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KNOWLEDGE GAPS AND RESEARCH NEEDS FOR BAMBOO IN CONSTRUCTION

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ABSTRACT
In November 2021, a symposium was held to identify knowledge gaps, and research needs and priorities in the bamboo community. Participants who were asked to complete a post-symposium survey on research gaps, needs and priorities. Both rank-order and open-ended questions were asked covering the broad areas of i) determination of material properties, testing and grading; ii) bamboo connection techniques and technology; iii) bamboo durability and fire performance; and, iv) construction using engineered bamboo. This paper reports the survey and its results. Subsequent discussion identifies priorities for future research that can be leveraged to move the use of bamboo in construction forward.

KEYWORDS
bamboo; connections; construction; durability; engineered bamboo; fire performance; grading; material properties; research needs

INTRODUCTION
In November 2021, a symposium - *Bamboo in the Urban Environment IV* - was held to identify knowledge gaps, and research needs and priorities as perceived by the bamboo community. The symposium attracted 240 unique participants (Table 1) who were asked to complete a post-symposium survey on research gaps, needs and priorities. 42 responses (18%) were received representing a range of stakeholders from at least 12 countries. Both rank-order and open-ended questions were asked covering the broad areas of i) determination of material properties, testing and grading; ii) bamboo connection techniques and technology; iii) bamboo durability and fire performance; and, iv) construction using engineered bamboo. This paper reports the survey and its results. The co-authors include the Symposium organisers and facilitators of each session (Table 1). The objective of the symposium and survey was to identify priorities for future research that can best be leveraged to move the use of bamboo in construction into the mainstream.

Each Symposium session included four invited speakers [1], followed by an open forum from which lists of research gaps and needs were developed – these formed the basis of the survey reported in this paper.

Table 1: Session titles and attendance

Session	attendance in session	views of recorded session[1]
Materials and Systems Testing and Grading	113	112
Connections for Bamboo Structures	140	98
Fire Performance and Durability of Bamboo Structures	104	106
Engineered Bamboo	64[2]	91

[1] as of 19 February 2022

[2] due to a scheduling error, few people attended the fourth session.

Post Symposium Survey

The post symposium survey announcement was distributed to all 240 unique attendees of the Symposium. 42 (18%) responses were received. Not all respondents replied to all questions.

Of the respondents who identified their interest, 24 were academic researchers, 6 were involved in the bamboo construction industry, 8 had an interest in bamboo, and 9 identified as being new to bamboo construction; some respondents identified more than one interest category while some did not respond to this question.

Survey responses came from at least (some respondents did not identify their country of origin): Australia, Brazil, Colombia, Ethiopia, Hungary, Indonesia, Kenya, Malaysia, New Zealand, The Philippines, UK and USA. It is understood that the survey may not have been available in some countries that filter internet activity without use of a foreign VPN.

SURVEY RESULTS

The survey required participants to place in rank order, 1 to 5, their top five perceived gaps and top five research priorities from a list of items generated in the symposium sessions. The eight ranking questions are reported in the following sections; the ranked items are reported in Figures 1 through 4. The weighted score – reported in Figures 1 through 4 – for each item was determined by summing the weighted number of votes received:

$$\text{weighted score} = 5r_1 + 4r_2 + 3r_3 + 2r_2 + r_1$$

where r_n is the number of votes received for rank n. That is, a first rank vote is assigned 5 points, a second rank: 4, etc.

Bamboo material properties, testing and grading

*Q1: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of bamboo in **determination of material properties, testing and grading**.*

*Q2: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of bamboo in **determination of material properties, testing and grading** over the next decade.*

The weighted results for questions 1 and 2 are reported in Figure 1. The ranking in this topic was dominated by the need for higher education to include aspects of engineering design and engineering with bamboo and the need for a global database of bamboo geometric, physical and mechanical properties. The next five ranked items are arguably related to the development of a practical and usable database.

Although at the bottom of the survey rankings, considerable discussion of developing better understanding weak matrix properties of the bamboo was recorded during the symposium open forum. Another issue raised in the symposium and not captured in the survey is investigating the

potential for supervised machine learning to be deployed in a database of bamboo geometric, physical and mechanical properties as it develops. Machine learning can be used to discover underlying correlations and derive secondary properties.

Another issue that was raised in the symposium (in multiple sessions) was the need to strengthen the supply chain for bamboo beginning with propagation. Issues of plantation needs were raised to produce enough bamboo of high quality to increase user confidence. As Professor Juan Correal put it, we "need to start the grading from the field".

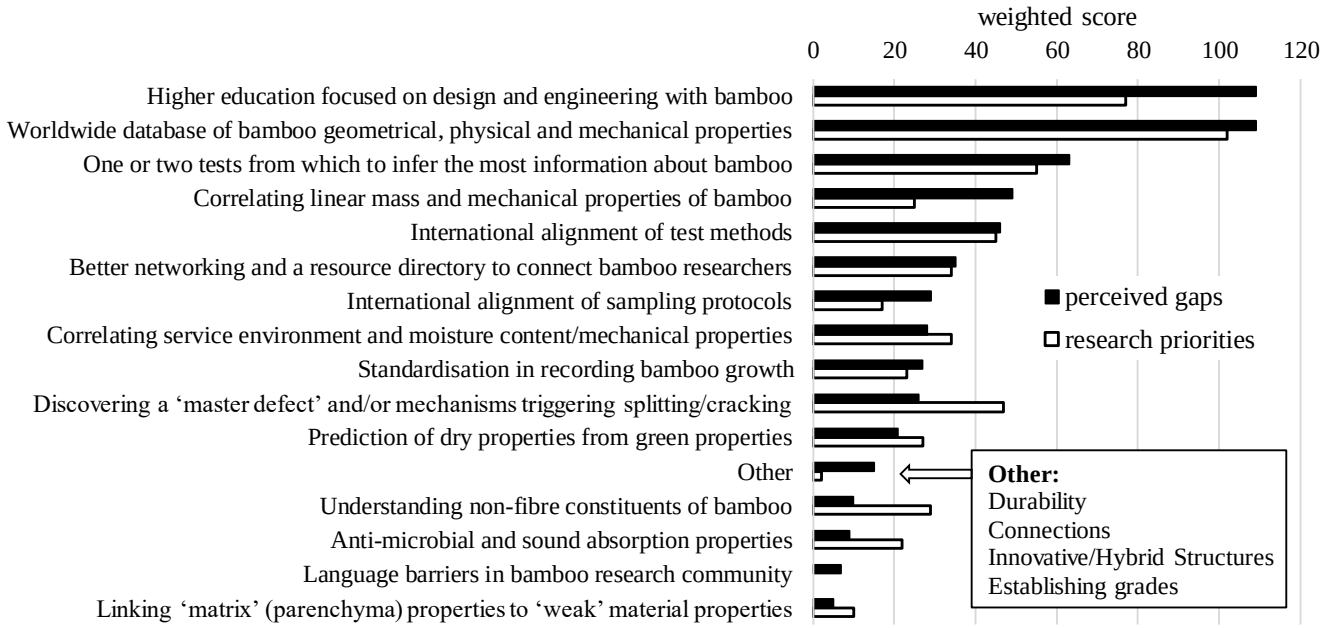

Figure 1: Weighted responses and ranking of Q1 and Q2.

Bamboo connections

*Q3: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **bamboo connection techniques and technology.***

*Q4: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **bamboo connections** over the next decade.*

The weighted results for questions 3 and 4 are reported in Figure 2. The need for predictability, and ways of avoiding splitting in bamboo connections was identified as a research priority. Otherwise, this ranking was relatively uniform. The second and third ranked items: understanding connection failure modes and correlating these with mechanical properties are intimately related, and thus lead the response. Interestingly, the specific issue of multiple culm elements received little interest in the survey responses. The environmental impact of the materials used in connections was ranked low as both a gap and priority. The potential for collaboration and integration with the [specialty] connector-manufacturing industry was raised in the symposium session.

The question was asked in the symposium *does bamboo **need** to be reinforced?* This led to discussion of identifying appropriate culm infill materials such as bamboo sawdust-resin paste, rather than cementitious grout as is presently used. The issue of potential thermo-mechanical mismatch of such infill materials was raised.

Not having a separate ISO standard for connections was perceived as a research gap, which shows that even though this is not a priority, moving towards this in the future makes sense.

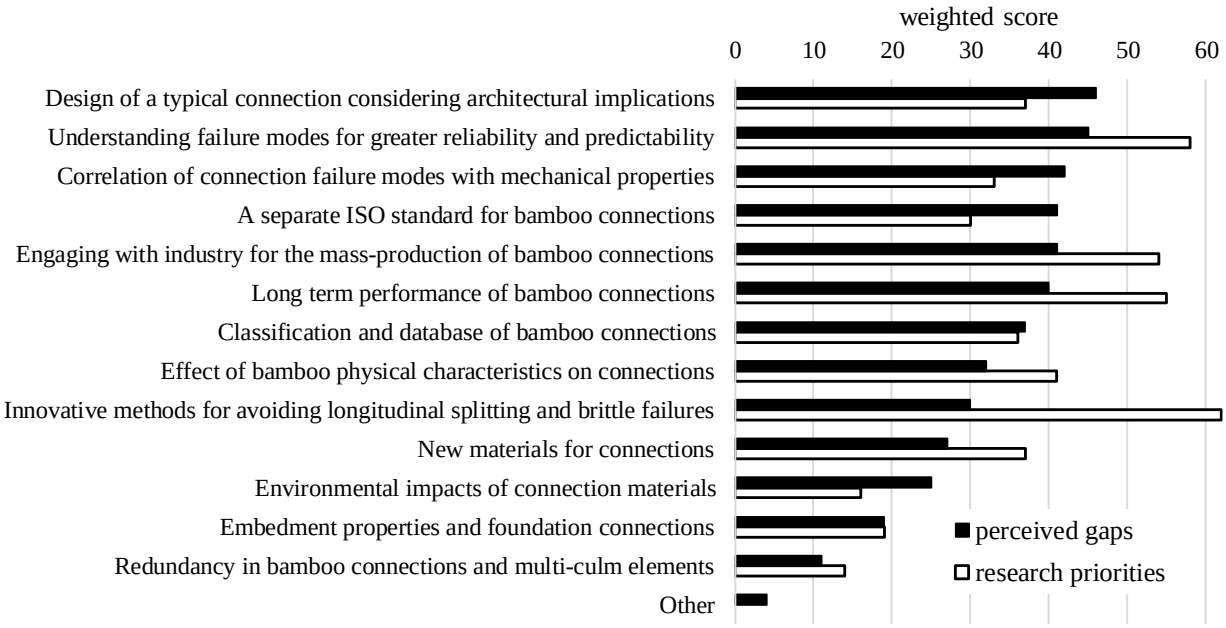

Figure 2: Weighted responses and ranking of Q3 and Q4.

Bamboo durability and fire performance

*Q5: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **bamboo durability and fire performance.***

*Q6: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **bamboo durability and fire performance** over the next decade.*

The weighted results for questions 5 and 6 are reported in Figure 3. Issues of fire performance were ranked 1, 2, 3 and 5 suggesting greater interest in fire performance or the view that durability is adequately understood but perhaps not integrated into design ('durability by design' was ranked 4). The preponderance of engineers in the group responding the survey may have skewed the results of this question.

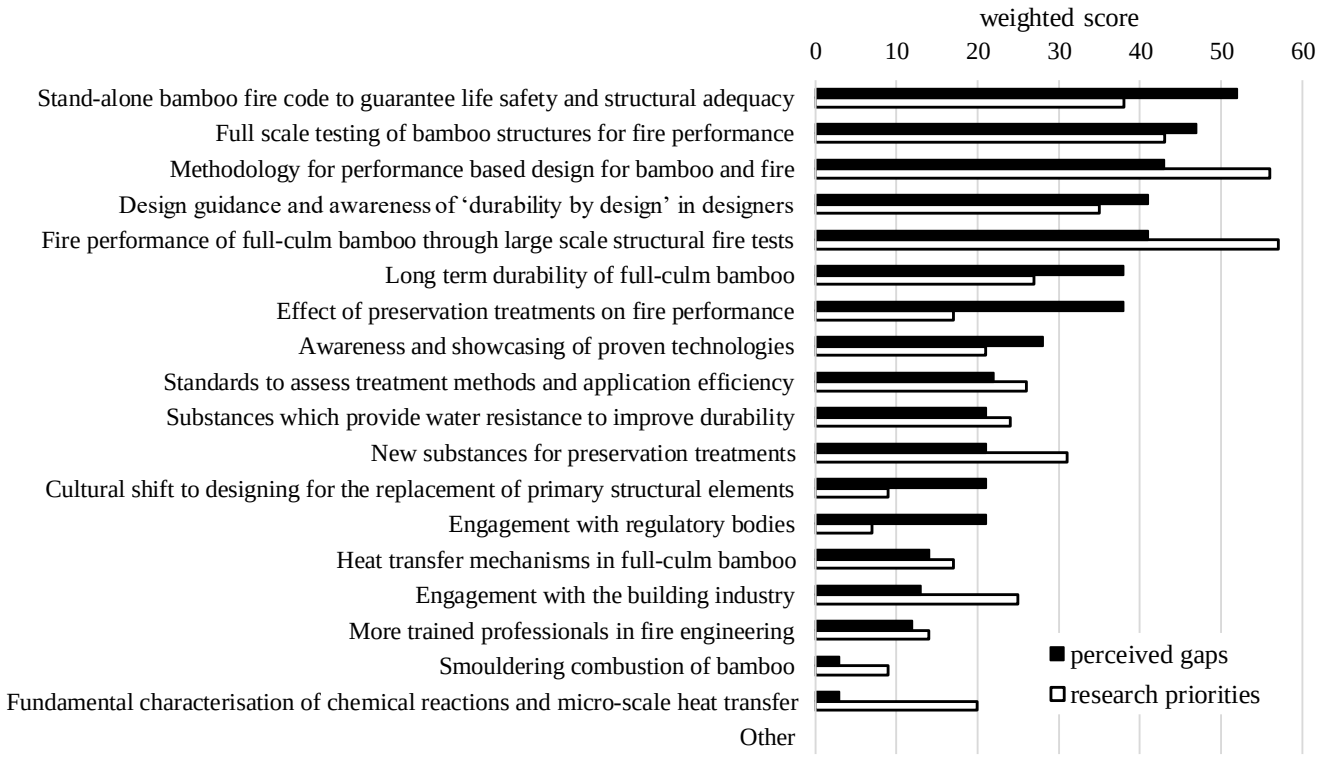

Figure 3: Weighted responses and ranking of Q5 and Q6.

Engineered bamboo construction

*Q7: Rank the top five **perceived gaps** in the current state-of-practice or knowledge of **construction using engineered bamboo.***

*Q8: Assuming reasonable and/or obtainable levels of funding/resources, rank the top five **research priorities** likely to advance the state-of-the-art of **construction using engineered bamboo** over the next decade.*

The weighted results for questions 7 and 8 are reported in Figure 4. When considering engineered bamboo, durability appears to be of primary interest (ranked 1 and 2), and fire performance received a similar score. The fire performance of resins in engineered bamboo products is perceived as a large research gap. In the session it was noted that in the cross-laminated timber (CLT) field there are adhesives which claim to have particular fire performances, but still lack confidence among designers.

Other topics discussed in the symposium session included the potential for chemical modification (in addition, or as an alternative to densification, delignification, and the sustainability of chemicals used in the manufacturing process. Tannin, lignin, polyurethane, and castor oil based resins appear promising for outdoor use since they are stable.

A general need to increase materials efficiency in the manufacture of engineered bamboo was identified**.**

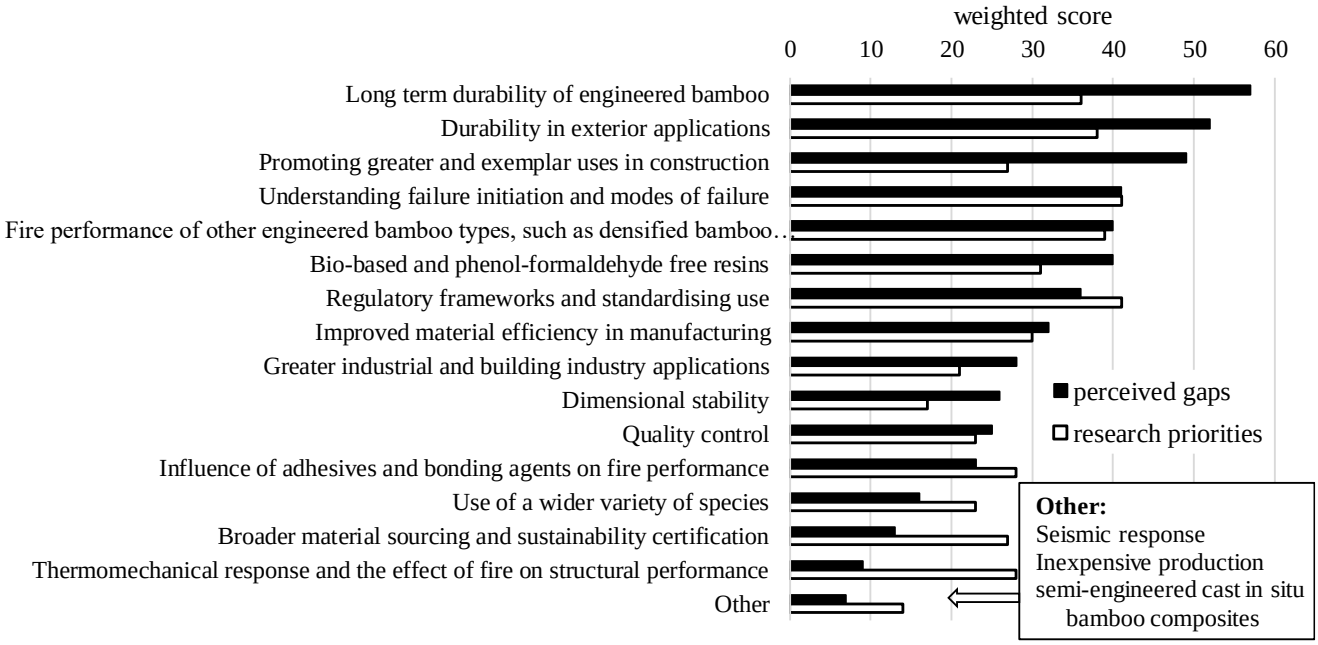

Figure 4: Weighted responses and ranking of Q7 and Q8.

Open-ended questions

Respondents were asked two open-ended questions. The questions and unedited responses received are below:

Q9: Given unlimited resources, please identify a single research priority likely to advance the state-of-the-art of bamboo (including engineered bamboo) construction.

- Simple, universal connections
- Improve joints efficiency, durability, ductile-modes, facility of construction, keeping in mind architectural considerations
- A data mapping of different bamboo species and their maxim[um] construction capability
- Standards connection of engineered bamboo
- Durability of bamboo for exterior use
- Improved fire resistance
- Understanding the impact of moisture content and thermal densification on Engineered bamboo products
- Test Standardization
- Preservation of bamboo used for construction. Information dissemination of bamboo species that are best suited for each climate type
- Bamboo Pole and Engineered Bamboo Connection
- Bamboo potential to decarbonize building construction sector
- Acoustical Properties
- More efficient and cheaper treatment, waterproofing, and adhesive products
- Cast-in-situ semi-engineered bamboo composite structural elements
- Zero Energy Bamboo Buildings
- Commercialisation of universal connectors for bamboo culms
- Material properties database
- Better knowledge and design guidance on bamboo connections

- Large scale pilot testing scheme with international collaboration to cover all major species and engineered bamboo products
- Research integrating bamboo and nanotechnology
- Wide[spread] use and manufacturing of engineered bamboo
- Durability study
- Research mechanical and physical property of bamboo species
- Long term durability
- Development of Codes and curriculum for engineered bamboo construction.
- Finding the cause of splitting and finding the solutions
- Research on mechanical grading of bamboo for industrialization applications
- Mapping the best uses of each bamboo species focusing on creating a world-wide industry capable of supplying the world demand for new buildings (using bamboo to decarbonize civil construction)

Of the 28 responses to this question received: 4 identified connections, 4 identified the need for a database or properties, 3 identified durability and 3 identified the development of codes and standards as the single greatest research needs.

Q10 Please provide any other comments and/or observations on research needs and gaps in the field of bamboo construction.

- Long time behavior of structures
- Advance mapping on the different species of bamboo and their maximum construction potential
- Education of bamboo structures is fundamental for the next decade
- Durability of bamboo in terms of strength, fire resistance, and moisture problem
- Densified bamboo connection to assess its full performance within the building and construction industry
- I really like the idea of one or two (likely would have to be two tests, something simple for E [modulus of elasticity] and deflection, and then a shear test for limiting failure behavior) to get a good understanding of the actual bamboo for design purposes. I would have [given] this more priority in rankings, but I am not sure it has nice solution. It was described as the "holy grail" for bamboo testing and design, and I've not sure anyone has found the Holy Grail, and the difficulty level may be similar.
- Detailed discussion on connections and innovative use of bamboo
- Bamboo Pole Connection
- Connections
- Engineered bamboo is the future, but cheaper machines need to be designed and supplied to encourage the opening of new companies in this field, and even for more researchers to carry out their investigations. Bamboo research must be multidisciplinary. It needs the joint work of engineers, architects, chemists, designers, agronomists, among others.
- The research community might be best to communicate with the manufacturing industry in a more advanced level to take a cut-edge lead rather than usage of the existing industrial products in research.
- How many storeys can be [achieved; is a] bamboo skyscraper [possible]? [*paraphrased by authors*]
- Greater integration with design professions
- Design code and awareness of bamboo construction among professional engineers/ builders
- Science, Technology & Innovation Metrics for non-conventional materials and technologies
- Need for changing public perception
- Workable connection details

- Bamboo bioenergy, Bamboo knowledge share to African Countries
- Standardisation and grading of bamboo per country
- [Much] research had been conducted just for the sake of the research, less relevant to the practice on the field. Action research should be done more often, combining research and practice on the real scale.
- Durability of bamboo and engineered bamboo to fire and water
- The adoption of bamboo in many countries, in special Europe, North America, and Oceania, will depend on the development of sustainable, durable, and non-toxic (throughout the whole processing chain) engineered bamboo products.

Here, 22 additional comments were received. Again, 4 identified connections and 3 identified durability as concerns. 6 respondents added comments regarding collaboration and/or the need for better education, outreach and advocacy for bamboo. These issues were not well captured in the ranking questions.

OTHER OBSERVATIONS

A few responses identified the need for better (less expensive) machining and processing equipment. This is an aspect of bamboo research that tends to be ignored. Most bamboo processing methods are adopted from other industries.

Very few responses identified the sustainability credentials of bamboo as being an important gap or research need. Nonetheless, this is often the basis of the primary argument for adopting bamboo as a construction material. Improved methods of validating the carbon sequestration and embodied carbon information of bamboo would be beneficial to designers, engineers and clients alike.

REFERENCES

[1] Recordings of *Bamboo in the Urban Environment IV* Symposium sessions can be found at: https://conferences.ncl.ac.uk/4th-bamboo-itue/linkstopresentations/

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

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