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MEETING REPORT

"Bamboo: A Very Sustainable Construction Material & the 3rd World Symposium on Sustainable Bio-Composite Materials and Structures" - 2022 International Conference summary report

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Abstract: The 2022 International Conference—Bamboo: A Very Sustainable Construction Material & the 3rd World Symposium on Sustainable Bio-Composite Materials and Structures—was held from November 8 to December 13, 2022. This conference was led by INBAR and INBAR Bamboo Construction Task Force and co-organized by 37 other national and international institutions. More than 80 experts from over 20 countries delivered speeches or presentations to approximately 1400 participants from 81 countries and shared the latest research and development on bamboo and timber construction with them. The conference convened global architects, engineers, forestry experts, researchers, entrepreneurs, and policy makers to present the potential uses and suitability of bamboo, timber, and other biomaterials as conventional construction materials in modern society. This paper summarizes the key deliberations and findings of the diverse research, including the state-of-practice and the means of moving the state-of-the-art forward. Further actions on training, standardization, and research were urged to be taken to promote this industry.

Keywords: Bamboo structure; timber structure; biocomposite materials; training; standardization; policy

1 1 Introduction

1.1 General information about the conference

From November 8 to December 13, 2022, the International Bamboo and Rattan Organization (INBAR), INBAR Bamboo Construction Task Force (INBAR TFC), School of Civil Engineering of Tsinghua University, School of Architecture of Tsinghua University, Architectural Design and Research Institute of Tsinghua University, Nanjing Forestry University, National Provincial Joint Engineering Research Centre of Biomaterials for Machinery Package of Nanjing Forestry University,

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School of Landscape Architecture of Beijing Forestry University, International Centre for Bamboo and Rattan, with support from 30 national and international institutions, co-organized the *2022 International Conference - Bamboo: A Very Sustainable Construction Material & the 3rd World Symposium on Sustainable Bio-Composite Materials and Structures* (the 2022 Conference).

The online seminar series "*Bamboo: A Very Sustainable Construction Material"* was initiated by INBAR and INBAR TFC in 2020 [1]. On the occasion of INBAR's 25th Anniversary and the Second Global Bamboo and Rattan Congress (BARC 2022)—which was organized by the National Forestry and Grassland Administration of China and INBAR from November 7 to 8, 2022, in Beijing, China [2]—the theme of the 2022 Conference was expanded to biocomposite materials and structures. The aim of the seminar series was to showcase the potential uses and suitability of bamboo timber and other biomaterials as conventional construction materials for modern society, as well as to convene global architects, engineers, and forestry experts to deliberate on the sustainable development of biocomposite materials and structures to build low-carbon, modern, and beautiful structures.

After the analysis of the abstracts received from a global call for abstracts, the 2022 Conference was categorized into eight sub-thematic sessions. Of these sessions, two were organized as parallel sessions of BARC 2022 and one was organized as a side event at UNFCCC COP 27 in Sharm El-Sheikh, Egypt. The titles of the eight sessions are as follows: 1) Exemplary architecture design of bio-based materials (BARC 2022 parallel session) [3]; 2) Bio-composite materials for contemporary construction sector: current scenario and future prospects (BARC 2022 parallel session) [3]; 3) The potential of bamboo as a material for sustainable construction and circular economic development (INBAR side event at UNFCCC COP 27) [4]; 4) Digital and other innovative technologies for designing bio-composite materials in modern construction [5]; 5) Lessons learnt: Construction business, products, techniques, technologies and future outlook [6]; 6) Recent research on timber materials and structures [7]; 7) Innovations on engineered materials and structures [8]; and 8) Round pole bamboo structures: research and innovations [9]. A list of all these sessions and the presentations with their recorded video links is provided in Appendix A.

1.2 Analysis of speakers and registered international participants

During the 2022 Conference, 14 specialists and experts were invited to moderate and chair the sessions. The eight sessions had 10 speeches and 64 presentations. Among them, 17 speakers were university students, which accounted for 23% of the total number of speakers; female speakers and moderators accounted for 26%.

Approximately 1400 registered participants from 81 countries attended the 2022 Conference. They were from more than 500 different institutions, including intergovernmental international organizations, national government agencies, universities, design studios, research institutes, and private companies. Compared to the 2021 online seminar on bamboo construction [1], the total numbers of registered participants and countries were higher for the 2022 Conference, with increases of 500 and 7, respectively. Participants from China, Ecuador, and India accounted for 32%, 10%, and 9% of the total, respectively. The remaining "top ten" participating countries were the Philippines (5%), Ethiopia (3%), Colombia (2.5%), Cameroon (2.4%), Peru (2.3%), Kenya (2.2%), and Nigeria (2.2%), all of which are INBAR's Member States. Four percent of the participants were from developed countries, especially the United States of America (USA), France, the United Kingdom (UK), Italy, Canada, Spain, Australia, and Switzerland.

Based on the registration data, more than 130 architects, 70 engineers, and 50 designers participated in the 2022 Conference. Note that over 280 university students, accounting for 21% of the total participants, attended the conference.

2 Why use biocomposite materials for the modern construction sector?

The latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR6) points out that "human-induced climate change is already affecting many weather and climate extremes in every region across the globe," and this trend has been strengthened since AR5 [10]. It is unequivocal that we need to expedite GHG emission reduction for all high energy consumption sectors. The construction sector is one of the largest GHG emitters, and the use of low carbon materials is an effective way to contribute to climate change mitigation. Recently, the idea of using time-tested natural materials, such as timber, bamboo, or straw, to reshape the global built environment has emerged as an alternative among global architects and engineers[11][12]. Moreover, many countries or regions with abundant forestry resources, such as Canada, China, the EU, Japan, and the USA, have released new policies or standards to promote the use of timber or bamboo in modern construction [13]-[17].

During the opening of the 2022 Conference and at the INBAR side event at UNFCCC COP27, representatives from INBAR, UNFCCC, the National Forestry and Grassland Administration of China (NFGA), the Ministry of Housing and Urban-Rural Development of China, the Ministry of Urban Development and Housing of Ecuador, Tsinghua University, the INBAR TFC, and the local government of China called upon global architects, engineers, designers, and forestry experts to explore the usage of natural solutions, such as timber, bamboo, and other biocomposite materials, in the modern construction sector to mitigate climate change. The following key suggestions were provided by the representatives: 1) get inspiration from existing research and applications to explore new low-carbon biocomposite construction materials and high-performance biocomposite structures; 2) promote collaboration between the forestry and construction sectors to guarantee a sustainable supply of qualified raw biomaterials; 3) learn from the mainstream construction sector to increase investment into the biocomposite material manufacturing industry; 4) promote the international and national standardization work of biocomposite products and structures; 5) establish the life cycle inventory database of biocomposite products and develop methodologies for the life cycle assessment of biocomposite structures; and 6) strengthen the capacities of construction professionals on the construction of biocomposite structures.

3 Exemplary architecture design of bio-based materials

The first session aimed to showcase exemplary architectural designs developed using biocomposite materials around the world. Three architects from China, Finland, and Indonesia shared their experiences of nature-led design by using timber, round bamboo, and engineered bamboo in large-scale public buildings and residential houses as structural components or decoration materials. Depending on the culture and climate, the purposes and ways of using natural materials differed across countries.

3.1 Carbon neutrality goal of China

Although China has a long history of using timber structures, there are still a series of constraints in the development of modern timber structures, including a shortage of timber resources, a lack of localized design methods and technical guidance, restriction of the scale of timber structures by current Chinese standards and regulations, and the incomplete value chain development of timber structures. Since 2020, an increasing number of local architects have started contemplating the use of timber or bamboo to help achieve China's carbon neutrality goal, proposed by the Government of China at the 75th United Nations General Assembly. Kai Cui, the chief architect at China Architecture and Research Group and a fellow at the Chinese Academy of Engineering, presented numerous building cases using timber and bamboo structures constructed in China. The main exhibition hall of Tianfu Agricultural Expo Park (**Fig. 1**), completed in 2022 in Chengdu, Sichuan Province, is the largest-span timber structure in Asia. The main exhibition hall comprises five groups of giant Vierendeel trusses with variable cross sections made of hybrid glued laminated timber chords and steel webs, spanning up to 118 m with a height of up to 44 m. The trusses are roofed by colorful ethylene tetrafluoroethylene membranes, which are well-integrated into the surrounding landscape environment. The innovative connections with shear design for truss components provides the structure with very good performance and earthquake resistance. An international collaboration was undertaken between the design team members from China, Canada, and the UK. Digital design assisted in the completion of the geometric shape of the structure. The integrated workflow enabled manufacturers in Austria to use the computer numerical control technology to process all structural components accurately, and workers assembled them on-site efficiently.

3.2 Bamboo in the eyes of a Finnish architect

Finland does not have any indigenous bamboo resources, but it hosts many wood species. Pekka Salminen, the founding partner of PES-Architects Ltd. and a professor and fellow at the Academy of Finnish Academy of Technology, believes that Chinese bamboo is equivalent to Finnish birch, both of which are easily accessible local materials. He used a large amount of local wood in his own home and office building in Finland, as well as bamboo furniture in his Shanghai office. The relationship between Salminen and bamboo began in 2008. His organization won the bid for the Wuxi Theatre project (**Fig. 2a**), which was the first large-scale public cultural construction project for his office in China. Inspired by the design of the bamboo ceiling of Richard Rogers' Madrid Airport project, Salminen suggested that bamboo decoration materials should be used indoors at Wuxi Theatre – mainly as acoustic wall panels in the main auditorium. During that time, Chinese acoustic designers opined that the use of bamboo materials would not be efficient, and that it would be too common and cheap. Therefore, PES worked closely with a manufacturer "Dasso," the company that manufactured bamboo veneer panels for the Madrid Airport project, to develop bamboo scrimber-based acoustic wall panels that could meet the fire-retardant standards of China. The computer numerical control (CNC) cutting technology was used to ensure processing accuracy for all products, which were seamlessly connected with metal, ultimately achieving a high-quality international building with Chinese characteristics. In 2019, Salminen designed the Fuzhou Strait Culture and Art Center (**Fig. 2b**), with its facade made of a large amount of ceramics and bamboo, both of which are sustainable materials in Fuzhou, China. Exploring the uses of local materials in China is a continuous endeavor for PES-Architects Ltd.

(a) Five groups of giant Vierendeel trusses (b) Interior view of one truss

Fig. 1. Main exhibition hall of Tianfu Agricultural Expo Park. (Credit: Liu Kewei)

(a) Wuxi Theatre (b) Fuzhou Strait Culture and Art Center

Fig. 2. Wuxi Theatre and Fuzhou Strait Culture and Art Center.
(Credit: PES-Architects Ltd., right photo by Marc Goodwin)

3.3 Nature-led design in Indonesia

In Asia, although most people are closely related to bamboo, few truly aspire to live in bamboo houses. There are many bamboo resources distributed across Asia, ensuring a sufficient supply of raw materials. The results of numerous property tests conducted on bamboo species have indicated that the tensile strength of bamboo is comparable to that of steel, and that the compressive strength is comparable to that of concrete. Its excellent compressive strength and flexural strength are often used in practical projects. Elora Hardy, the founder and creative director of IBUKU, showcased her team's work to build over 200 bamboo structures across the world, particularly the design and structural elements of an iconic bamboo structure in Bali, Indonesia. According to her, although the completed round bamboo buildings look very relaxed and enjoyable, in reality, it is difficult to design and execute structures using round bamboo. Most of the design experience with other materials is not applicable to bamboo, and the same design may not be applicable to different bamboo species. For example, replacing the structure designed using *Dendrocalamus asper* (a common bamboo species in South East Asia) with *Guadua angustifolia* (a common bamboo species in Latin America) may not be possible. Due to technological advancements, virtual modeling is of great help in design, but the production of physical models is also equally important. Sometimes, it is even required to build a 1:1 model for on-site testing. The newly completed project "the Arc Gymnasium" (**Fig. 3**) was designed and constructed in the abovementioned manner. IBUKU has always insisted on creating its own bamboo building language, attempting to utilize the diverse forms of bamboo to fully integrate the architectural design into the site environment while making the indoor space comfortable, intimate, and full of natural texture. Hardy believes that bamboo holds a promising future as a sustainable construction material.

(a) Exterior of the Arc Gymnasium (b) Exterior of the Arc Gymnasium

Fig. 3. The Arc at Green School in Indonesia. (Credit: Fig. 3a, IBUKU; Fig.3b, Tomasso Riva)

4 Bio-composite materials for the contemporary construction sector: current scenario and future prospects

The second session presented the overall trend of bamboo industrial development in China, a leading country in the global bamboo construction sector. The speakers provided a comprehensive analysis of the entire industry chain from multiple perspectives, including material supply, research and development, architectural and landscape design, enterprise development, standards, capacity building, and national strategy.

4.1 Research and development of bamboo-based materials and structures in China

China has the most advanced manufacturing industry for structural bamboo materials. Various bamboo structures, such as round bamboo structures, engineered bamboo structures, bamboo and wood composite structures, and bamboo filament-wound integral composite residential structures, have been constructed in China. Wang Ge, a professor at International Centre for Bamboo and Rattan, pointed out that the front-end manufacturing of bamboo products for the construction sector still faces a series of challenges in China, including 1) the lack of a grading system for structural bamboo materials, 2) the lack of an evaluation system for the durability of structural bamboo materials, 3) limited research and development for the manufacturing technology of large-scale structural components, and 4) the lack of relevant national standards for bamboo structures. Therefore, there is a critical need to improve the manufacturing technology and equipment, promote the development of national standards, and build capacity for bamboo construction professionals in China.

4.2 Chinese standards and engineering practices for timber structures

Recently, numerous timber and bamboo structures with international influence have been implemented in China. Weiguo Long, the president of China Southwest Architecture Design and Research Institute Corp. Ltd. and the chair of committee of Timber & Composite Structures, China Association for Engineering Construction Standardization, introduced the frame of timber and bamboo standards in China, which can be divided into two categories: engineering construction standards (design, construction, and quality inspection standards) and product standards (product and testing methods). The former is managed by MHOURD, while the latter is being developed by the National Forestry and Grassland Administration. All the current Chinese national timber standards are required to follow the mandatory *General Code for Timber Structures* [18], based on which engineers can choose other relevant standards for designing, construction, and quality inspection. The National "*Standard for Design of Timber Structure*" [19] has been created for almost 70 years, which has significantly helped the implementation of timber practices in China. The latest Qingmiao project of Tianfu Agricultural Expo Park is a good example (**Fig. 4**). Inspired by the shape of clover and the architectural characteristics of folk houses in western Sichuan, the design is fully implemented using materials such as blue pottery tiles, gray Béton brut, and warm Douglas fir. The five single buildings appear as seedlings wildly growing in a field. The structural system fully combines the mechanical advantages of wood, concrete, and steel. Each single building is based on four concrete columns and three groups of Douglas fir arches, each spanning more than 30 m and forming three wings. The main force-bearing system of each wing is supported by smaller sections of timber beams and columns through connection with steel rods in tension laterally. To avoid damage to the aesthetics of the building, sprinklers were added, and each wing with an area of 600 m^2 was designed to the upper limit of the fire protection zoning of the national standard.

(a) Exterior of Qingmiao (b) Interior of Qingmiao

Fig. 4. Qingmiao project. (Credit: China Southwest Architectural Design & Research Institute Corp. Ltd.)

4.3 Application and development of bamboo materials in landscape architecture

Traditional gardens have a long history of planting bamboo and using it for construction. However, the application of bamboo in modern garden construction is still in its infancy, and the numerous excellent properties of bamboo need to be explored. Zheng Xi, a professor and the dean of the School of Landscape Architecture of Beijing Forestry University, shared his experience in organizing the BFU Garden-Making Festival in China since 2018, which provides an excellent opportunity for the experimental exploration of using bamboo in garden construction, and trained thousands of university students from the landscape architecture department. He participated in the design works of numerous bamboo structures in modern gardens, and his presentation showcased practical and theoretical examples of using bamboo materials in garden construction from the following six dimensions: spatial atmosphere creation, structural innovation, connection construction, parametric design methods, interactive device construction, and the combination of plants and bamboo structures. In 2019, the practical activity was moved to Chengdu, Sichuan Province of China. All designs were allocated in parks, which is a good opportunity for not only students to know how to use bamboo in design but also for citizens in Chengdu to re-recognize the use of this traditional plant in cities. The theme of the activity in 2023—named vigor, which contributed 20 designs in Chengdu to welcome 2021 Summer Universiade—was held in August 2023, showcasing 16 students' work (**Fig. 5a**–**Fig. 5p**) and 4 designers' work (**Fig. 5q**–**Fig. 5t**).

4.4 Technology roadmap for the development of the bamboo construction sector in China

From 2018 to 2021, Tsinghua University led a national consulting project "Research on Development Strategies and Key Technologies for the Bamboo Construction Sector in China towards 2035," funded by the Chinese Academy of Engineering [20][21]. Yang Jun, a professor at Tsinghua

University, shared the findings of the project and presented a technology roadmap to promote the bamboo construction industry toward 2035 in China. The overall goal was to establish a green, environmentally friendly, and high-performance modern bamboo construction sector for which the following core construction technologies were expected to be obtained: 1) develop green and environmentally friendly high-performance adhesives; 2) develop innovative bamboo building structural systems with the capacity to withstand various disasters; 3) promote multiple systems, multiple application scenarios, and large-scale demonstration projects; 4) create opportunities for bamboo construction enterprises and improve their competitiveness; 5) establish the state's key laboratory and national engineering centers; 6) set up national scientific research funds and international special cooperation projects; 7) strengthen the top-level design of national technical standards for bamboo construction; 8) promote demonstration of bamboo construction projects; and 9) strengthen international exchanges and cooperation.

(a) Delivery across thousands of years (b) The bamboo grove (c) Life and sound are endless (d) The dancing sails

(e) Hua Zhu Wan Xiang (f) Dancing in the wind (g) The hustles and bustles of Chengdu (h) Leafy rooting

(i) As the wind blows (j) Weightless (k) Flowers boom and birds fly (l) Breaking through the clouds

(m) Breakaway (n) The angle of wind (o) Sacred tree (p) Keep chasing

(q) Scattering flowers (r) Bamboo rest (s) Mountain play (t) Color-matching Dome

Fig. 5. 2023 Chengdu Park City International Garden Season and the 6th BFU International Garden-Making Week. (Credit: Beijing Forestry University)

4.5 Engineered bamboo materials and structures

According to a recent study, the Chinese government contributes the most to global bamboo construction research and the dominant interest in engineered bamboo products [22]. Since the 2000s, many universities and research institutions in China have been focusing on the study of engineered bamboo materials and structures. Researchers and manufacturers use quantitative control technology to produce innovative engineered bamboo products with clear mechanical parameters, such as glued laminated bamboo and bamboo scrimber, which can meet the basic requirements (strength, stiffness, and durability) of engineering construction. In the latest association standards of China, characteristic and design values for the main mechanical properties of glued laminated bamboo and bamboo scrimber have been provided and divided into six categories per their modulus [23]. Huang Dongsheng, a professor at Nanjing Forestry University, shared his achievements in his theoretical research on the design of engineered bamboo structures and application research on the demonstration of engineered bamboo buildings and bridges. He detailed the basic mechanical properties of engineered bamboo, which can be described using the theories of fiber composite materials. Engineered bamboo exhibits the following orthotropic characteristics: linear stress–strain relationships for tensile force and shear stress parallel to the fiber and nonlinear stress–strain relationships for compression parallel to the fiber, tensile perpendicular to fiber, shear perpendicular to fiber, and so on. Therefore, the limit state analysis method for engineered bamboo components should consider its abovementioned characteristics by using appropriate constitutive equations. Unlike other homogeneous materials, facture failure is a characteristic of engineered bamboo that can be simulated by using energy dissipation theory. Meanwhile, creep performances caused by variable temperature and humidity, carbonization and softening under high temperature, and connections are the future key research areas for engineered bamboo.

4.6 Paradigm shift from conventional to green and sustainable materials

Depending on the local bamboo resources in Sichuan Province, China, the manufacturer of bamboo scrimber, Bamboo Era has devoted itself to the construction sector for 12 years and completed dozens of projects in China. However, their path of development has been full of ups and downs. The financing acquisition and equity reform in 2019 through absorbing the addition of several shareholders who have been engaged in the traditional building materials industry, such as concrete and ceramics, brought the company back to life. They actively expanded the production capacity and scale and built eight production lines, including panel, flooring, furniture, doors and windows, and prefabricated building materials made of bamboo scrimber. The CEO of Bamboo Era, Chen Shuwei, pointed out the difficulties faced by the company currently, including lack of automation equipment, professional high-quality talents, and national standards, which are also the common problems faced by Chinese bamboo building materials and construction enterprises at present. He opined that the private sector should work together to develop intelligent production lines, jointly train young talents by collaborating with universities, assist in the development of national standards, and explore the potential of national and international markets.

5 The potential of bamboo as a material for sustainable construction and circular economic development (INBAR-UNFCCC side event for COP 27)

This session provided a global perspective on using bamboo as a sustainable construction material across the world. The reasons for the lack of interest in using bamboo as a contemporary construction material globally are similar, such as the nonavailability of appropriately treated bamboo at the local level, the lack of an adequate number of good examples of bamboo houses, and poor designs due to the lack of bamboo construction training courses for architects and engineers in universities. Similarities in growing interest among different stakeholders could also be found among different countries in choosing bamboo for modern construction, including the recognition of bamboo as a low-carbon material and innovative ways of using traditional bamboo, which will eventually help boom the local economy.

Several successful cases of using bamboo for community structures were shared by experts from the Philippines, Myanmar, India, and Uganda. The session demonstrated that the appropriate uses of bamboo can greatly benefit communities with a qualified living environment using locally available resources.

The cement-bamboo frame technology provided by BASE, a foundation based in the Philippines, is an alternative building technology of using local bamboo to enable the people of communities to live in comfortable, affordable, resilient, and eco-friendly houses. This technology was accredited by the Innovative Technologies for Housing by the National Housing Authority of the Philippines. Luis Felipe Lopez, the head of technology at Base Bahay Foundation, Inc., shared the research of Base Innovation Centre on local bamboo species, connections, and housing systems, based on which more than 400 qualified bamboo houses in one or two stories were built in different provinces of the Philippines as well as in Nepal (**Fig. 6**).

(a) Rejoice Children's Village, Nasugbu, Batangas. (b) Bagong Silangan Kawayan Housing Initiative, Quezon City.

Fig. 6. One-or two-story bamboo houses in the Philippines. (Credit: Base Bahay Foundation, Inc.)

There are various traditional uses of bamboo in Uganda, such as roofs, fences, foot bridges, bathrooms made of bamboo, bamboo-earth shear walls, and bamboo poultry houses. However, due to the poor management of bamboo forests, thereby lack of age-graded bamboo poles for construction, lack of bamboo preservation and treatment facility and knowledge, and poor design to expose bamboo to the sun or rain, bamboo is not durable enough, which has degraded the reputation of bamboo houses in Uganda. As a result, bamboo is widely considered a low-quality, temporary construction material. However, Fred Ijjo, CEO of FOB Consult Limited, pointed out that the narrative is gradually changing with the massive capacity building and technology transfer support from the international projects of INBAR. New bamboo structures have been developed during the past years (**Fig. 7**). However, considerable work still needs to be undertaken to develop the bamboo construction sector: 1) design and construction professionals need to dispel the myths of bamboo being a poor-quality and less-durable construction material; 2) bamboo technology skill needs to be included in the teaching curriculum of vocational and tertiary institutions; 3) the public awareness of using bamboo as a tool to fight climate change, poverty, and housing deficits needs to be increased; 4) government needs to provide promotion schemes and tax incentives to promote the bamboo construction industry; and 5) the latest ISO 22156 *Bamboo structures – Bamboo culms – Structural design* [24] needs to be adopted as the national building code to overcome the constraint to scale up bamboo housing in Uganda.

(a) Bamboo cottage in Moyo, Uganda. (b) Bamboo housing unit in Moyo, Uganda.

Fig. 7. New bamboo housing in Uganda. (Credit: Fred Ijjo)

P.K. Das, international consultant on Green Rural Housing and consultant to the Government of India, shared the status of using bamboo for rural housing in the country. Although bamboo can create employment opportunities, help reduce carbon emissions, and provide high-quality affordable housing to people below the poverty line in India, bamboo housing proposals for rural areas have been rejected many times at the state level. There are several reasons for this rejection. On one hand, local people's inherent beliefs have always existed. Reinforced cement concrete is considered a permanent and disaster-safe material and reinforced cement concrete-brick houses are a symbol of modern society. On the other hand, the engineering department has techno-managerial questions on bamboo and the non-availability of appropriately treated bamboo at the local level. However, since 2014, the prime minister's Rural Housing Programme in Tripura, India, has gradually solved people's doubts and revitalized traditional technologies on using bamboo with the compressed stabilized earth block to build resilient houses (**Fig. 8**). Until 2022, almost 100 bamboo houses were built in Tripura. The evidence of withstanding earthquakes and several high winds has established the image of hazard safety for bamboo houses. Therefore, the key learnings on significant impact are as follows: 1) government of India, government of Tripura, and district magistrate built some degree of confidence in bamboo; 2) local people changed their initial strong opposition, leading to the final acceptance; 3) engineers accepted the analysis of bamboo design with the compressed stabilized earth block; and 4) bamboo workers increased their income and enhanced their social status.

(a) Bamboo house under construction. (b) Completed bamboo house.

Fig. 8. Rural bamboo housing in India. (Credit: P.K. Das)

Due to the national civil war in 2021, the number of internally displaced communities in Myanmar has increased rapidly; housing has become an urgent need for the local people. Raphael Ascoli, the co-founder of Housing Now of Myanmar, shared his experience of how to use unconventional small-diameter bamboo culms to construct low-cost housing to help address the crisis. *Oxytenanthera spp.* is a small-diameter local bamboo species in Myanmar, which is a cheap and abundantly available resource. After proper modular designing and a series of structural tests, the culms were made into bundles to form the columns or beams of the building, and a pilot preschool in a refugee camp with the participation of the local community was built near Bago, north of Yangon (**Fig. 9**).

(a) Prefabricated bamboo trusses. (b) Completed bamboo preschool.

Fig. 9. Bamboo housing made of small-diameter species in Myanmar. (Credit: Raphael Ascoli)

Since 2000, the market availability of engineered bamboo as an innovative material has been gradually increasing, and many universities and research institutes in China are taking interest in its structural and decorative uses. Yan Xiao, a professor at Zhejiang University, shared his research of over 15 years on glubam (glued bamboo) and cross-laminated bamboo timber (CLBT), as well as relevant structures, especially on its mechanical properties, earthquake performance, fire performance, and acoustic and vibration tests. Approximately 20 engineered bamboo buildings were showcased, among which a six-story zero-carbon engineered bamboo structure will be completed by the end of 2023.

From the perspective of developing national policies for promoting the bamboo industry, Tom Obong Okello, the executive director of the National Forestry Authority of Uganda, shared their experience. Uganda has low bamboo species diversity, with two indigenous species: *Yushania alpina K. Schumach* (highland bamboo) and *Oxytenanthera abyssinica Munro* (lowland bamboo). Through INBAR’s Dutch Sino East Africa Bamboo Development Programme, the Uganda National Bamboo Strategy and Action Plan 2019–2029 was developed and proclaimed to ensure coordinated development of the bamboo industry to propel green economic development and production of high-value products targeting domestic, regional, and international markets. It is estimated that, by 2030, planting and managing bamboo will make 15% contribution toward Uganda’s goal of restoring 2.5 million ha of forest landscape, and that the strategy will help create 150,000 full-time jobs, producing 140 million bamboo poles each year. Several challenges were also pointed out, including lack of awareness, high costs of planting materials, limited access to finance, lack of knowledge on site-bamboo species matching, shortage of land, and encroachment and illegal harvesting of bamboo forest resources.

In Ecuador, the National Strategy of Bamboo 2018–2022 was released to manage technical information and the formulation of actions for developing the bamboo industry. Meanwhile, a specialized credit line for bamboo with public banking institutions was set up. Microcredit and SMEs credit up to ISD 150,000, with a term of 10 years, a 3-year grace period, and an interest rate of 9.76%–11.25% for SMEs is operational now. Xavier E. Lazo Guerrero, former minister of agriculture and livestock of Ecuador, highlighted that the following seven dimensions of economic and social potentials of using bamboo can be explored: 1) promotion of economic development in poor areas without agricultural potential; 2) innovation of housing industry by using ecological material, which includes reducing housing deficit and increasing employment rate; 3) eroded soil recovery and carbon capture; 4) improved access to education for more children in poor areas; 5) promotion of farmers’ empowerment through fair trade conditions; 6) associativity to produce, trade, and compete in better conditions; and 7) implementation of technical assistance, low production costs, and good agricultural practices.

Wendy Vera, a student at the Bamboo Sustainable Construction Workshop School in Ecuador, shared project outcomes of the workshop school. The project seeks to train a specialized and certificated workforce that can supply the demand for sustainable construction (**Fig. 10**). Until the end of 2022, the project had trained more than 80 qualified workers in the following four modules: cabinetry and carpentry, electrical installation, civil works, and bamboo construction—which broke niches by including 21% women in construction processes. This initiative generated opportunities for women, which greatly helped them improve their economic status and technical skills.

(a) Visited treatment facility of bamboo. (b) Processing bamboo components.

Fig. 10. Bamboo construction training in Ecuador. (Credit: INBAR)

6 Digital and other innovative technologies for designing bio-composite materials in modern construction

This session focused on the introduction of innovative design technologies covering aspects such as digital design (building information modeling and digital twins), CNC machine tool processing, innovative architectural design methods, and the latest achievements and experiences in bio-based recyclable materials research.

Hanaa Dahy, an associate professor at the Department of Planning of Aalborg University and the director of BioMat@Copenhagen Research Centre, shared her latest achievements and experiences in the field of bio-based recyclable materials. The goal of her team is to provide innovative solutions to the sustainable construction of the future and to explore new resources and technologies to create a lighter and more efficient architectural environment. Their design philosophy views materials as a design tool that integrates technologies from different fields, such as material research, architectural design, and digital construction, to promote the sustainable application of the built environment. As a natural and eco-friendly material with excellent physical and mechanical properties, bamboo has wide application prospects in the field of architectural design, which perfectly matches BioMat's idea. In 2021, the team independently designed and built an arch-shaped pavilion out of the pultruded biocomposite profiles of flax and hemp natural fibers by using digital design and fabrication technologies. The profiles were set in a cross-beamed fashion, which created a strong sense of geometrical beauty and spatial tension (**Fig. 11**).

(a) Pavilion in the campus. (b) Under the pavilion.

Fig. 11. LightPRO Shell Pavilion. (Credit: BioMat@Copenhagen Research Centre)

Balas Lagash, Ph.D. candidate at University College London, highlighted that bamboo is an ideal building material to reduce the carbon footprint of the construction sector. The university team developed a data-driven digital design system for round bamboo structures, including a 3D scanning system and an automated testing system for round bamboo components, which can be used throughout the life cycle of the structure based on the building information modeling (BIM) system. The digital design system allows designers to systematically analyze round bamboo structures and compare them with traditional models of round bamboo structures. Lagash also introduced methods to reduce deflection, stress, and stiffness variations in round bamboo structures, which are also realized through the database created by the automated analysis of individual digitized round bamboo elements. The basic parameters of round bamboo components obtained using this digital design system can significantly improve the utilization of the members, thus improving the overall performance and efficiency of the structure and ultimately reducing the overall carbon footprint of round bamboo buildings.

BIM technology is also popular in China. Zhi Li, an associate professor at Zhejiang University, presented a two-story bamboo-wood structure house built in Zhangbei, China, using a BIM system (**Fig. 12**). The house was built in a lightweight bamboo–wood composite structure. The main structural elements included lightweight bamboo–wood frame shear walls, bamboo–wood composite floor slabs, and a truss system. Li demonstrated the concept and details of the design through several aspects: use of building materials, design of the connection system, treatment of the main structural members, processing of components, and installation on the BIM platform. The team established a BIM system for the house that can effectively simulate the construction process. At the same time, a family database of components for shear walls, beams, and roof trusses was created. Based on the database, prefabrication and preparation of the connection system and structural components were realized in the factory. Such structures can help achieve a good balance between structural performance requirements and economic efficiency due to the ease of manufacturing, transportation, prefabrication, and installation. Finally, Li made two suggestions for the development of the bamboo construction sector: (1) the bamboo construction sector needs more talent, and (2) buildings should be constructed in line with the local conditions. When buildings are designed, the historical and cultural contexts of the region should be taken into consideration.

Wei Gao, owner-principal of ADR Studio, shared his experience on the design of the gate of Zhangcun Primary School in Jinyun, China (**Fig. 13**). The design and construction of the gate was a joint effort of students, teachers, NGOs, and designers in the context of rural revitalization. First, the design team taught the students some basic ideas about architectural design to inspire them to think. Following that, the designers took both local conditions and the students' suggestions into account, and then came up with two elements for the architectural design—bamboo and tea leaves—which are cultural symbols of the region. The school gate was, therefore, built in the form of a round bamboo structure using the parabolic bamboo structure to create the imagery of "tea leaves." The new bamboo gate boldly conveys a new concept to the public—the gate is an opening for communication instead of a warning to keep out strangers. For the teachers and students, a gate made of bamboo is like a dream come true, demonstrating their unique creativity and love for their hometown.

a) Completed bamboo residential house. b) Interior look.

Fig. 12. Demonstration of residential houses in Zhangbei, China. (Credit: Zhi Li)

a) Surrounding environment of the bamboo gate. b) The bamboo gate.

Fig. 13. Bamboo gate of Zhangcun Primary School. (Credit: Wei Gao)

Mia Tedjosaputro, an assistant professor at Xi'an Jiaotong-Liverpool University, delivered a presentation titled "A Decade of Technical Support for Bamboo Design." She summarized 14 bamboo architecture design cases driven by various innovative technologies in the past decade and tried to answer the question "What insights has technology provided in shaping digital bamboo architecture design?" Currently, four main types of innovative technologies are used in global bamboo architecture projects: digital design, computational design, digital manufacturing, and augmented reality and virtual reality technologies. These innovative technologies can be combined with traditional design and construction practices to evaluate and implement more complex designs, which allows bamboo to be used as a nonstandard material at the outset of the design, rather than first standardizing the bamboo components. She believes that a future direction for bamboo construction is mechanization, where sophisticated technology can combine systematic heat-bending processes with mechanized assembly techniques, virtual technology and holograms can be applied to the design and construction process of bamboo structures, and round bamboo components can be scanned to be translated into a digital language to supplement the underlying database for users to conduct further research on their material features. In addition, she suggested that courses on bamboo structures could be introduced into the curriculum of undergraduate students in bamboo-rich regions of the world to enhance their knowledge of the bamboo architecture and to foster their interest in this field.

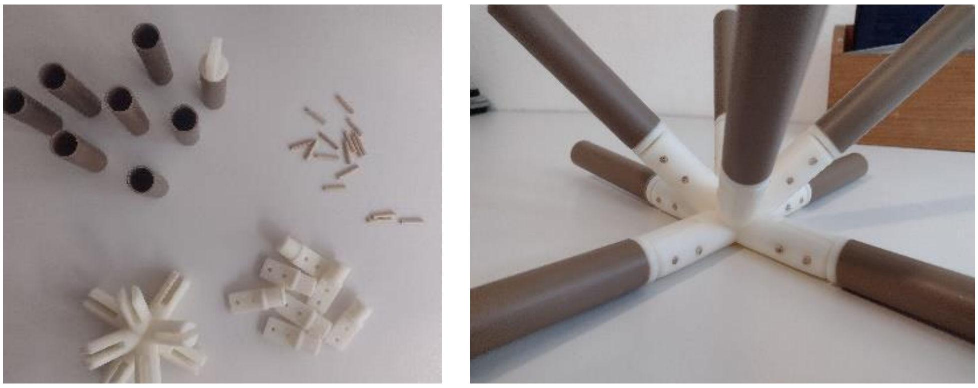
Jian Zhang, director of the Design Center of Haoyuan Group, presented the design and construction of a bamboo bridge in Tao Sense Art Park (**Fig. 14**). The team used round bamboo to transform the bridge, which had a concrete and steel structure that looked heavy and lifeless, such that it can fit the surrounding wetland landscape. The upper part of the bridge takes its form from the winding streams of the wetland, and the two elegant curves transform the originally dull skyline of the bridge into a scenery of the wetland. With a length of nearly 100 m and width of 10 m, the positioning of the curves creates a balance between accessibility and aesthetics. The upper skeleton of the bridge is made of steel to meet the load-bearing requirements and to withstand local typhoons, while its outer appearance is made of a natural bamboo roof that blends in with the surrounding landscape. A waterproof layer is installed between the bamboo roof and the main steel structure, which is supported by a woven bamboo skin net to keep rainwater out. The bamboo mesh is woven by hand in an irregular manner to obtain a better artistic effect. Sunlight can be scattered onto the bridge surface through the gaps of the multilayer material so that visitors can have a better visual experience and experience being one with nature.

a) Surrounding environment of bamboo bridge. b) On the bridge.

Fig. 14. Bamboo bridge in Tao Sense Art Park. (Credit: Jian Zhang)

Ying Wu, a lecturer at Beijing University of Civil Engineering and Architecture, introduced her research on multisensor fusion technology for crack monitoring of historical timber structures based on digital twins. Cracking has become the most common form of damage to historical timber structures in China due to aging, earthquakes, and wind loads. Assessing their safety has become an urgent problem in architectural heritage conservation. Based on BIM technology, Wu developed a multisensor digital twin platform for crack monitoring of historical timber structures. The platform includes vector analysis, attribute transformation, and standard model-based construction representing timber structure cracking data. After collecting data on timber structure cracking in multiple spatial and temporal dimensions, vector analysis was performed. Timber structure cracking is an attribute transformed using identification algorithms such as principal component analysis and Bayesian analysis, and finally, the data from each sensor monitoring timber structure cracking is integrated using edge operations. Based on the digital twin platform, the integration of the preventive protection monitoring data, basic information data, cultural heritage safety supervision data, and digital protection data of historical timber structure cracking can be realized. Finally, Wu used a northern historical timber building model to verify the feasibility of the proposed platform.

Brianna Catharina Bussinger, a Ph.D. candidate at the University of São Paulo, gave a presentation on "Parametric Designed Joints for Bamboo Spatial Structures as a Strategy for Incrementing Bamboo Architecture in Brazil." Due to bamboo's abundance, improved eco-friendly production chain, and the introduction of new regulations, Brazil is embracing new opportunities for its bamboo industry. However, Brazil is facing challenges such as a lack of qualified construction personnel and construction experience based on the local culture. Bussinger believes that the differences in the physical properties of each species and varied sizes of bamboo among and within species pose the greatest challenge in the designing of joints, which drastically reduces the efficiency during construction. Such problems can be effectively solved using modern digital technology and 3D printing technologies to design joints of bamboo structures (**Fig. 15**), which can be perfectly connected through the friction present on the inner surface or by transferring force to the bamboo diaphragm. At the same time, this technology can be used as a tool to fill the labor shortage of professionals, creating a new trend in the development of bamboo construction technology.



a) Different components of joint. b) Assembled joint.

Fig. 15. Digital fabrication and assembly of bamboo joint. (Credit: Brianna Catharina Bussinger)

Esti Nurdiah, a Ph.D. candidate at the University of Sheffield and an assistant professor at Petra Christian University from Indonesia, shared the design, construction, and analysis of a round bamboo gridshell structure. It is considered an efficient structural system that can be built using lesser material than usual. However, the inherent differences in the physical and mechanical properties of bamboo make the design and construction of round bamboo gridshell structures more challenging. There is a certain degree of uncertainty from the design to the construction of a round bamboo gridshell structure. Changes in materials, design, and construction processes may seriously affect the final construction results. First, Nurdiah modeled a bamboo gridshell structure using two software programs, Grasshopper and Kangaroo, to determine the attainable height and potential curvature of the structure. After that, she constructed two full-size models using round bamboo poles and bamboo strips, loaded them, and tested the deformation. At the same time, she used Abaqus to carry out finite element analysis for the digital models. Through the analysis of the whole design and construction process, she found that the limitation of using bamboo comes from the curvature of the gridshell structure, and the failure of some members is caused by the buckling and cracking of the rods. The results showed that the maximum curvature of the solid round bamboo gridshell structure was smaller than that of the calculated model. In addition, the deformation of the solid model was higher than the calculated value of the numerical model. Therefore, the curvature magnitude should be used as a control variable in the design of a round bamboo gridshell structure.

7 Lessons learnt: Construction business, products, techniques, technologies and future outlook

On the basis of the online seminar "Bamboo: A very sustainable construction material" held last year [1] and based on the project "Survey and research on the development of manufacturing enterprises of bamboo construction materials in China," implemented by INBAR in August 2022, a thematic session on entrepreneurs with a focus on China was organized this year. Several Chinese entrepreneurs were invited to share their valuable experiences and insights on leadership, main products, marketing, key technology development, and future applications.

In addition to the entrepreneurs' presentation, this session also invited Yubing Leng, Director of the Research and Development Centre at the Shanghai Research Institute of Building Sciences Co., Ltd. (SRIBS), to share key technologies of engineered bamboo structures and the latest Chinese association standards released in 2022. Leng shared the results of various research projects conducted by SRIBS over the years, including the physical and mechanical properties of structural engineered bamboo materials and the long-term performances, durability, and fire performances of engineered bamboo structures, as well as the defect detection technology of engineered bamboo structures. After that, she introduced the three latest standards of the China Engineering Construction Standardization Association, which were jointly developed by SRIBS, INBAR, and other organizations. These three association standards, including *Standard for design of engineered bamboo structures* (T/CECS 1101-2022) [23], *Standard for construction and acceptance of construction quality of engineered bamboo structures* (T/CECS 1102-2022) [25], and *Standard for inspection of engineered bamboo structure* (T/CECS 1103-2022) [26], were officially released in November 2022. These standards provide strong support for the design, construction, and operation and maintenance of engineered bamboo structures in China. Finally, Leng provided an outlook on the future development of engineered bamboo structures. She highlighted the importance of conducting research on the long-term performance, durability, and fire resistance of structures. She also highlighted the need to enhance collaboration across the entire industry chain, including management, production, academia, research, application, and maintenance. This collaboration will contribute to the development of engineered bamboo structures worldwide, providing valuable references for the industry.

7.1 Valuable experience and insights from entrepreneurs on the development and future of the bamboo construction sector

Sichuan Province in China has abundant bamboo resources, especially *Dendrocalamus affinis*, which is a small-diameter bamboo. A local bamboo construction material manufacturer, Bamboo Era, has successfully achieved the large-scale production and application of bamboo scrimber products using the abovementioned species. Bamboo scrimber has several characteristics, such as high strength, high density, high weather resistance, low carbon emission, flame resistance, corrosion resistance, and termite resistance. Following Session 2, Shuwei Chen, CEO of the Bamboo Era, delivered a presentation with other Chinese entrepreneurs in this session to showcase their practical experience in implementing China's green and low-carbon development. In the past 10 years, Bamboo Era has completed hundreds of bamboo construction projects in China and has created many typical cases together with both international and domestic architects. Chen introduced dozens of typical cases to show in detail the applications of bamboo scrimber in large public construction projects, exhibition projects, urban renewal projects, tourism construction, and urban landscape projects, some of which are shown in **Fig. 16**.

a) Zhaojun Museum. [22] b) MUJI Hotel. [22]

c) Qishe Courtyard Renovation. [22] d) Youth Hostel at Niubeishan Mountain. [22]

Fig. 16. Cases of Bamboo Era.

Traditional round bamboo construction has shortcomings, such as short service life, monotonous shape, and lack of standardization, which limit its use. Yanfei Wang, general manager at Anji Zhujing Bamboo Industry Technology Co., Ltd. (Zhujing), shared his practices regarding the preservation and promotion of traditional round bamboo construction craftsmanship in China. Zhujing possesses patented technologies in the treatment, structure design, and construction of round bamboo structures, which have significantly extended the service life of round bamboo structures to 20–30 years. Meanwhile, Zhujing has made great efforts to promote the application of round bamboo structures in China (**Fig. 17**). They achieved this by organizing various bamboo design and marketing activities, including national bamboo architecture competitions, garden building festivals, and regional bamboo architecture experience-sharing meetings. Zhujing invests 5% of its annual sales revenue in research, which has led breakthroughs in technologies, such as anti-corrosion, anti-mildew, anti-cracking, fire retardant, and joints of round bamboo structures. Wang proposed the following plans for the future development of the company. First, standardize the production of indoor round bamboo decoration products, enabling mass production and strengthening the current market sharing and position. Second, establish a bamboo architecture industry, academic, and research base, leveraging the abundant bamboo forest resources and bamboo industry of Anji.

a) Bamboo Exhibition Corridor of Ancient Kiln in Jinshan Mountain. [22]
b) Tangxing No.5 Residential House. [22]
c) Tea Market of Zhuguanlong Township. [22]
d) Reception Center of Jiufeng Village. [22]

Fig. 17. Cases of Zhujing.

Zhenhua Xiong, general manager of Ganzhou Sentai Bamboo & Wood Co., Ltd. (Sentai), shared his thoughts on bamboo. Sentai has collaborated with renowned architects and designers both domestically and internationally across more than 20 countries (**Fig. 18**). Xiong believes that the Chinese bamboo industry is a traditional but globally leading industry. With innovation and modern technology, bamboo has been found to have extensive uses in modern architectural structures (both interior and exterior decoration), as well as household products. However, there is still ample room for progress in terms of market expansion, talent training mechanisms, equipment mechanization, etc. In the future, it is necessary to expand the application of bamboo materials beyond just replacing wood. By addressing the barriers to market entry and fully exploring the unique advantages of bamboo, new markets can be created, leading to significant growth in the market space. Sentai has established a comprehensive product segmentation system, which includes design-driven special lifestyle products, semi-scale technical products (such as engineering customization, structural bamboo materials, and furniture accessories), and large-scale standard product series (including flooring, ceilings, wall panels, and furniture). Finally, Xiong conducted a comprehensive analysis of the strengths, weaknesses, opportunities, and challenges of the development of his enterprise by using a SWOT (strengths, weaknesses, opportunities and threats) analysis. His purpose was to share experiences and foster stronger connections with his peers to collectively advance the global bamboo industry.

a) Ilan and Assaf Ramon International Airport, Israel.

b) Gymnasium of Hang Seng University of Hong Kong.

c) Office building of Sentai.

d) Outdoor Bamboo Landscape of Shanghai Qinsen Group at 2019 Beijing Expo. [22]

Fig. 18. Cases of Sentai. (Credit: Ganzhou Sentai Bamboo & Wood Co., Ltd.)

Junlong Wang, CEO of Hangzhou Bamboo Technology Company (Hangzhou Bamboo), introduced the development of his company in detail. Over the years, Hangzhou Bamboo has collaborated with various Chinese scientific research institutions to develop a range of patented technologies. These technologies effectively address key challenges in the application of round bamboo structures, such as the treatment and processing of round bamboo materials, as well as the construction process of round bamboo structures. He shared his experience in reducing the cracking of round bamboo poles, preventing insects and mold, anti-aging techniques, hot bending and straightening processes, surface treatment processes, connection, and installation technologies. After that, he showcased the application cases of Hangzhou Bamboo in new modern round bamboo structures and steel–bamboo hybrid structures (**Fig. 19**).

Zhicheng Xue, CEO of Hunan Taohuajiang Bamboo Science and Technology Co., Ltd. (Taohuajiang), presented the topic “Research and Applications on Modern Structural Engineered Bamboo Materials.” First, he compared different types of modern engineered bamboo products and their applications, including bamboo plywood, bamboo particle board, bamboo scrimber, and glued laminated bamboo. Following that, he presented a systematic overview of the research conducted by Taohuajiang and focused on structural engineered bamboo materials. Its key research and development efforts have resulted in exceptional structural bamboo-integrated timber products that excel in terms of strength, durability, ease of processing in various sizes, and fireproof performance. The technology developed by Taohuajiang can now produce panels that are 10 m long with a high level of gluing strength. Taohuajiang plans to build a three-story office building using structural glued laminated bamboo. Finally, Xue pointed out that there is a lack of experts in China who are knowledgeable about both the characteristics and processing technologies of bamboo materials, as well as their design and applications in the construction sector. This hinders the ability to efficiently and effectively address the challenges faced during the promotion of structural bamboo construction materials. He called for more design experts to join the research in the future.

a) Fish-shaped pavilion of INBAR Garden at 2021 Yangzhou Horticultural Expo. *(Credit: INBAR)*

b) Yibin International Bamboo Products Trading Centre, Sichuan, China.

c) Rural reconstruction project, Zixi, Jiangxi, China

d) Baizhishan Tourist Reception Center, Chongqing, China.

Fig. 19. Cases of Hangzhou Bamboo in China. (Credit: Hangzhou Bamboo Technology Company)

Yongjie Chen, CEO of Jiangsu Jianzhu Green Bamboo Construction Technology Co., Ltd. (Jianzhu), shared the diversified application of engineered bamboo construction in indoor and outdoor installations, rural transformation, tourist projects (visitor centers, restrooms, and gateways), large building auxiliary structures, and subsidiary structures (**Fig. 20**). Chen highlighted the current bottleneck in the development of engineered bamboo structures as follows. First is the lack of industry talent. There is a significant shortage of professional design talents and project managers in the field of bamboo architecture. Moreover, there is a lack of training mechanisms and systems for specialized talents in the industry. Second, there is a dearth of relevant industry standards and regulations, including design, construction, and acceptance specifications. These deficiencies severely hinder the promotion and use of bamboo architecture in engineering projects. Third, there is a lack of professional mechanized equipment, such as automatic assembling equipment and molding processing equipment. The degree of automation is low, and the industry relies heavily on manual labor, resulting in low production efficiency and high product costs. He believes that further development of bamboo construction enterprises in engineering needs to integrate design, production, and construction. This integration will establish a new model of bamboo architectural design and construction guided by digital technology.

7.2 Discussion

Finally, the speakers were invited to discuss their expectations for the future development of the global bamboo construction industry, as well as their respective enterprises and research fields. The speakers hoped that, through the INBAR platform, they could collaborate with counterparts from different countries and regions in the future. Their goal is to foster cooperation in talent training, standard development, technology research, and marketing. The session attracted the active participation of global attendees, who were amazed by the impressive examples of Chinese bamboo building materials and bamboo construction enterprises. Attendees also strongly identified with the business development concepts shared by the entrepreneurs. Susanne Lucas, president of the World Bamboo Association, expressed her astonishment at the remarkable examples of bamboo architecture showcased by Chinese entrepreneurs. However, she lamented that these architectural wonders remained relatively unknown beyond China. She urged that in the future, strong collaboration will be required to promote the development of the global bamboo construction industry.

a) Tourist Service Room for Tangshan Mine Camp, Nanjing, China.

b) Courtyard N4, Lixiang Village, Nanjing, China.

c) Yibin Cuiping Mountain Tourist Centre, Sichuan, China.

d) Bamboo Technology Park at Xuzhou Garden Expo, Jiangsu, China.

Fig. 20. Cases of Jianzhu. (Credit: Jiangsu Jianzhu Green Bamboo Construction Technology Co., Ltd.)

8 Recent research on timber materials and structures

This session focused on the latest research on timber materials and structures. First, two invited speakers introduced the global research needs for mass timber construction and the development of spatial timber structures in China, respectively. Then, the other nine speakers introduced their latest research on structural timber components, such as mechanical performances of beams or joints, fire performance of walls or columns, and vibration properties of cross-laminated timber (CLT) flooring.

Y. H. Chui, a professor at the University of Alberta, fellow of the Canadian Academy of Engineering, and chair of ISO Technical Committee 165 “Timber structures,” presented on “Research needs for mass timber construction - global perspective.” First, he introduced various mass timber construction products that have been used worldwide over the past three decades, including glued laminated timber, CLT, structural composite lumber, and dowel laminated timber. These products are processed into large-sized components by highly sophisticated machinery, which offers several advantages, including reducing on-site construction time and cost, minimizing construction waste, decreasing construction noise, and facilitating transportation. Recently, while multistory mass timber structures have been constructed worldwide, there is still a significant need for research on making these structures more cost-effective and safer to withstand natural disasters like earthquakes and hurricanes. Next, Chui presented his study on the research gap in mass timber structures. The results showed that the most important technical research gaps in wood structures are connection performance, seismic and wind-resistant performance, floor sound and vibration insulation, fire performance, construction methods, product and system development, and environmental benefits. In terms of connections, new high-performance connection systems that can transmit greater lateral forces and exhibit ductility need to be developed. Additionally, new connection fasteners, such as self-tapping screws, adhesive connection rods, and adhesive connection plates, need to be explored. Regarding seismic and wind resistance, research should focus on the lateral force resistance of horizontal partitions (floor/roof panels) in mass timber structures. The continuous construction of CLT walls, energy-consuming connections, and support combined with vertical load resistance systems also requires further investigation. For sound insulation and seismic performance of floor slabs, a cost-effective sound insulation design should be studied. Furthermore, research is needed on the seismic performance of multispan, beam-supported wood–concrete combination floor slabs. In terms of fire performance, further research is necessary on the fire design of connections and exposed structural members. Additionally, fire prevention research and safety education during the construction process should be emphasized. To promote advanced construction methods, it is important to encourage the use of BIM and lean construction guidelines. Additionally, integrated approaches that combine design and construction should be utilized. In terms of innovative product/system development, high-performance, heavy structural wood products should be developed, and when appropriate, other building materials should be fully utilized to adopt hybrid structural forms to enhance the competitiveness of heavy wood structures in the market. In terms of the environmental impact of wooden structures, further research should be conducted to emphasize the role of heavy wooden structures in achieving zero-carbon goals.

Minjuan He, a professor at Tongji University, presented on the topic of "Spatial timber structures in China and research on the performance of their typical connections." Wood is a renewable resource and an excellent building material. Under the concept of "conservation application," wood frame construction can effectively promote the sustainable use of forest resources. With the advancement of the manufacturing process, engineered wood products can now be processed into large-scale components. Additionally, the use of various metal connectors enables the connection of complex components, which has significantly contributed to the global development of spatial timber structures. The application of spatial timber structures in China is relatively new. However, in recent years, there has been an increasing trend in its usage and scale. It is now widely used in various sectors, such as real estate residential buildings, industrial buildings, tourist buildings and facilities, sports venues, conference centers, and exhibition centers. In the development of spatial timber structures, numerous structural problems need to be addressed, with a particular emphasis on research related to connection performance. Due to the complex force situation, the connections of spatial timber structures need to meet various performance requirements and different forms. These connections are nonstandardized and require a series of experimental and numerical simulation analyses. The use of self-tapping screws for connections has become a new trend. Taking the single-story wood mesh shell structure of Taiyuan Botanical Garden as an example, Minjuan He introduced experimental research on various connections by using self-tapping screws. These include rod orthogonal nodes, screw-steel insert nodes, and half-lap nodes. In addition, she introduced the commonly used infill plate-type wood mesh nodes in single-layer mesh shell structures. She emphasized the need for the continuous development of new connection forms with high stiffness, load-bearing capacity, and disaster resistance toughness to meet the demands of spatial timber structures. Additionally, she emphasized on conducting research on connections and overall structural performance in engineering practices.

Huifeng Yang, professor and assistant dean of Nanjing Tech University, presented his research on the evaluation of effective flange width for timber–concrete composite (TCC) beams with crossed inclined coach screw connections at the serviceability state. TCC offers new prospects for the development of multistory wooden structures by leveraging the favorable tensile properties of wood and the exceptional compressive capacity of concrete. This combination can improve building comfort and reduce CO_2 emissions. By conducting bending tests on TCC beams with varying slab widths, Yang investigated the shear hysteresis effect presented in concrete slabs. The presenter also provided experimental data to support the design and application of the braced wood–concrete combined floor system. Additionally, a parametric nonlinear finite element analysis was performed on the bending performance of TCC beams using the Abaqus finite element analysis platform. The experimental results showed that the tensile strain at the bottom of the concrete slab exhibits a more significant shear hysteresis effect than the compressive strain at the upper surface of the concrete slab. The finite element model performs well in predicting the damage mode, stress–strain relationship, deflection, and slip of the TCC beam. The parametric study showed that the effective flange width of TCC beams is primarily influenced by load type, width-to-span ratio, slab thickness, and shear member stiffness.

Haoyu Huang, Lecturer at Newcastle University, presented on the topic of “Serviceability of Cross-laminated Timber (CLT) Floor Considering the Environments.” CLT is commonly used in floor slab systems. However, its light mass makes it susceptible to vibration when subjected to human-induced excitation, causing discomfort for occupants. Huang first shared an experimental study on the vibration comfort of floor slabs by using virtual reality technology. It has been found that various environments significantly impact the comfort of floor slabs in terms of vibration. Furthermore, people have a lower tolerance for vibration in bedroom environments compared to gym environments. Second, he investigated the impact of boundary conditions on the vibration of CLT floor slabs. The influencing factors included the support situation of the floor slab, the size and spacing of the support beams, and the connection between the support beams and CLT flooring. Finally, he introduced technology for controlling floor vibrations by using the CLT system and multiple tuned mass dampers (TMDs). He also discussed an experimental study conducted on this technology. The test results showed that TMDs can effectively reduce CLT floor vibration. Shape memory alloy TMDs are super elastic and better than steel TMDs.

Bo Wen, a Ph.D. candidate at Nanjing Tech University and lecturer at Sanjiang University, shared his experimental research on the dynamic properties of TCC beams. Due to its relatively low mass and low stiffness, wood is prone to experience a high level of vibration when used in building structures, which can impact the comfort and safety of the building. Wen analyzed the current status of research on the vibration performance of timber joist, CLT, and TCC floors. Among them, TCC is a structural form that can significantly enhance the performance of wooden buildings, particularly for multistory and high-rise structures. A detailed analysis was conducted through laboratory tests, site tests, subjective evaluation, and finite element analysis to assess its static load deflection, self-oscillation frequency, damping ratio, excitation response velocity, and acceleration. The test results indicated that the natural vibration frequency of TCC beams is closely associated with the combined effect of interfaces. Slip stiffness and number of connections are significant factors that influence this frequency.

Yuan Tang, a Ph.D. candidate at Central South University of Forestry and Technology, delivered his presentation on “Experimental Investigation on the Long-Term Performance of FRP-Glulam-UHPC Composite Beams.” Traditional concrete bridge deck slabs are heavy and require large wooden beams for support, which compromises the structural efficiency. Additionally, concrete slabs are susceptible to cracking and leakage, reducing the durability of the wooden beams. To enhance the long-term performance of traditional wood–concrete composite beams, Tang proposed a novel, fully prefabricated composite beam. This beam combines glued timber members with ultra-high-performance concrete (UHPC) slabs by using horizontal steel plates and bolts. By conducting experiments on different types of TCC beams, it has been shown that UHPC can significantly improve the initial stiffness and long-term performance of these beams. By considering wood creep and concrete shrinkage creep, he established a long-term deformation calculation model for glued timber and UHPC composite beams. The model calculation results are in good agreement with experimental data and can effectively simulate the long-term deformation trend of components affected by environmental temperature and humidity in actual situations.

Xinhao Lv, a Ph.D. candidate at Southeast University, conducted a numerical simulation study on the long-and short-term flexural performances of steel–timber composite beams. Due to the relatively low stiffness and load-bearing capacity of timber, it is often challenging to meet structural load-bearing capacity and deformation requirements on its own. Therefore, combining wood with other materials has become an effective method to expand the application of wood structures. Steel–timber composite beams can effectively address the vulnerability of steel members to instability and can fully utilize the compressive strength of wood. Based on the simplified Hashin’s criterion, Lv carried out a secondary development of the elastoplastic intrinsic model of timber. He also established a steel–timber composite beam model with both full and partial shear connections. This study focuses on the damage mechanism of the composite beam under four-point bending loading, the impact of the degree of shear connection on the short-term flexural performance of the composite beam, and the determination of creep limit. At the same time, he studied the effect of the degree of shear connection on the creep of the composite beam under long-term loading. He analyzed the stress redistribution phenomenon caused by creep and provided the long-term creep coefficient of the composite beam.

Xuesong Song, a Ph.D. candidate at Nanjing Tech University, reported on the study of the fire resistance of modified timber cladding on glulam columns. The purpose of the fire resistance modification of timber is to extend the ignition time of timber, reduce the charring rate, and improve its fire resistance. Song used resin impregnation and compression densification to prepare modified domestic cedar for use as fire-exposure side laminates of glued laminated timber columns. He conducted unilateral fire-exposure tests on the components. The experimental results showed that using a combination of resin impregnation and compression to modify the laminated surface significantly improves the fire resistance of glued timber columns. The remaining section of the glued timber column decreases with the increase in fire time, leading to a transition from strength failure to instability failure in the residual bearing capacity test.

Tianyi Wu, Ph.D. a candidate at Nanjing Tech University, shared an experimental investigation on the fire-resistance performance of wood-framed walls sheathed with gypsum–wheat–straw composite (GWSC). Gypsum board (GB) has excellent fire resistance and is widely used as a fire-resistant cladding for light wood frame (LWF) walls. However, GB cladding is prone to cracking and peeling under high temperatures, which can lead to premature failure of LWF walls. Wu introduced a new GWSC sheathing board and conducted a fire test study on it. The experimental result showed that the temperature of the GWSC-covered wall at the same measuring point in the fire is lower than that of the GB wall. The fire resistance limit of IGW cladding walls is 44% more than that of GB walls; after a fire, GWSC can still maintain structural integrity. Overall, GWSC has better fire resistance, which can replace GB as a LWF wall cladding panel.

Haotian Tao, a Ph.D. candidate at Southeast University, presented a finite element analysis of the connections between a timber beam and a steel column using screwed-in threaded rods. To promote the development of multistory timber structures, new high-performance timber connections have received wide attention, such as screwed-in threaded rod (STR) connections. Based on previous low-perimeter repeated load tests on timber beam-steel column nodes using STR connections, he developed a finite element model of STR connections using Abaqus. To analyze the plastic deformation and fracture behavior of materials, he developed an Abaqus subroutine to create a three-dimensional model of elastic-plastic damage principles for steel and wood. In the finite element model, the tensile force exerted by the STR is simulated by introducing viscous cells between the screw and wood hole. The slip and damage resulting from the cyclic pulling process of the STR are considered by implementing a dedicated viscous cell instantiation. The research showed that the finite element model could present all failure modes of the connections by using the Abaqus subroutines; the numerical stiffness of the connections was slightly higher than that of the experimental ones; and the slip was caused by the excessive deformation of the washers in some STR connections due to the oversized reserved holes in the test, which led to distinctions between the experimental and numerical results.

Jiwei Liu, a Ph.D. candidate from Southeast University, presented on robust parameter identification for ductile timber connections. Ductile flexural timber frames have good resistance to lateral forces, which offers the advantage of reducing carbon emissions and the potential for wide application in medium-and high-rise buildings. Liu proposed a special steel member for a ductile timber frame beam-column node and conducted experimental research and numerical analysis. He used the unscented Kalman filter, a Bayesian filter approximation method for nonlinear systems, to identify the parameters of the connection model. He also replaced the Cholesky decomposition with a singular value decomposition, incorporating an adaptive noise estimator. The numerical results were in good agreement with the experimental results. The stability of the unscented Kalman filter algorithm was improved, and the model error was reduced to below 10%.

9 Innovations on engineered bamboo materials and structures

This session focused on the latest research on engineered bamboo materials and structures, including mechanical properties, long-term performances, and manufacturing techniques of bamboo scrimber; mechanical properties of cross-laminated bamboo (CLB) and a novel CLTB; sound insulation performance of bamboo nail-reinforced CLT; and fiber-reinforced concrete materials.

Wenji Yu, a professor and chief scientist at the Chinese Academy of Forestry, shared the status and trends of manufacturing technology for high-performance bamboo scrimber. China is the country with the richest bamboo resources in the world, with a bamboo forest area of around 7 million ha. In 2021, the annual export of large-diameter bamboos reached USD 2.51 billion and a domestic production and consumption value of RMB 350 billion. High-performance bamboo scrimber is a bamboo-based fiber composite material produced using directional recombination technology. It can be manufactured from various bamboo species found in China, including *Dendrocalamus affinis Phyllostachys edulis, Bambusa chungii,* and *Dendrocalamus sinicus*. Bamboo scrimber offers controllable performance, adjustable specifications, and designable structures. This is a solution to the limited availability of high-quality timber resources in China and promotes low-carbon green development. High-performance bamboo scrimber products have excellent mechanical properties, termite resistance, dimensional stability, fire resistance, and high corrosion resistance. They are widely used in engineering and construction, furniture decoration, public facilities construction, and other fields. Yu hopes that by enhancing cooperation both domestically and internationally, high-performance bamboo scrimber and other environmentally friendly building materials can be promoted widely around the world, which will help reduce the embodied carbon emissions associated with building materials and effectively help address the global climate change issue.

Qingfang Lv, a professor at Southeast University, shared a study on the influence of bamboo fibers on the mechanical behavior of high-performance, lightweight aggregate concrete. This concrete has high brittleness, and adding fibers can enhance its mechanical behavior. Compared to steel and synthetic fibers, natural bamboo fibers are locally accessible, non-polluting, and affordable. Lv's team conducted an experimental study on high-performance, lightweight aggregate concrete specimens with natural bamboo fibers of varying lengths (7.5, 15, and 30 mm) and volumetric contents (0.1%, 0.3%, and 0.5%). The results indicated that the cubic compressive strength of bamboo fiber-reinforced concrete decreases as the fiber volume content increases. The bonding between bamboo fibers and the concrete matrix leads to a notable increase in splitting tensile strength and a decrease in brittleness. Furthermore, the inclusion of bamboo fibers, specifically those with a length of 15 mm and volume content of 0.1%, significantly enhances the toughness and energy absorption rate of the material when compared to ordinary high-performance lightweight aggregate concrete.

Yue Qi, an assistant research fellow at the Chinese Academy of Forestry, presented on the topic titled "The Effect of Multi-Cycle Artificial Accelerated Aging on the Physical and Mechanical Properties of Bamboo Scrimber." Dimensional stability, insect resistance, mildew resistance, and strength retention are important indicators for evaluating the durability of outdoor bamboo scrimber products. She conducted mechanical property tests on samples with varying treatment times, simulating accelerated aging and natural weathering processes. The results indicated that the mechanical strength of recombinant bamboo decreased as the accelerated aging time and natural weathering time increased. The flexural strength of bamboo scrimber did not show significant changes when soaked in different types of water (seawater or freshwater), but freshwater had a notable impact on its shear strength. Specimens exposed to the southern region of China experienced higher losses in flexural and shear strengths. Additionally, the bending and shear destruction of bamboo scrimber underwent changes after undergoing accelerated aging and natural weathering tests.

Maria Cristina David, an associate professor and a chairperson at Pampanga State Agricultural University, shared the development of a bamboo-shaving reinforced concrete wall panel. She used bamboo shavings, which are processed from agricultural and industrial waste, as raw materials. These shavings were then mixed with silicate cement, gravel, and water to produce a bamboo shaving-reinforced concrete material. Mechanical tests were conducted on the concrete specimens with varying percentages of bamboo shavings to determine the optimal ratio. Additionally, the aesthetics and cost-effectiveness of non-load-bearing bamboo shaving-reinforced concrete wall panels were evaluated based on the optimal ratio. The results showed that bamboo shaving-reinforced concrete wall panels can meet the required properties of low-cost building materials, contribute to the reduction of bamboo product waste, and can be used for the development of non-load-bearing walls for small houses in rural and urban areas.

Juanito Jimenez, a researcher at the Forest Products Research and Development Institute from the Philippines, shared his research on the development of arc-laminated giant bamboo using thermally modified segments. Due to the inefficient utilization of raw materials in the traditional rectangular strip lamination process, he explored a new lamination process for curved bamboo sheets. Jimenez utilized two thermal modification techniques, steam and oil heating, to assemble bamboo sheets using polyurethane and curved press molds. Subsequently, physical and mechanical property tests were conducted on the samples. The results showed that the treated bamboo laminates were less hygroscopic and more dimensionally stable than the non-thermally modified samples. The compressive strength, tensile strength, shear strength, and modulus of elasticity of steam-or oil-treated bamboo laminates were unaffected or minimally affected. However, their moduli of rupture were significantly reduced. Jimenez believes that this process can be further optimized to produce durable bamboo laminates with improved dimensional stability.

Yao Wu, an assistant professor at Nanjing Tech University, China, presented on "Mode I Translaminar Fracture of Cross-Laminated Bamboo and Layup Effects." CLT is widely used in multistory buildings globally due to its significant advantages in resisting bidirectional forces and reducing seismic energy consumption. CLB is a product similar to CLT and is expected to emerge as a new sustainable building material. However, bamboo is prone to cracking, and the assembly of components can create stress concentration, facilitating easy formation of cracks and their expansion at the edges of holes. Therefore, studying bamboo based on fracture mechanics theory is of great significance. Wu conducted a fracture study on CLB, which involved a three-point bending fracture test to determine the equivalent modulus of elasticity, R-curve, fracture toughness, and cohesive traction-separation law of CLB. The test results showed that CLB has high energy dissipation capacity: the arrangement of fibers in both transverse and longitudinal directions can significantly enhance fracture toughness and energy absorption capacity, thereby considerably improving destabilizing toughness. As the fiber content increases, the energy consumption mechanism shifts from pull-off to pull-out, which improves the material's resistance to brittle failure to some extent. However, excessive fiber content can lead to a significant difference in strength between the transverse and longitudinal directions, resulting in damage and weakness in other directions. The tensile strength and fracture toughness show a linear correlation with the transverse fiber content, while the fracture strength and viscoplastic behavior exhibit a linear correlation with the transverse fiber content. Additionally, fracture toughness and viscoplastic behavior demonstrate a linear correlation. However, the growth rate of fracture toughness was greater than that of the transverse fiber content.

B.U. Kelkar from the Institute of Wood Science and Technology, Bangalore, India, conducted an experimental study on the performance of laminated bamboo lumber coated with water-based polyurethane against accelerated UV and natural weathering. Laminated bamboo lumber, being a lignocellulosic material, is prone to degradation by various abiotic factors, such as moisture, UV radiation, temperature, and oxidation. However, its durability can be enhanced by applying protective surface coatings, such as polyurethane. The study conducted by Kelkar utilized water-based polyurethane (PUW) coatings and subjected the coated products to accelerated UV light and natural weathering conditions for 250 h and 90 days, respectively. The surface color, roughness, wettability, chemical composition, and microstructural changes of the integrally coated bamboo products were systematically evaluated. The results showed that the degradation of the uncoated bamboo integrals was significant due to the photodegradation of lignin, an increase in roughness and wettability, and weathering and cracking. In contrast, the changes in the surface color, roughness, and wettability of laminated bamboo lumber coated with PUW were significantly reduced under both UV light and natural weathering conditions. This indicates that PUW can effectively enhance the aging resistance of laminated bamboo lumber in outdoor areas.

Yue Wu, a Ph.D. candidate at Nanjing Forestry University, delivered a presentation on the sound insulation performance of the bamboo nail reinforced-cross laminated timber (BN-CLT). To utilize the resource advantages of bamboo over wood and the excellent mechanical properties of bamboo scrimber to enhance the rolling shear performance and acoustic properties of CLT as a floor slab, Wu developed a new type of BN-CLT. This BN-CLT retains the original structure and manufacturing process of CLT, with a base made of plywood from Chinese cedar. The plywood has pre-prepared holes arranged periodically, in which square bamboo scrimber nails are inserted as diffusers. The length of the nails matches the CLT thickness. The sound insulation performance of BN-CLT was investigated through simulation and the impedance tube method in the frequency range of 50–2000 Hz. The results showed that the sound insulation performance of BN-CLT was higher than that of fir CLT. In the frequency range of 200–600 Hz, there were significant peaks in the sound insulation curves of BN-CLT, indicating that the periodically arranged bamboo nails suppressed the propagation of sound waves at low and medium frequencies. The diameter and spacing of the pre-drilled holes in the BN-CLT affected the distribution and peak of the sound insulation curve, resulting in different sound insulation effects.

Xinlong Su, a Ph.D. candidate at Southwest Forestry University, shared his study on bamboo–timber composites produced from *Dendrocalamus sinicus* (dragon bamboo) and *Eucalyptus*, called CLBT. CLBT specimens produced of bamboo contain a green outer skin of bamboo as the surface material and eucalyptus as the core material for orthogonal assembly, glued with phenolic isocyanate resin. The research focused on evaluating the gluing performance, bending resistance, dimensional stability, and strength-to-weight ratio of CLBT. The result showed that CLBT has higher flexural strength than CLT specimens made of *Eucalyptus* and avoids bottom tensile failure. The dimensional stability is better, and the performance can meet the requirements of the Chinese forestry industry standard “LY/T 3039-2018: Cross Laminated Timber” [27]. This study demonstrates the feasibility of using dragon bamboo as a substitute for some timber species to manufacture CLBT.

Qiuqin Lin, a Ph.D. candidate at the Chinese Academy of Forestry, delivered a presentation titled “Directional Bamboo Laminated Lumber: A New Material with Infinite Lengthening.” Due to the growing demand for large-sized components in engineering projects, the process of lengthening bamboo laminated lumber has always been the research focus. The bamboo processing technology of “first joining and then molding” avoids the shortcomings of low production efficiency, a high material loss rate, and significant loss of mechanical properties in the traditional production process. Through the pre-processing technology of the bamboo sheet unit, the glue-less directional lengthening technology for joints, and the laminated coating technology using phenolic resin with different molecular weights, key support is provided for preparing large-sized bamboo laminated lumber structural components. This significantly enhances the market competitiveness of bamboo laminated lumber production and processing enterprises.

For outdoor use, bamboo scrimber is exposed to the sun and rain. Along with the synergistic effects of ultraviolet rays, oxygen, moisture, temperature, microorganisms, and other factors, it often leads to natural aging phenomena. These include surface discoloration, rotting, and cracking of the end face, which limit its application. Wencheng Lei, a Ph.D. candidate at the Chinese Academy of Forestry, shared his research on the impact of density enhancement on the water resistance of bamboo-fiber-reinforced composites. Lei conducted a study on mainstream bamboo scrimber products (density 1.20 g/cm^3, glue content 18%). The research focused on hydrothermal–drying–hydrothermal cyclic treatment following the Chinese national standard *GB/T 30364-2013: Bamboo Scrimber Flooring* [28]. The study measured the quality and dimensional changes of the products and examined the microscopic changes using super depth of field microscopy and the pressurized mercury method. The test results showed that the swelling ratio sharply increased in the initial stage and then became stable in the aging period; the swelling ratio of the samples decreased as the density of bamboo scrimber increased.

10 Round pole bamboo structures: research and innovations

This session focused on the latest research on round pole bamboo structures. The speakers introduced relevant ISO standards, a novel low-rise round bamboo structure, a novel FRP–bamboo composite anchor bolt, bamboo–concrete composite columns, as well as hot bending techniques, structural grading, and mechanical properties of round bamboo culms.

Kent Harries, a professor at the University of Pittsburgh, demonstrated the round bamboo connection capacity determined by the ISO 22156 [24] provisions for “Complete Joint Testing” [29]. The provisions permit the design performance of joints to be evaluated by testing complete, full-size joints with the same geometry, fastener configuration, and connecting elements as those being prescribed. The test protocol was carried out in accordance with the requirements of *ISO 16670:2003 Timber structures – Joint made with mechanical fasteners – Quasi-static reversed-cyclic test method* [30]. The performance of the joints was determined using the provisions of *ISO/TR 21141:2022: Timber structures – Timber connections and assemblies – Determination of yield and ultimate characteristics* [31]. Characteristic values for joint strength and stiffness were determined in accordance with *ISO 12122-5 2018: Timber structures – Determination of characteristic values – Part 5: Mechanical* *connections* [32] and/or *ISO 12122-6 2017: Timber structures – Determination of characteristic values – Part 6: Large components and assemblies* [33], as applicable. Harries demonstrated how this protocol is applied to determine the flexural performance of a simple bolted fish–mouth joint. The protocol included a description of the measured joint performance parameters, how they were derived from the tests, and the subsequent calculation of characteristic values appropriate for design. The limitations of full joint testing were discussed. The performance parameters of the tested bolted fish–mouth joints exhibited significant variability, leading to relatively low characteristic design parameters for yield strength, ultimate strength, and rotational stiffness.

Xin Zhuo, an associate professor at Zhejiang University, presented on "The Novel Low-Rise Bamboo Culm Structure Building System Composed of Prefabricated Frame Units." The traditional round bamboo structure uses nails or ropes as the connection method. However, these friction-type connections are susceptible to loosening or even failure due to fluctuations in the moisture content of bamboo or the surrounding temperature. The novel round bamboo structural system proposed by Zhuo comprises rectangular, trapezoidal, and triangular framing units connected in parallel by screws. By changing the combination and number of bamboo culms and bamboo nodes, the structural load-carrying capacity can be significantly improved. Based on the material properties of round bamboo and the performance requirements of the structure, he proposed a modular system that combines frame units. Practice has proven that the frame unit assembled around the bamboo structural system is feasible. This system allows for mass production and warehousing in factories, reducing the workload of on-site assembly and shortening the construction period. At the same time, Zhuo combined the use of lodging functions and other compounds with the rationality of the structure to propose a block combination structure for intelligent algorithms. This structure is programmed to rapidly form and optimize the spatial layout of low-rise round bamboo building units through parameterization. He believes that the low-rise round bamboo structure will have great market potential as long as the quality is good and the cost is reasonable.

Xinmiao Meng, a lecturer at Beijing Forestry University, presented on "Ecologically Self-Anchored FRP-Bamboo Composite Anchor Bolts: Concepts and Experiments." With the rapid and extensive construction of infrastructure in China, supporting slope projects are facing challenges such as poor stability, the proliferation of secondary wasteland, and severe soil erosion. The anchors used for ecological slope protection only consider slope safety, disregarding the synergistic interaction with plant roots. To address these challenges, Meng proposed a novel self-anchored composite anchor composed of fiberglass-reinforced plastic (FRP) and bamboo. The anchor is made of slender bamboo sheets that are formed into a U-shaped anchor head through hot bending. The center is then bonded together using FRP winding layer-by-layer. He conducted a tensile test and a resistance-to-pullout test on the anchor rod and analyzed the mechanical properties of the U-shaped anchor head. The results indicated that the bending modulus of bamboo was influenced by temperature during the thermal bending process. Among the different widths of the bamboo strips tested, the 4.5-mm-width strip performed the best, achieving optimal results at a thermoforming temperature of 210 ℃. The use of the U-type anchor head ensured that the tensile strength of the bamboo was fully utilized while preventing the lateral pressure caused by the anisotropic nature of the material. Combining the results of the tensile test, he developed a mathematical model for determining the tensile strength of bamboo pieces. This model can be used to regulate the mechanical characteristics of anchors. Based on the analysis results, the stress distribution and development at the anchor and bond interfaces can be determined. In addition, a mechanical model for determining the ultimate bearing capacity can be established to provide a theoretical foundation for structural optimization.

Louisa Molari, an associate professor at the University of Bologna, Italy, shared a study on the effect of the heat treatment process on the mechanical properties of bamboo. Natural bamboo has good mechanical properties, but its durability does not directly meet the requirements of being a construction material. Usually, methods for improving the durability of bamboo are categorized into chemical and nonchemical treatment methods. Among nonchemical treatment methods, heat treatment has received increasing attention due to its ability to enhance the durability of bamboo effectively. However, this treatment method may have significant effects on the mechanical properties of bamboo. Molari's study aimed to investigate the effect of the heat-treatment process on the mechanical properties of bamboo. She specifically examined the impact of conventional heat treatment on *Phyllostachys Viridis* bamboo samples from Italy. In accordance with *ISO 22157:2019: Bamboo structures – Determination of physical and mechanical properties of bamboo culm – Test Methods* [34] and *UNI 11842:2021: Determination of the physical and mechanical properties of bamboo culms* [35] standards, she conducted flexural, compressive, and tensile tests along the fiber direction. Additionally, she examined the impact of UV irradiation on heat-treated bamboo. The study results indicated that the mechanical properties of bamboo in the fiber direction remained unaffected regardless of UV light exposure. However, the microscopic findings suggested that the properties perpendicular to the fiber direction were impacted. Further testing is necessary to confirm this.

Miretu Tadesse from Bahir Dar University, Ethiopia, shared his research related to the prediction of bending stress in *Oxytenanthera abyssinica* bamboo based on the geometric section. He conducted a study on bending stress in different parts of lowland bamboo material of varying ages. This study focused on the geometric cross-section characteristics of lowland bamboo, which is the main bamboo species in Ethiopia. Bending tests were conducted in accordance with ISO 22157 international standards. The test results showed that the ratio of the diameter (D) at the bottom of lowland bamboo to the average length between nodes is a reliable indicator for determining the bending strength of lowland bamboo at 11%–13% moisture content. The bending strengths of two-, three-, and four-year-old lowland bamboos could be calculated using 5.8D, 6.4D, and 7.2D, respectively. Additionally, there was a linear correlation between the solid cross-section of lowland bamboos and their bending strengths. This suggests that the geometric characteristics of the cross-section can be used to predict the bending strength of lowland bamboo.

Sijie Niu from Anhui Agricultural University, China, shared the effects of hydrothermal treatment on the bending properties of moso (*Phyllostachys edulis*) bamboo. To enhance the flexibility and morphological adaptability of bamboo and explore its diverse applications, the researcher opted to treat bamboo using acidic or alkaline water baths. Niu controlled the temperature and duration of the water bath to investigate the variations in the bending properties of bamboo under different treatment conditions. The results showed that the bending performance of bamboo was negatively correlated with water bath temperature, water bath time, and treatment solution concentration, among which the effect of water bath time was the most significant; the effect of acidic treatment solution on the bending performance of bamboo was slightly higher than that of alkaline solution.

Beibei Jin, a Ph.D. candidate at Xi'an University of Architecture and Technology, China, studied the axial compressive performance of sprayed composite mortar-original bamboo composite columns and their engineering applications. Natural bamboo material has various forms and is known for its poor durability and tendency to deform. To address these issues, a composite mortar was sprayed onto the surface of the round bamboo skeleton. After proper maintenance, this created a structural system that combined sound insulation, heat preservation, fire prevention, and other functions. This spraying composite mortar-round bamboo combined structural system effectively compensates for the weaknesses of natural bamboo materials. He studied the axial compression performance of 23 short columns and 7 long columns. He proposed strength and stability calculation methods for the sprayed composite mortar–original bamboo composite columns and demonstrated the construction process of this structural system.

Rui Ma, a Ph.D. candidate at Tianjin University, China, shared a study on the structural grading of moso bamboo culm based on its minimum external diameter. Bamboo is a traditional material used in house construction, and its utilization in building rural houses promotes green and low-carbon development. However, the construction of traditional bamboo houses is usually based on the experience of artisans rather than a standardized design process. The study of the structural grading of moso bamboo timber is crucial for the standardized design and construction of moso bamboo structures. Ma proposed a method for grading moso bamboo based on the diameter of the small end. She measured, counted, and analyzed the geometric dimensions and physical properties of 653 moso bamboo poles treated in three different ways: untreated, chemically treated, and carbonized. The results indicated that the outer diameter of the bamboo pole can be determined from its outer circumference; the processing method has a significant impact on the geometric size and physical characteristics of bamboo poles; three types of bamboo poles treated in different ways can be divided into three levels based on their small head diameter, providing theoretical support for establishing standard design methods and specifications for bamboo structures.

Daniel Hindman, an associate professor at Virginia Tech, USA, shared his research on the evaluation of the bending strength perpendicular to the fibers of Tre Gai (*Bambusa blumeana*) along the culm height. His research focused on developing lightly modified bamboo panels to create orthogonally glued bamboo panels with minimal mechanical processing. The goal was to retain the natural round shape and cross-section of round bamboo culms. He tested the flexural strength and stiffness of the nodes and internodes of bamboo culms lengthwise, perpendicular to the fiber direction. He divided the bamboo culms into equal lengths of 4 m each and measured the inner and outer diameters using a novel digital scanning method. The test results showed that the node strength was approximately 2.9 times greater than the internode strength. While variations in strength and stiffness were observed along the culm length, no clear trend was identified. Additionally, there was a correlation between the culm's thickness and its strength values.

11 Conclusions

The 2022 International Conference—Bamboo: A Very Sustainable Construction Material & the 3rd World Symposium on Sustainable Bio-Composite Materials and Structures—was held from November 8 to December 13, 2022. The conference encompassed eight thematic sessions and was co-organised by INBAR, INBAR TFC, School of Civil Engineering of Tsinghua University, School of Architecture of Tsinghua University, Architectural Design and Research Institute of Tsinghua University, Nanjing Forestry University, National Provincial Joint Engineering Research Centre of Biomaterials for Machinery Package of Nanjing Forestry University, School of Landscape Architecture of Beijing Forestry University, and International Centre for Bamboo and Rattan, with support from 30 national and international institutions.

Ten keynote speeches and 64 presentations were delivered, and 14 moderators chaired the sessions. Among them, 17 speakers were university students, accounting for 23% of the total number of speakers. Female speakers and moderators accounted for 26%. Approximately 1400 registered participants from 81 countries attended the 2022 Conference, who belonged to more than 500 different institutions. The information delivered during the 2022 Conference, summarized in this paper, presented the diverse and potential uses and suitability of bamboo, timber, and other biomaterials as conventional construction materials in modern society. The conference convened all stakeholders, such as global architects, engineers, forestry experts, entrepreneurs, and policy makers, to make a joint effort to promote the development of the industry.

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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. Thematic sessions and topics of Bamboo: A Very Sustainable Construction Material & the 3rd World Symposium on Sustainable Bio-Composite Materials and Structures

Theme	Topics	Video links
Opening words & Session 1: Exemplary architecture design of bio-based materials	1. Carbon peak & neutrality goal calls for more timber architecture	[3]
	2. Hybrid bamboo: a sustainable Chinese architectural material	
	3. Nature-led design	
Session 2: Bio-composite materials for contemporary construction sector: current scenario and future prospects	4. Innovation and application of structural engineered bamboo materials	[3]
	5. Introduction to Chinese standards and engineering practices on timber and bamboo structures	
	6. Bamboo and gardens: Applications and development of bamboo materials in landscape architecture	

	7. Technology road mapping for the development of bamboo structure in China: Based on bibliometric analysis and experts survey	
	8. Engineered Bamboo Composite (EBC) and EBC Structures	
	9. Paradigm shift from conventional to green and sustainable materials	
Session 3: The potential of bamboo as a material for sustainable construction and circular economic development	10. Affordable Bamboo housing as a resilient alternative to reduce the carbon emissions in the global south: Case study in the Philippines and Nepal	[4]
	11. Engineering bamboo for structuring buildings	
	12. Bamboo Workshop School in Manabi -Ecuador	
	13. From traditional bamboo architecture to sustainable housing solutions in Uganda -The paradoxes to scaling up explored	
	14. Rural housing in India- What's stopping bamboo	
	15. Small-diameter bamboo for low-cost housing in Myanmar	
	16. Innovations and challenges in bamboo strategy development and implementation in Uganda	
	17. Financial and non-financial stimulus in Ecuador's bamboo sector	
Session 4: Digital and other innovative technologies for designing bio-composite materials in modern construction	18. Re-discovering our resources and technologies for lighter and more-efficient built environment	[5]
	19. Analysis optimization of bamboo pole trusses based on data from digitized bamboo culms	
	20. Design and construction of lightweight bamboo-wood structure based on building information model, the case study of a residential house in Zhangbei, China	
	21. The bamboo gate of Zhangcun Primary School	
	22. A decade of technological support for bamboo design	
	23. Bamboo bridge in Tao Sense Art Park	
	24. Research on multi-sensor fusion technology for crack monitoring of historical timber structure based on digital twins	
	25. Parametric designed joints for bamboo spatial structures as a strategy for incrementing bamboo architecture in Brazil	
	26. Bamboo gridshells through computational design and construction	
Session 5: Lessons learnt: Construction business, products, techniques, technologies and future outlook	27. Study on key technologies and standards for engineered bamboo structure	[6]
	28. Green practices of bamboo scrimber: How we contribute to the low-carbon development	
	29. Rescue and guidance of traditional handicraft - the thought and practice of the original bamboo construction	
	30. Feelings and thoughts immersed in bamboo	
	31. Raw Bamboo Creates Infinite Artistic Space	
	32. Research and applications for modern structural engineered bamboo materials	
	33. Suitable scenarios for engineered bamboo structures	
Session 6: Recent research on timber materials and structures	34. Research needs for mass timber construction - global perspective	[7]
	35. Spatial timber structures in China and research on the performance of their typical connections	
	36. Effective flange width evaluation for timber-concrete composite beams with crossed inclined coach screw connections at the serviceability state	
	37. Serviceability of cross-laminated timber (CLT) floor considering the environments	
	38. Experimental investigation of dynamic properties of timber-concrete composite beams	
	39. Experimental investigation on long-term performance of FRP-	

	Glulam-UHPC composite beams	
	40. Numerical simulation research on long-term and short-term flexural performance of steel-timber composite beams	
	41. Study on fire resistance of modified wood cladding on glulam columns	
	42. Experimental investigation into the fire-resistance performance of wood-framed walls sheathed with gypsum-wheat-straw composite	
	43. Finite element analysis of the connections between timber beam and steel column with screwed-in threaded rods	
	44. Robust parameter identification for ductile timber connection	
Session 7: Innovations on engineered materials and structures	45. The statues and trends of manufacturing technology for high-performance bamboo scrimber 46. Influence of bamboo fibres on the mechanical behavior of high performance lightweight aggregate concrete 47. Development of bamboo shaving reinforced concrete wall panel 48. Effect of multi-cycle artificial accelerated aging on physical and mechanical properties of bamboo scrimber 49. Development of arc laminated giant bamboo using thermally modified segments 50. Mode I translaminar fracture of cross-laminated bamboo and layup effects 51. Performance of laminated bamboo lumber coated with water-based polyurethane against accelerated UV and natural weathering 52. Sound insulation performance of bamboo nail reinforced cross-laminated timber 53. Feasibility study of bamboo-wood composite cross-laminated timber made from dragon bamboo and *Eucalyptus urophylla* 54. Directional bamboo laminated lumber: a new material with infinite lengthening 55. Study of dimensional stability and microstructure of bamboo fiber-reinforced composite under hygrothermal cycle environment	[8]
Session 8: Round pole bamboo structures: research and innovations **& Closing words**	56. Bamboo joint capacity determined by ISO 22156 'Complete Joint Testing' provisions 57. The novel low-rise bamboo culm structure building system composed of prefabricated frame units 58. Ecologically self-anchored FRP-bamboo composite anchor bolts: Concepts and experiments 59. The effects on mechanical properties of bamboo treated with fire 60. Bending stress prediction of *Oxytenanthera abyssinica* bamboo based on geometric section 61. Effects of hydro-thermal treatment on the bending properties of moso bamboo 62. Study on the axial compressive performance of sprayed composite mortar-original bamboo composite columns and engineering application 63. Structural grading of moso bamboo culm based on its minimum external diameter 64. Evaluation of Tre Gai (*Bambusa blumeana*) bending strength perpendicular to the fibers along culm height	[9]