


Fig. 15. Bamboo construction training courses of AA-ITB BambooLab. (*Credit: John Naylor*)

7 National policies and strategies [12]

Although bamboo – a renewable biomaterial – has great potential to be widely used in the low-carbon- and green-driven building environment, the uptake of bamboo construction products in mainstream construction markets remains limited. However, the development of national policies and strategies is critical to the development of a bamboo construction sector in different countries. The 2021 seminar took China as an example to introduce the latest research on the development of Chinese national policies and strategies for the bamboo construction sector (See Appendix A, Topic 4).

Co-authors Yang and Liu are two of main researchers of the national consulting project "Research on Development Strategies and Key Technologies for the Bamboo Construction Sector in China towards 2035", funded by Chinese Academy of Engineering. The project aimed to assess China's use of bamboo construction, and how to expand the sector. Approximately half of the available international literature on bamboo in construction originates in China [24] and the National Natural Science Foundation of China has consistently increased its support year on year [25]. The final report of the project, published in 2021, included a series of suggestions to the Chinese government for further actions to create an enabling environment for the sector, including enhancing the scale and core competitiveness of enterprises, setting up national key laboratories, establishing research funds, promoting demonstration projects, as well as strengthening national standardization and international cooperation [24].

At the end of 2021, the China Forestry and Grassland Administration, together with nine other ministries including the Ministry of Housing and Urban-Rural Development, jointly issued a national policy entitled "Opinions on Accelerating the Innovative Development of Bamboo Industry". It clearly indicates that China will enhance the utilization of bamboo construction materials to contribute toward 2060 carbon neutrality [26].

8 Standardisation of round-pole bamboo structures [27]

ISO 22156:2021 Bamboo Structures – Bamboo culms – Structural design was issued by the International Organization for Standardization (ISO) in June 2021. The standard was jointly developed by global bamboo construction experts convened by INBAR in Working Group 12 on Structural Use of Bamboo within the Timber Structures Technical Committee of ISO (ISO TC165 WG12). Combined with *ISO 19624:2018 Bamboo structures — Grading of bamboo culm — Basic principles and properties* and *ISO 22157:2019 Bamboo Structures — Determination of physical and mechanical properties of bamboo culms — Test methods*, the basic framework for international standardization of round pole bamboo structures has been established.

A core group of experts worked since 2016 to completely revise the 2004 version of the standard. Using a model in which the INBAR TFC provided critical feedback prior to ISO TC 165 balloting, the expert input of both the INBAR bamboo community and the standards development community of ISO was fully engaged, resulting in a robust standard.

ISO 22156:2021 applies to "the design of bamboo structures whose primary load bearing structure is made of round bamboo or shear panel systems in which the framing members are made from round bamboo"; it can be used for "one- and two-storey residential, small commercial or institutional and light industrial buildings which are below 7 m in height" [28]. The standard addresses "fundamental requirements of designing with round bamboo, explicitly addressing the tendency for bamboo to split longitudinally; different 'service classes' based on anticipated equilibrium moisture content; as well as issues associated with maintenance, inspection and the ability to replace structural members" [29]. ISO 22156 is also made more widely applicable through direct reference to ISO 19624, ISO 22157, and other established ISO standards. (See Appendix A, Topic 13).

By the end of 2021, ISO 22156 has been produced as a national standard in the UK, The Netherlands and the Philippines, and is expected to be adopted elsewhere. A design guide based on ISO 22156 is expected in 2022 [29].

9 Discussions

Research on bamboo as a structural material is less mature than other conventional building materials. For round-bamboo structures, the expert panels and Q&A sessions of the Seminar discussed building scale, fire prevention, redundancy of components and structures, service life, bamboo treatment (for resistance to biological attack) and selection of species for construction. In general, as a natural material, round bamboo does not have natural fire resistance, and is vulnerable to insects, mold and extreme environments. Additionally, bamboo has a propensity for splitting and typically exhibits brittle failure modes. These issues are barriers to widespread use of round bamboo construction and should be seen as critical research needs. However, with proper preservation and treatment, appropriate design and architecture, the major constraints of insect attack and problems of extreme environment can be solved. Further research is necessary for making the material fire resistant and avoiding / minimizing splitting.

Engineered bamboo, on the other hand, exhibits greater durability and fire resistance, and dimensional stability. Based on customized production, engineered bamboo is widely used in building decoration and is seeing more applications as a structural load-bearing material. Engineered bamboo can make a great contribution to development of the low-carbon economy in the future. Experts and entrepreneurs have called for accelerating the development of research on fire-resistance and standardization to promote its commercial use.

For the latest international standard, experts and participants reached a consensus that countries should adopt ISO 22156 as soon as possible, develop their national standards through research and practice, and supplement and improve the basic data. Round bamboo materials are regionally diverse due to different species, climates and environments. ISO 22156 is a model standard, intended to be supplemented by appropriate regional data. The Colombian national standard for *Guadua* bamboo structures is an example. Researchers in Colombia have established and maintain a large database for the application of *Guadua* bamboo. This supports the application of Colombia's national standard for bamboo structures although necessarily limits its scope to *Guadua* bamboo. At present, Colombia is updating this standard.

10 Conclusions

2021 International Online Seminar - Bamboo: A Very Sustainable Construction Material was held November 2021, organised by INBAR and 16 other national and international institutions. Nineteen experts from 10 countries delivered presentations and shared the latest information about bamboo construction with approximately 900 participants from 74 countries. The seminar called upon global architects, engineers and landscape designers to rethink time-tested traditional bamboo architectural forms and related technologies, and use innovative ideas to reshape the global built environment. The information delivered during the 2021 Seminar, and summarised in this paper, demonstrated the bamboo is growing in acceptance as a construction material but that considerable efforts remain to see bamboo as a mainstream material. The current research on bamboo as a structural material is less mature than that of other building materials. Architects and engineers using bamboo all over the world should work together to contribute to the basic work of bamboo architecture research, standardization and industry development.

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Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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Appendix A

Theme	Topics	Video links
Opening words & Session 1: Architectural use of bamboo	1. Using bamboo to construct healthy homes in Africa 2. Fish-shaped Bamboo Pavilion of INBAR Garden at 2021 Yangzhou International Horticultural Expo, China 3. Bamboo Engineering	[2]
Session 2: Development of Contemporary Bamboo Architecture in China	4. Technology roadmap for the development of bamboo structure in China——based on bibliometric analysis and experts survey 5. Bamboo Realm: Environmental Beauty and Technical Realization 6. Large-scale steel-bamboo hybrid structure application: Yibin International Bamboo Products Trading Centre	[12]
Session 3: Global Bamboo Construction Business Development	7. Bamboo applications: challenges and opportunities to facilitate innovation in Europe 8. Global applications of Chinese bamboo construction materials: experience sharing by a local enterprise in China 9. Industrialising the production of *Guadua* in Colombia	[19]
Session 4: Capacity Building of Bamboo Construction Professionals	10. Competition-Driven Bamboo Construction Education in Landscape Architecture: Experience from the 1st to the 4th BFU International Garden-Making Week 11. Developing bamboo in construction through architectural design education 12. Y-Project of Solar Decathlon China 2021	[17]
Session 5: Standardisation of Round Culm Bamboo Structure **& Closing words**	13. ISO 22156: 2021 — Bamboo structures — Bamboo culms — Structural design	[27]