



Living Root Bridges: State of knowledge, fundamental research and future application

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Abstract

Living root bridges are *Ficus elastica*¹ based suspension bridges within dense tropical rainforests of Meghalaya in the North Eastern Indian Himalayas (25° 30' N and 91° 00' E). Ranging in span from 15 feet to 250 feet, these bridges are grown by Khasi² tribes over a time period of 15 to 30 years, and last for several centuries. With 1) exceptional robustness³ under extreme climatic conditions, 2) minimal material and maintenance cost, 3) no environmental damage, 4) progressive increase in load-bearing capacity, 5) carbon sequestration, 6) remedial properties on surrounding soil, water and air, 7) collective grass root involvement based on human-plant interaction across multiple generations, 8) support to other plant and animal systems, and 9) keystone⁴ role of *Ficus* plant species in local ecology, living root bridges offer an extraordinary model for long-term socio-ecological resilience⁵ and sustainable infrastructure solutions, and warrant further scientific study.

Keywords: *Ficus*; living root bridges; biological systems; resilience; robustness; redundancy; sensitive environments; developing economies; collaborative approaches; human-plant interaction.

1 Introduction



Figure 1. Location diagram of living root bridges

The indigenous Khasi tribes of Meghalaya in the North Eastern Indian Himalayas exemplify a unique relationship with their environment. Demonstrating a high degree of self-sufficiency, which in part is owing to their remote location and distinctive environment⁶, Khasis have developed numerous sustainable practices based on collective and planned cooperation. One such practice is the 'living root bridge'. Locally known as *jing kieng jri*, this indigenous technology uses the aerial roots of *Ficus elastica* to grow bridges ranging in spans from 15 feet to 250 feet over a time period of 15 to 30 years. Situated in heavily forested and wet places, which are prone to unexpected environmental disturbances, the underlying growth process of these plant-based structural systems involves nurturing the aerial roots of *Ficus elastica*, and guiding them across deep gorges and rivers. The supporting

horticultural technique was developed using locally available materials, skills and tools at a time when concrete and steel were non-existent. Recent attempts to build steel suspension bridges in these fragile eco-systems have highlighted their limitations, and underlined the potential of hybrid structures, which combine advantages of both technologies for an overall improved performance.

Key advantages of the living root bridges include exceptional structural robustness and resilience, progressive increase in load bearing capacity with time and use, remedial impact on surrounding soil, water and air, grass root community involvement in the growth process across multiple generations, carbon sequestration, low cost, and support for other plant and animal systems. Key challenges of this technology include a long growth phase, low safety during initial growth stage, need for appropriate growth conditions (soil, water, sunlight and nutrients), and a sensitized community support for nurturing its growth and maintenance. Comparatively, conventional bridges are extremely safe, precisely calculable for load and performance, can be installed quickly and have a long history of documented knowledge. However conventional bridge building methods have certain limitations especially in ecologically sensitive remote tropical regions in developing countries. These include high material and maintenance cost, relatively short life span (40 to 50 years as compared to several centuries for living root bridges), extensive environmental damage (caused during material transport and construction), and use of specialized materials (steel and concrete) with high carbon footprint. In addition, traditional engineered structures are driven by principles of efficiency, optimization and strength, with a precise economy of materials applied for specific environmental conditions. Conversely living root bridges, which are fibre based natural biological structures, use high degree of redundancy⁷ and complexity to respond to extreme environmental stresses and dynamic loads. This paper discusses the potential of fusing these structural systems for a plant-based hybrid system, which can withstand climatic imbalances and have significant remedial impact on its environment.

2 State of knowledge

2.1 Living root bridges

Khasis, who follow an oral tradition, have limited written documentation about their history and customs. This also applies to the living root bridges. No scientific documentation or analysis of these bridges has been found. This paper is based on author's independent field visits in 2013 and subsequent ongoing research. The author has documented 11 living root bridges and these are listed below for reference:

Table 1

Location [india]	Span [feet]	Growth stage	Safety level [5 is safest]
Riwai	75	Mature	5
Wahryngkoh	15	Mid life	3
Mawkyrnot	250	Early life	1
Mawkyrnot	150	Early life	1
Mawkyrnot	250	Mid life	3
Nongthymmai	60	Mid life	3
Nongthymmai	80	Early life	1
Nongthymmai	20	Mature	5
Nongriat	40	Mature	5
Nongriat	50	Mature	5
Nongriat	60	Mid life	3

Based on witnessing these eleven bridges at different growth stages, it can be said that the technique used to grow these bridges is still practiced by the Khasis. The underlying growth process (Fig 2) involves recurring inosculation (joining by twining⁸) of *Ficus* aerial root fibres over a gorge or river. The process begins with placing of young pliable aerial roots growing from *Ficus* trees in hollowed out *Areca catechu* trunks⁹. These provide essential nutrition and protection from the weather, and also perform as root

guidance systems by redirecting the positive gravitropic movement of the aerial roots. This assemblage is structurally supported by a bamboo scaffold, which spans the river and performs as a temporary river crossing for the community. Over time, as the aerial roots increase in strength and thickness, the *Areca catechu* trunks are no longer required. Periodic replacement of green bamboo poles is essential with increase in aerial root thickness and gradual deterioration of bamboo owing to wet tropical conditions of Meghalaya. Gradually, more roots are inosculated to the primary root system with morphological variations like steps and handrails integrated at a later stage. Dead load, in the form of heavy stones, timber planks, leaves and soil is added in succession to plug the gaps and to test the entire living root structure for weight (Fig 3). Heavy humidity, ambient moisture content and pedestrian movement together contribute to soil compaction. Eventually, over 15 to 30 years, the root assemblage becomes strong and stable

enough to support substantial human and material weight without the bamboo scaffolding. The author has witnessed the mature bridges in Riwai (Fig 4) and Nongriat (Fig 5) carrying upto 35 and 20 people at one time. Unlike contemporary construction materials and structures, these living root structural systems become stronger, more robust and resilient with time and use. Despite turbulent weather conditions, the author did not witness any mechanical failure of these bridges under external water or wind loads. In addition, no disease or attack from insects or fungi has been observed. Further, Khasi tribes' sacred worldview and unique understanding of 'time' with respect to material strength and shelf life is a key aspect of the growth process. Precise synchronisation of periodic changing of bamboo and *Areca catechu* trunks, with progressive addition of dead load is a critical step in the growth process, and ensures a continual relationship between the living bridge and the local community.

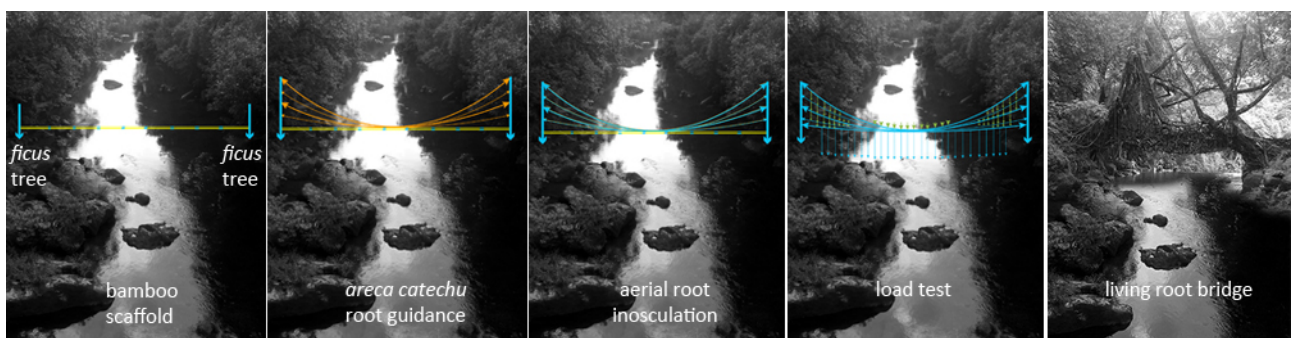


Figure 2. Growth process of living root bridges



Figure 3. Early stage, Nongthymmai Figure 4. Mature bridge, Riwai Figure 5. Mature bridge, Nongriat

2.2 Living plant-based construction

Historic precedents in the domain of living plant-based construction include 'tanzlinden' lime treetops of Europe, and unrealized proposals of gardener and landscape engineer Arthur Weichula (Fig 6). Recent works by Terreform (founded by Dr. Mitchell Joachim) and Baubotanik¹⁰ (founded by Dr. Ferdinand Ludwig) have explored the potential of living plant-based constructions as structural systems within architecture and infrastructure. Additionally, research of Inca natural fibre suspension bridges by Prof. John Ochsendorf has highlighted the potential of

appropriate local technologies, which combine social integration with environmental performance for sustainable solutions. Ongoing research by Baubotanik is specifically relevant for understanding and investigating living root bridges. The group has employed the growth processes of living woody plants within construction, through the integration of design, structural engineering, biological research and horticultural procedures¹¹. Through full scale prototypes (Fig 7 and Fig 8) and accurate analysis, the group is developing an understanding of the challenges involved in designing living plant based constructions.



Figure 6. (i) Drawing by Weichula A. (ca. 1925); (ii) Tanzlinde Peesten ©www.tanzlindenmuseum.de; (iii) Terreform, Fab Tree Hab (Joachim M., 2009)



Figure 7. Footbridge (Ludwig F. and Storz O., 2005); Tower in the first and second year of development (Ludwig F. and Hackenbracht C., 2009); Plane Tree Cube Nagold (ludwig.schoenle, 2011)

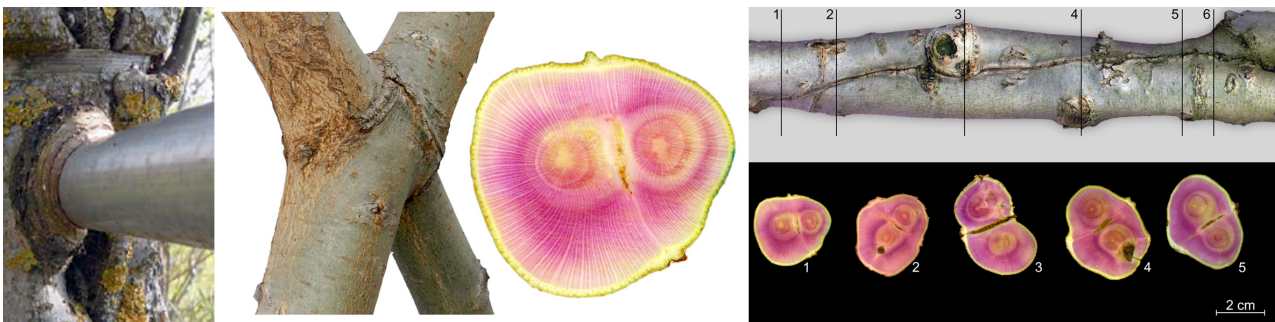


Figure 8. Experimentation for adequate construction techniques: Vegetal-technical joint (Storz O., 2010); Crosswise inosculation with *Salix Alba* and cross cut showing development stage (Ludwig F., 2010); Crosscuts through parallel inosculation showing different development stages (Ludwig F., 2010)



Figure 9. Bamboo bridge failure Figure 10. Steel suspension bridge failure Figure 11. Ficus-steel twining

3 Fundamental research

Understanding the performance of living root bridges and its underlying technology will require a precise in-situ analysis of the bridges and the *Ficus elastica* plant specie used for growing these structures.

3.1 Comparative analysis

Based on eyewitness accounts, onsite documentation and information provided by Meghalaya Basin Development Authority¹², it can be said that the structural resiliency of living root bridges is comparatively superior to steel suspension bridges and vernacular bamboo bridges in Meghalaya's remote, vertical and wet tropical landscape. Annual failure and deformation of bamboo bridges is common when impacted by heavy water loads during the monsoon season (Fig 9). There are recorded cases of bamboo bridges being swept away causing loss of life and severely impacting rural connectivity. In steel suspension bridges, failure is caused by high wear and tear, and corrosion of the cables (Fig 10). This is due to the extremely wet conditions of this region, and gradual decline in cable strength. These bridges also require periodic maintenance, which needs specialized expertise, government approval and financial resources. As a result numerous steel suspension bridges remain in a precarious condition. Comparatively, living root bridges withstand heavy dynamic water loads in the form of flash floods and storm surges, and avoid resonance catastrophes¹³ with minimal maintenance over many centuries. In many cases

they are the only means of connectivity in the monsoon season. Their success and relevance is demonstrated in case studies where Khasis' have applied this technology to the damaged steel suspension bridges by using the corroded cables as a scaffold for root guidance, support and growth (Fig 11).

3.2 Biological systems

Ficus elastica is a living biological system. Investigating the growth and physiology especially morphology and biomechanics of the aerial root fibres along with their inosculation is a prerequisite to understand, improve and replicate the performance of these plant-based structures. Research on plant systems has revealed that a high degree of redundancy at multiple scales within the hierarchical arrangement of cells and tissues produces sufficient excess capacity for adaptation to changing environmental stresses.¹⁴ Additional attributes of material self-organisation, complexity, non-linearity, anisotropy, differentiation and visco-elasticity contribute to variable stiffness and elasticity, which is useful for resisting dynamic and unpredictable water loads. Recent scientific investigations have established that all aerial roots of *Ficus elastica* are under tensile stress, which is an essential aspect for the efficiency of fibrous structures in biological systems.¹⁵ The tensile stress in *Ficus* aerial roots is inversely proportional to the diameter of the aerial root, and its distance from point of connection to soil or another aerial root.¹⁶ This stress is generated due to gelatinous fibres within the roots, which are in turn produced by stimuli in

the form of attachment or anchorage.¹⁷ Although yet to be confirmed, it is estimated that at a macro level the principle of multiple resonance damping noticed within Douglas Fir (*Pseudotsuga menziesii*)¹⁸ can be applied to understand energy dissipation of the *Ficus elastica* based living root bridge assemblage. The constituent aerial root fibres are grown in successive layers over 15 to 30 years resulting in a complex root network, where each fibre is at a different growth stage, and possesses different material properties and capacity for energy dissipation. This high degree of differentiation contributes to higher overall damping. A material property chart, which estimates the stiffness and density of *Ficus* aerial roots in comparison to contemporary construction materials is included here for reference (Fig 12). The author recognizes that the stiffness and density values of *Ficus* plant specie are time dependent, vary with local conditions and need precise scientific tests for validation.

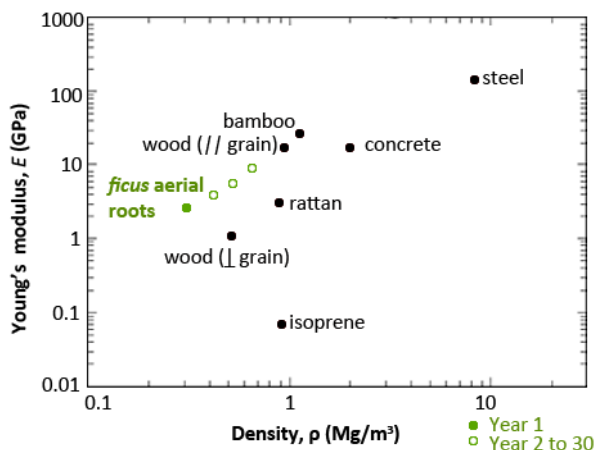


Figure 12. Modulus-Density chart

(Modified and redrawn) Ashby M., Shercliff H. and Cebon D. *Materials Engineering, Science, Processing and Design*, Elsevier, Pg 57, 2007.

3.3 Optimization

Despite demonstrating extraordinary structural and socio-ecological resilience (Fig 13), living root bridges are being replaced by inappropriate solutions owing to increasing resource needs, and the nexus of poverty, population explosion and environmental degradation in North Eastern India. The author proposes systematic optimization and value-addition for technology revival.

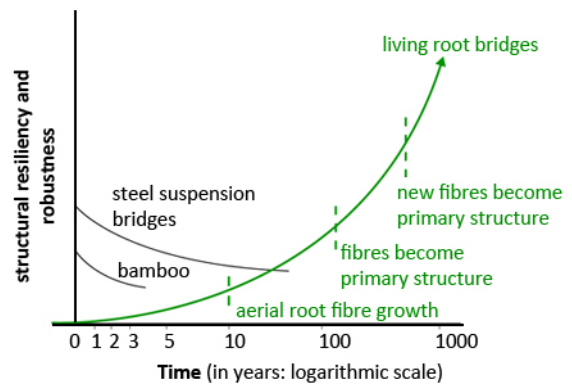


Figure 13. Structural resiliency-time chart

The primary challenge of living root bridge technology is its long gestation period of 15 to 30 years. Although yet to be confirmed through scientific analysis for *Ficus* plant specie it can be said that possible methods for expediting the growth process include 1) producing (breeding) of *Ficus* saplings, which fulfill several physiological - especially morphological and biomechanical prerequisites, in off-site nurseries before replanting them onsite, 2) providing ideal growth conditions (especially moisture and light) in these nurseries¹⁹, 3) engineering the aerial root inosculation process using different joining methods, 4) applying engineered stress to aerial root fibres in early growth stage, 5) engineering the bamboo scaffold and *Areca catechu* root guidance system using structural topology optimization, 6) increasing anchorage based stimuli to enhance gelatinous fibre production and tensile stress within the aerial roots, and 7) developing a digital planning tool based on growth principles of *Ficus elastica*.²⁰

Second key challenge of the living root bridge technology is its low-safety during early growth stage. This can be addressed by developing symbiotic hybrid structures, which combine living plant based matter with inanimate matter.

3.3.1 Value addition

Living root bridges perform as rural pedestrian bridges for remote mountain villages. The author proposes strategic interventions, which will build local enterprise and align rural development with *Ficus* ecology. Key interventions discussed with local stakeholders include redesign and widening of the bridge to support vehicular movement, and

potential adaptation of the bridge as a host biome for orchids, other epiphytic plants, food for humans and other biota.

4 Concluding remarks

Living root bridges offer an exemplary model for sustainable community-based infrastructure solutions. This paper consolidates the author's findings and puts forth future research directions for the global engineering community. The author acknowledges that he is not in possession of full scientific facts and the estimates in certain cases may be incorrect or at least simplistic. Findings from a precise scientific investigation would lay a foundation for understanding these structures, upgrading the technology and adapting it for other tropical and sub-tropical regions using appropriate native plant systems e.g. *Ficus benghalensis*. It may also lead to novel design strategies based on redundancy and irregularity for achieving structural robustness in classical engineered structures. The author envisages establishment of a trans-disciplinary consortium for initiating in-situ research of living root bridges through a research and demonstration station in Meghalaya. This platform will engage all stakeholders in a participatory process to leverage this knowledge for rural connectivity, conservation, education and livelihood.

5 Acknowledgements

The author is indebted to the Khasi tribes of Meghalaya for sharing their knowledge about the living root bridges and for guiding him through Meghalaya's challenging geography. He would also like to thank Dr. Ferdinand Ludwig, Prof. A G Rao, Prof. Anna Dyson, Prof. Renee Borges, Prof. Ananthasuresh, Prof. Arup Kumar Sarma, Dr. Tejas Gorur Murthy, Dr. Rekha Shangpliang and Mr. Aiban Swer for critical information about living plant-based constructions. Gratitude also goes to other scientists, engineers, architects and government representatives who have inspired the author with their suggestions and support.

6 References

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- [2] The term "Khasi" means "born of the mother". For a detailed elaboration, see Shangpliang R. *Forest in the Life of Khasis*. New Delhi, Concept Publishing Company, p. 1, 2010.
- [3] Robustness is used to describe a system that can survive extreme external variations. For a detailed elaboration, see Weinstock M. *Self-Organization and the Structural Dynamics of Plants*, AD Emergence: Techniques and Technologies in Morphogenetic Design, Vol 76, No 2, 2006.
- [4] A keystone species is a plant or animal that plays a unique and crucial role in the way an ecosystem functions. Without keystone species, the ecosystem would be dramatically different or cease to exist altogether. http://education.nationalgeographic.com/education/encyclopedia/keystone-species/?ar_a=1
- [5] Resiliency is the ability of a system to change and adapt to external disturbances and yet remain within critical thresholds. <http://www.stockholmresilience.org/21/research/what-is-resilience.html>
- [6] North East India is a global hot spot for biodiversity. Characterized by varied physical geography, it is marked by distinct orography, heavy monsoon rains and a diverse range of flora and fauna.

- Mawsynram and Cherrapunjee receive the highest annual rainfall in the world. Shangpliang R., *Forest in the Life of Khasis*. Concept Publishing Company, New Delhi, p. 5, 2010.
- [7] In biological systems, redundancy occurs when the same function is performed by identical elements. For a detailed elaboration, see Weinstock M. *Self-Organization and the Structural Dynamics of Plants*, AD Emergence: Techniques and Technologies in Morphogenetic Design, Vol 76, No 2, 2006. See also Guilo T., Olaf S. and Gerald M.E. *Measures of degeneracy and redundancy in biological networks*, Proceedings of the National Academy of Science USA, Vol 98, Issue 6, pp. 3257-3262, 1999.
- [8] Twining is a type of weave structure, which involves the twisting of two or more linear elements around another set of linear elements, which are perpendicular or inclined to the first set. Dunkelberg K., *IL 31, Bamboo*, Kraemer Karl GmbH + Co, p. 357, 1985.
- [9] *Areca Catechu* (betel nut) is a slender, single trunked palm that can grow to 30 m (100 ft). It is cultivated from East Africa and Arabian Peninsula across tropical Asia and Indonesia to the central Pacific and New Guinea.
<http://agroforestry.org/images/pdfs/Areca-catechu-betel-nut.pdf>
- [10] The term “Baubotanik” was developed at the Institute for Architectural Theory, University of Stuttgart and describes an approach to engineer with living plants. It is a German neologism that can be translated as “Living Plant Constructions”.
http://www.baubotanik.de/index_en.html
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<http://mbda.gov.in>
- [13] Resonance phenomenon can be thought of as a vibration that is caused by the tendency of a system to absorb energy from an external force that is in harmony with the natural frequency of the structure. For a detailed elaboration, see Weinstock M. *Self-Organization and the Structural Dynamics of Plants*, AD Emergence: Techniques and Technologies in Morphogenetic Design, Vol 76, No 2, 2006.
- [14] Ibid.
- [15] Jeronimidis G., *Biodynamics*, AD Emergence: Morphogenetic Design Strategies, Vol 74, No 3, 2004. See also Elices M., *Structural Biological Materials*, Pergamon Press, Amsterdam, 2000.
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