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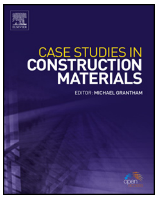

Case study

Influence of grain distribution on orientation of saw cuts: Reference to heritage structures

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ABSTRACT

Longitudinal arrangement of wood fibers are known as timber grains. It is one of the most important physical aspects of timber in applications. The properties differ along the grain and against the grain. Straight grains run parallel to the longitudinal axis of the wood. Meanwhile the cross grain deviates from the longitudinal axis as spiral and diagonal grains. This orientation has a high influence on the timber and affects physical properties during application. In order to study this, a detailed analysis was performed on *Ambalam* structures, a cherished heritage structure originated from the vernacular architecture in Sri Lanka. These structures are existing living proofs of vibrant construction materials with an exposed environment for more than 50 years. *Badulla Ambalama,Padivitiya Ambalama*, *Panavitiya Ambalama*, *Karagahagedra Ambalama*, *Giruwa Ambalama* and *Rukula Ambalama* were selected as case studies. The growth ring distribution of the exposed surfaces of the structural components were mapped using AutoCAD software. The results of overlapping and mapping the growth ring distribution of the specific timber helps to generate clues on size of the tree and sawing pattern of the wood log. The generated growth ring map revealed the sensitivity and the adequate knowledge in material manipulation utilized for specific structural components with respect to the load distribution. The *Ambalam* heritage structures have enlighten timber as an acceptable construction material with a respectable service life for tropical countries.

1. Introduction

The ability to become a “tree” has been acquired many times during the evolution of plants, and so there can be great variability between tree species [1]. Trees can be classified into two, such as endogenous and exogenous. Exogenous trees grow outward from the center, generating approximate concentric rings across the longitudinal section of the stem in a systematic way. The pith at the center and then the heartwood that is made up of dead cells and next the sapwood that carries water, minerals and the glucose from roots to leaves. Then the very thin layer of living cells called the cambium is placed. These are the manufacturers of the wood, this layer is covered with a protective layer named the bark, the layer

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exposed finally to the nature. These concentric rings represent the number of years per layer. These rings are known as growth rings.

There are methods of timber sawing practiced around the world which contains different physical and mechanical properties. A standing timber converts to a saw logs conversion proceeding to a sawn timber requires a sequence of manufacturing process. There are few common sawing techniques practiced such as ordinary sawn or flat sawn, quarter sawing, rift or radial sawing, tangential sawing that was sawn inter related with the grain orientation. When considering the diameter of the log, it is more or less self-possessed of a nested cylinders of grain distribution. They are visible at the end of the log as growth rings. Depending on where the saw passes through a log, the grain pattern orients differ. In this case diameter of the log directly effects to define the sawing pattern. These lines together contribute to communicate the material characteristics. Since that wood has become an anisotropic material where it contains different properties from different directions, these influence on generating the growth stress on the timber. The growth stresses are very important during the sawing process to determine the appropriate application of the structural component [2].

The ability to conduct an assessment of the condition of heritage timber structures mandates a deep understanding of their past and current states, including aspects of their conservation, maintenance and use [3]. The collection of comprehensive data from specific different typological structures are aimed at creating the knowledge base for a future timber construction typologies and technologies. Construction material assessment and the structural assessment is also the first step toward an intervention that might itself range from mere preservation of an artistic artifact to the full rehabilitation of a structural function and material library in order to preserve it or adapt it for future use.

1.1. Ambalam *structures*

An *Ambalam* structure is an open colonnaded rectangular or a square shape, hip roofed space, introduced as a prestigious building type that comes under vernacular architecture in Sri Lanka. The basic task is to provide shelter for a comfortable stay to a considerable time for travelers. These were allocated to charitable services commenced by the villages under the patronage of the village head or the chieftains. Ambalam conferred the travelers as a landmark to accomplish the journey and a public gathering place for the villages.

Assessment of exposed historic timber structures, encompassing the fields of wood science and technology, structural engineering, architecture related to the field of construction is important. This paper presents a review of six *Ambalam* structures where the major construction material is timber with a history of more than 50 years. The scope of the study is to identify and analyze the saw pattern followed by the medieval constructor and conclude how the saw pattern influence toward the service life of the structure. Thus, this paper highlights the relationship between the grain orientation and the saw pattern influencing when utilizing timber for specific structural components.

1.2. Growth rings and grain distribution

Tree ring analysis is a potential tool for obtaining information on vast range of parameters. As it may provide information about the affiliation between growth and environmental variables such as climate and allows the detection of past environmental conditions changes, subsequently may aid in understanding forest dynamics. Annual rings exist in trees where the climate halts growth at some point during the year. Dozens of very thin rings in a year are created in tropical forests as and never the same number from one year to the next. Therefore, it is frequently difficult, even impossible, to distinguish them with the naked eye [4].

Orientations of the cell fibers in wood is referred grains. The variation in size of the wood cells are referred to as texture. Therefore, these two terms are integrated with each other from the origin of a tree. Texture of wood can be classified mainly as fine textured wood and coarse textured wood. Some confusion surrounds what is meant by grain, texture and figure when used to describe the wood surface. The grain refers to the wood fibers relative to the length of the tree on the faces and edges of a piece of timber. Texture is the relative size and variations of the elements. Figure refers to the pattern on a board caused by the arrangement of the different elements and the nature of the grain [5].

1.3. Growth stress

Self-generated in the cambium during the cell maturation are introduced as growth stresses. Highest growth stresses are usually found during the formation of tension wood. High growth stresses are suspected to have more tension wood, while at least have wood that is different from less-stressed wood [6]. Growth stresses are present in all tree species [2,3]. The growth strains are the relief of growth stresses. Strain is the dimensional change per unit of the original length (tensile or compressive). With a given modulus of elasticity and within the proportional limit of elasticity, a greater strain results from a higher stress. Growth stresses are generally resolved in the longitudinal, tangential and radial directions, following the natural geometry of the trees. 'Lignin swelling' theory and the leading theories attempt to explain how growth stresses are generated. The 'lignin swelling' theory and the 'cellulose tension' theory are two proposed theories to designate that growth stresses arise during the lignification process of maturation of newly formed cells.

In general polymerization of lignin reasons contraction or swelling of wood cells in lateral directions [9–11]. Also elongation or shortening of fibers in their axial direction depend on the micro fibril angles in these cells [7,8]. According to the ‘cellulose tension’ theory, growth stresses are generated as a consequence of the contraction of micro fibrils in the newly formed cells. Meanwhile their continuing crystallization is inhibited by the deposition of lignin [12,13]. The endless formation of growth stresses during tree growth results in an uneven and continuously changing distribution of stresses across tree stems [2]. Growth stress management and a thorough knowledge would have both a national and global economic significance.

Hence, the objectives of this study are to,

i. Analyze the prevailed log sawing techniques practiced in Sri Lanka.
ii. Investigate the influence of the sawing technique on the service life of the structure.
iii. Investigate the influence of the sawing techniques on load bearing and structural stability.
iv. Analyze the best sawing techniques which leads to a higher resistance of wood deterioration and its service life.

2. Materials and methodology

2.1. Materials

Six *Ambalam* structures were considered where the main construction material is timber. These six *Ambalam* structures were identified in different areas. *Giruwa Ambalama* is located in Aluthnuwara Dedimunda Dewala premises (Fig. 1). Padiwita Ambalama is located in Kumbiyagoda road, Higula. It is believed to be built during the Kandyan kingdom, before the British invasion (Fig. 2). *Karagahagedara Ambalama* is located in Kurunegala road, Narammala (Fig. 3). *Panavitiya Ambalama* is situated in Dangolla in Dambadeniya (Fig. 4). *Rukula Ambalama* close to *Giruwa Ambalama* in Aluthnuwara (Fig. 5). *Badulla Ambalama* lies inside the Kachcheriya land in the middle of the Badulla town (Fig. 6). These *Ambalams* were believed to be built in between late 13th and 19th centuries. The timber architectural remains include species like Jac, while some species are still unidentified (Chart 1).

2.2. Selection of structural elements

Exposed cross sections of the structural components representing the grain pattern were chosen. The selected materials of the study are relatively out of complete timber structures. Basically, they contain a similar colonnade structure constructed using two different techniques where it is placed on stones maintaining a significant stability and balance representing the *Tampita* concept, while the other representing the structure placed on a simple podium. Timber buildings under *Tampita* concept were constructed on bearers and floor joist. On this the edges are a good exposed section to study the grain distribution of the utilized timber. Therefore, structural components such as bearers, joists, wall plates and rafters are analyzed within the scope of this study.

2.3. Documenting the cross sections

Close up photographs were taken perpendicular to the surface which helps to map the grain distribution relevant to the study using a Canon 80 D, 18 – 135 mm lens and 50 mm, 500 mm lens. A basic specific grid and a code was followed to plot the timber sections to make a flow and to make the procedure a formal document. The grain distribution was then plotted using photographs on Autodesk AutoCAD software.

Fig. 1. *Giruwa Ambalama.*

Fig. 2. *Padivitiya Ambalama.*

Fig. 3. *Karagahagedara Ambalama.*

2.4. Mapping the growth ring distribution

Initially the mostly visible arcs were drawn and then the most justifying center of that arcs were figured out. Therefore, a line was drawn to denote the axiom length from center to the edge of the section of the structural component. A diagonal from the center to the edge of the section will justify a continual plotting area. Then match the closes proximity to tally the arc which meets the diagonal and continue drawing the circles matching with the arches. And trace the grain distribution very thoroughly (Map 1).

Fig. 4. *Panavitiya Ambalama.*

Fig. 5. *Rukula Ambalama.*

Fig. 6. *Badulla Ambalama.*

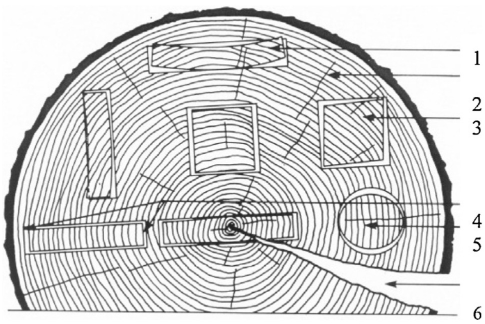
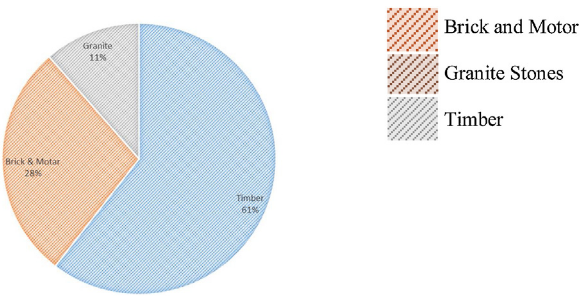


Chart 1. Utilized constructive material.



Map 1. Demonstrating on analyzing the grain Distribution.

Fig. 7. A: *Panavitiya Ambalama* (bearer); B: *Badulla Ambalama*; C and D – *Giruwa Ambalama* (king rafter, rafter, bearers).

3. Visual inspection and documentation

All six selected structures are framed structures; the loads transfer through the roof to beams, beams to columns and columns to the footings, whereas the specific *Tampita* structure, which was a prevailed building typology under vernacular architecture transfer the load from roof to the beam. Conferring to the medieval timber architecture, "*Pekkada*" is a structural element in the joinery of the beam and the pillar interference where it handles the load transfer to the ground. This significant intermediate structural bracket is still visually seen in Ambalam structures. The load is transferred from columns to bearers and finally from bearers to the footings which are stumps/stone (Fig. 7).

Timber bearers are one of the major structural components that directly attach to the stumps that undertake the responsibility on the support to the entire framework. *Pandivitya Ambalama* is a *Tampita* type construction established in vernacular architecture where the structure is placed on the stones or stumps. The most commonly utilized size of the bearer in *Padivitiya*, *Panavitiya* and *Karagahagedara Ambalama* was approximately 152.4 mm by 152.4 mm, 203.2 mm by 203.2 mm and 279.4 mm by 279.4 mm (timber spices – unidentified). The visual analysis illustrates that most of them were sawn with the closet approach proximity to the center of the log or the pith. Distribution of the growth stress around the trunk is uneven in a tree. But considerably there is growth stress distribution perpendicular to center which means from pith to bark of a tree [14]. The experienced carpenters who created these significant structures that lasts for approximately 50 years or more, had predicted that the timber suits for the bearers will long last as it is sawn from close to the pith. This is clearly evident with living samples in *Pandivitya Ambalama* that is still in good condition. Distribution of growth stress is as pith with compression, changes to neutral in the mid area and tension is distributed close to the bark. The timber sawn to a 200 mm × 200 mm was taken including the minimum tension stress of a log along with the center where it includes a higher percentage of compression and neutral stresses. Also this grain pattern grid has been considerably adding a unique strength and had helped on load distribution on the bearer (Fig. 8).

Further, since it concludes that a majority has sawn as a distribution from center to the bark, it represents the approximate size of the tree and the availability of trees that suit for structural usability in the particular context. The

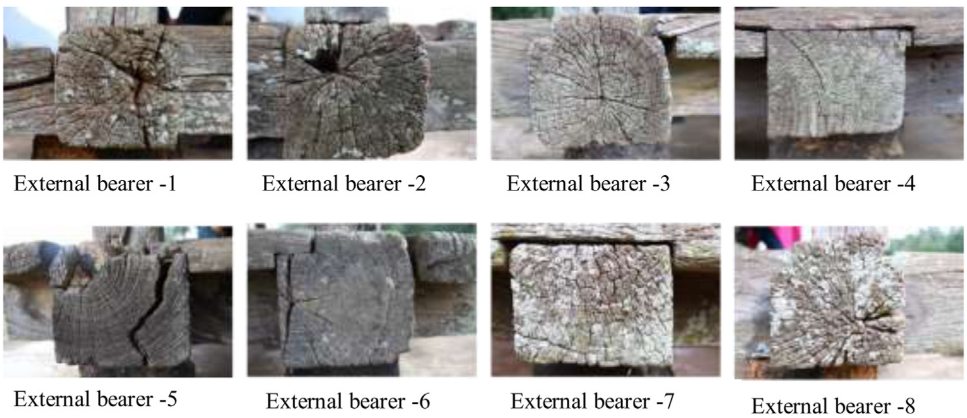


Fig. 8. *Padivitiya Ambalama* external bearers.

Fig. 9. Joint detail of the *Badulla Ambalama*.

Fig. 10. Rafters of *Giruwa Ambalama*.

difference in texture was caused due to the distribution of pores, size and the cell arrangements or rays. Timber is an anisotropic material with vibrant properties in different directions with its makeup of oriented cell fibers. Majority of the cell fibers are oriented parallel to the longitudinal axis of the tree. Subsequently it has proved that the strength parallel to the cell fiber direction is comparatively better when the strength perpendicular to the cell fibers direction is low. In *Ambalam* structures bearers are particular in the compression strength perpendicular to the cell fiber direction that needs to be taken into account (Figs. 9 and 10).

In *Tampita* structures the entire structural weight lies on the *tamas* or the stones where the bearers are placed. Structure is balanced significantly without any connection with the bearer and the stone. When the timber bearers are subjected to a compression load that comes from holding the entire roof structure, the load perpendicular to the cell fibers react by causing considerable deformations crushing the cell fibers. The orientation of the cell fibers play a major role to minimize the deformation caused due to the load (Map 2).

4. Results and discussion

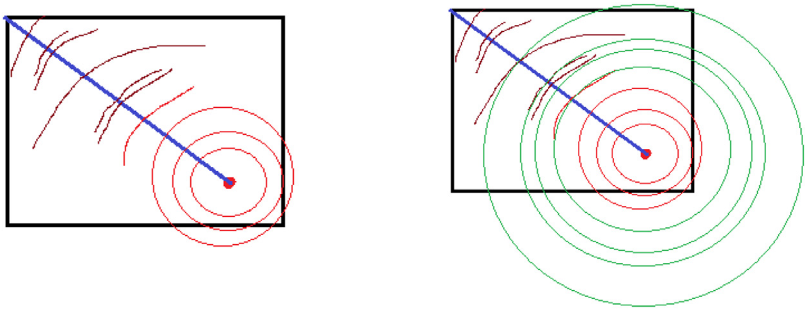
Individually plotted grain distribution finally gained to a single illustration to do an analysis. (Maps 3–14 are the following grain maps of the six case studies.

5. Conclusions

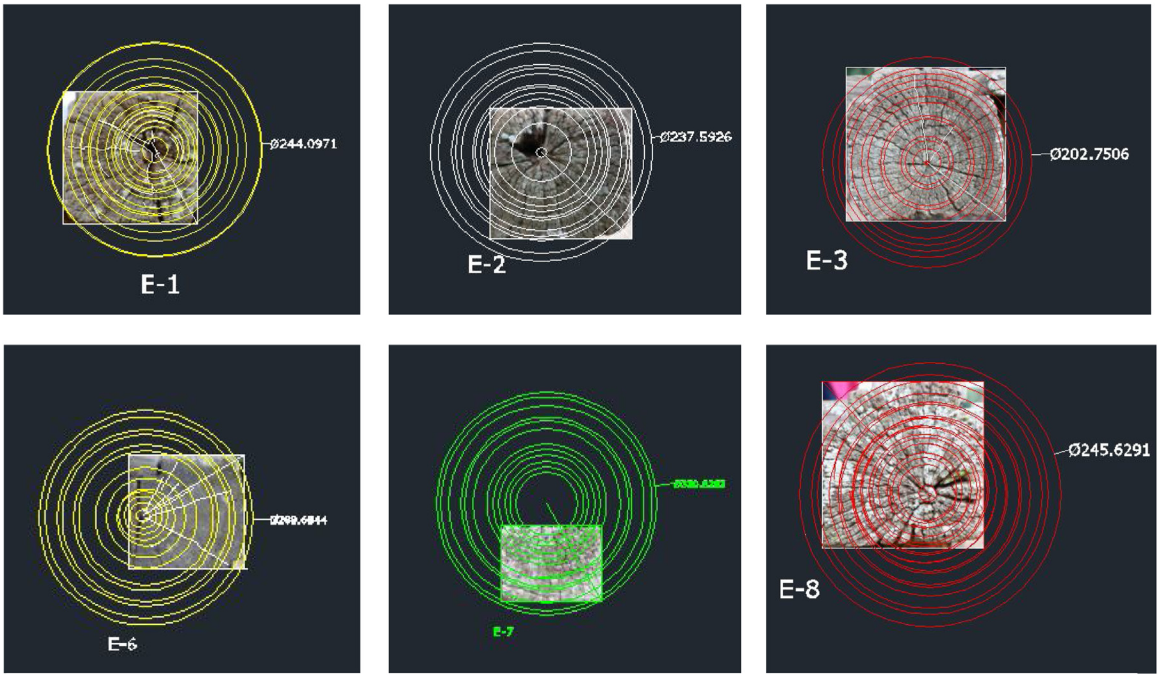
This study identifies four different sawing patterns specific to a particular structural component such as the bearer, joist, rafter and wall plates (Maps 15–22).

Thorough observations conclude that a majority of the deterioration were caused among the identified types are from outer surface to the inner surface where it emphasizes the service life variation from pith to the bark (Maps 23–26)

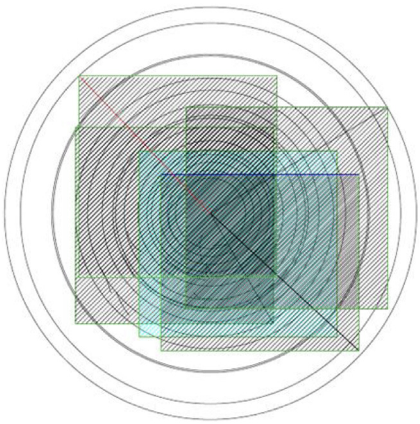
Wood consist of vibrant set of properties in different directions since it is an orthotropic material. Structurally wood is considered as an anisotropic construction material. Among the above-mentioned stresses, the compression strength that is perpendicular to the grain is an important parameter that determines the bearing strength as it depends on loading conditions. This study emphasizes that medieval constructors have use to grade the sawn material into strength classes by studying their applications. Among the utilized sawn orientations, type A and type D have been utilized more in main



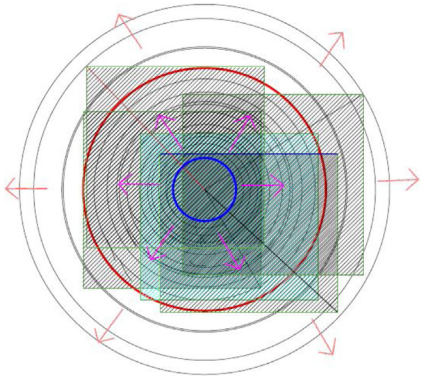
Map 2. Mapping the curves using AutoCAD software.



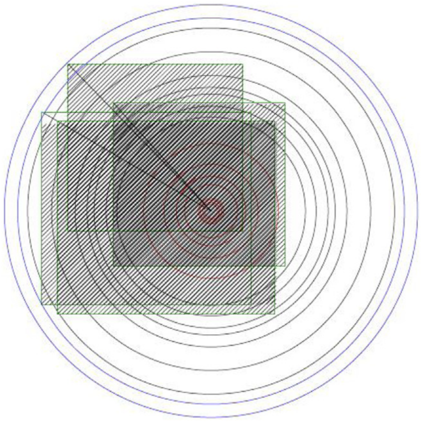
Map 3. Sawing location placed on the timber log external bearers (*Padivitiya Ambalama*).



Map 4. Stress zone on the cross section perpendicular to the grains (*Padivitiya Ambalama*).



Map 5. Sectional placements of the internal bearers (*Padivitiya Ambalama*).

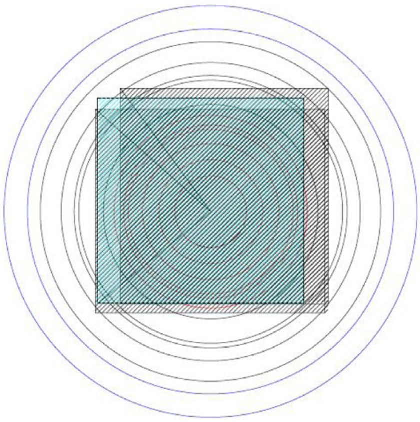


Map 6. Sectional placements of the internal bearers (*Pandivitya Ambalama*).

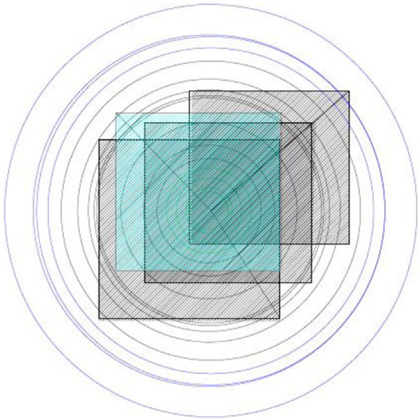
structural components where higher degree of load distribution has taken place. Type C has been used for rafters and reapers where there is a lesser load distribution. Type A and type D consist of high percentage of compression and neutral stresses whereas type B and C consist of tension comparatively to the other two.

The resistance for physical and mechanical forces depends on the microstructure of wood. Strength is influenced by the dimension of the structural elements of wood. This means more elements and thicker cell walls contribute to a higher wood strength [15].

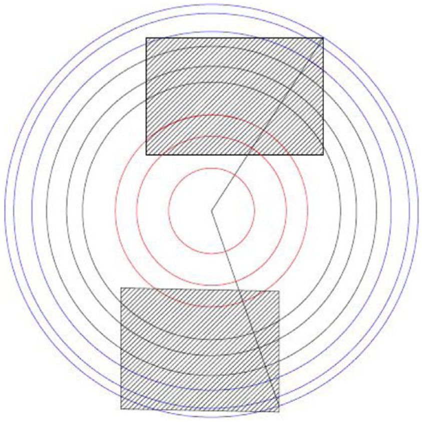
Radial conduction of water, organic substances and minerals are processed through medullary rays. The main function of them is to transport the substances from pith to the bark of a standing tree. These medullary rays positively influence during



Map 7. Sawn log distribution corresponding to the center (*Panavitiya Ambalama*).



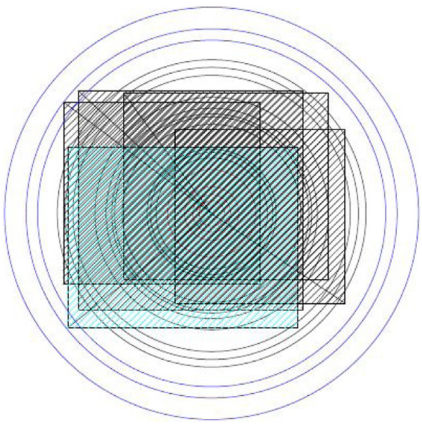
Map 8. External bearers sawn log distribution corresponding to the center (*Karagahagedara Ambalama*).



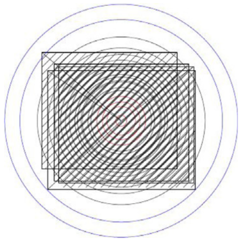
Map 9. External bearers sawn log distribution corresponding to the center (*Karagahagedara Ambalama*).

compression perpendicular to the grain. Comparatively deciduous wood that are from giant flowering trees with broad leaves that drop their leaves during a particular time period consist of wide rays in a radial direction and has a higher compression strength [16].

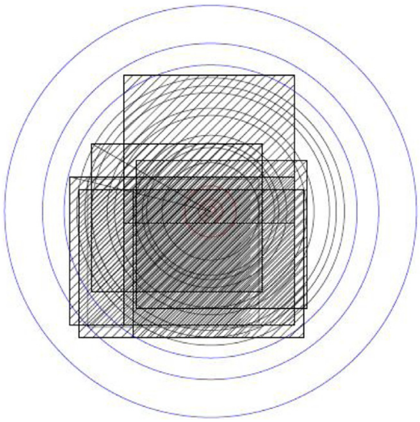
Statistically the density variation between trees are significant. Axial and radial variation of wood density are significant characteristics when selecting the sawing pattern for the relevant structural component. This has larger influence on the behavior of the wood that is directly proportionate to strength. Axial density variation within a tree is negligible. The density



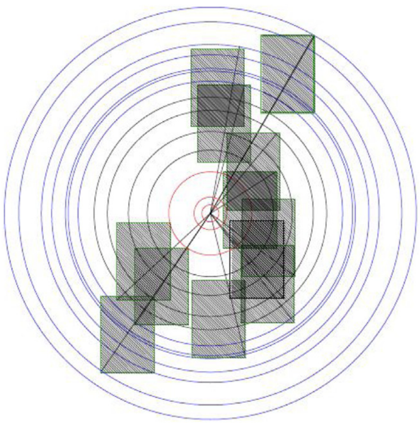
Map 10. Sawn log distribution corresponding to the center (*Giruwa Ambalama*).



Map 11. Wall plate sawn log distribution corresponding to the center (*Giruwa Ambalama*).



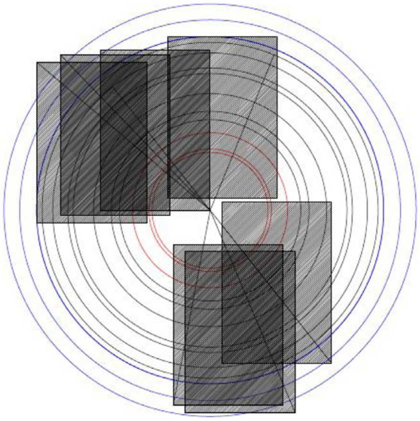
Map 12. Rafters sawn log distribution corresponding to the center (*Giruwa Ambalama*).



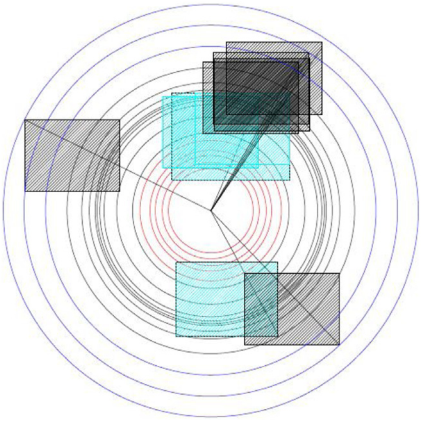
Map 13. Rafters sawn log distribution corresponding to the center (*Rukula Ambalama*).

variation on the radial direction within a cross section is one of the main origins. The density decreasing from pith to the cambium in radial variation corresponds. Density has to be defined in terms of moisture content, wherein the mass and the volume were dependents of water content of a tree. Water content and the moisture level in timber is a high impacting factor to the properties of wood. These properties together conclude facts on to the strength to the timber as an anisotropic construction material. It is clear that medieval constructors had a clear understanding on this physical property where they have decided the sawing pattern for the higher loading structural components sawn close to the pith where that captures more volume with a higher magnitude knowing that magnitude of the density variation will be affecting on the service life of the structural components. This is obvious with the existing timber components studied. This study has identified four types of sawing orientations. Among the four types type D is the strongest component where it consists of the highest density of the log as it distributes with the core.

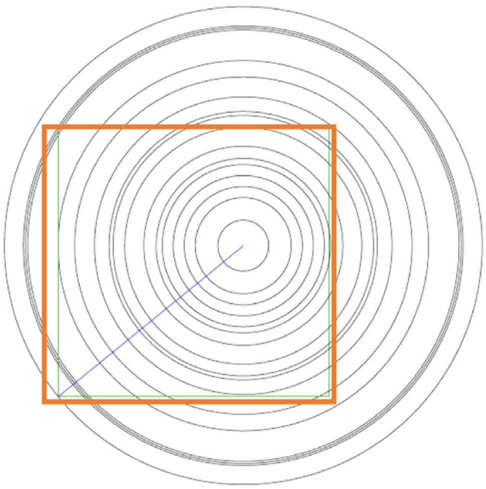
$$\text{Type } D_{density} > \text{Type } A_{density} > \text{Type } B_{density} = \text{Type } C_{density}$$



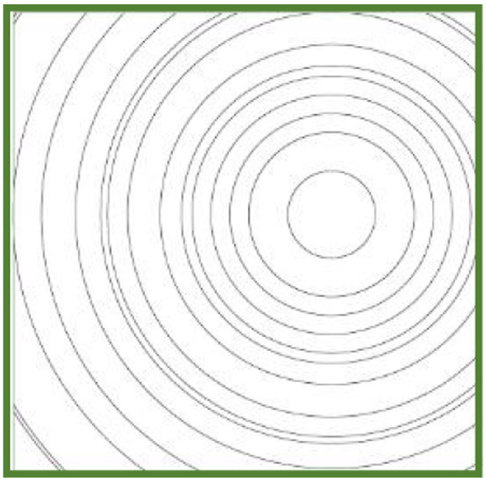
Map 14. Sawn log distribution corresponding to the center (*Rukula Ambalama*).



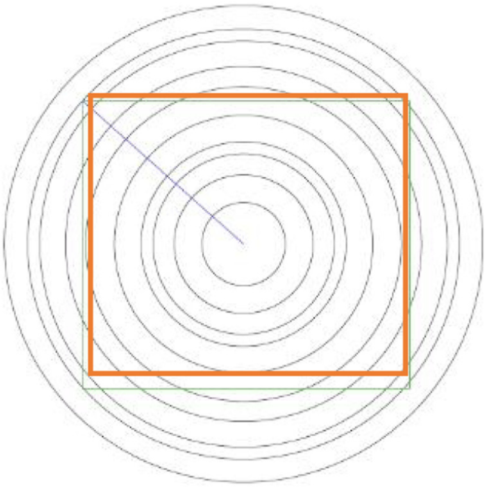
Map 15. Type A.



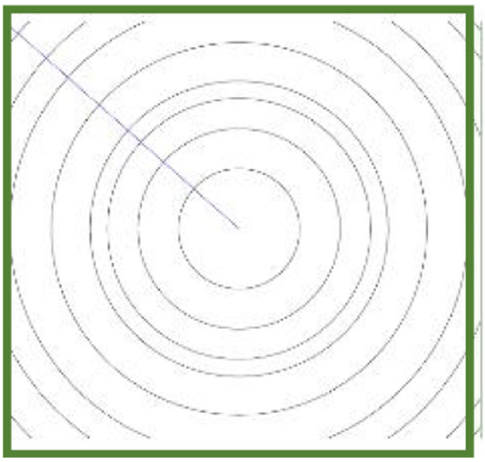
Map 16. Grain distribution model.



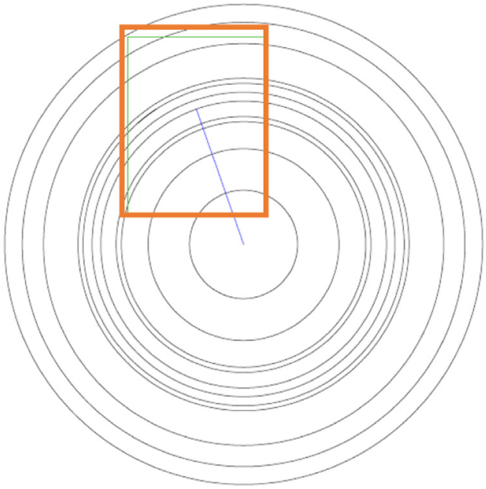
Map 17. Type D.



Map 18. Grain distribution model.



Map 19. Type C.

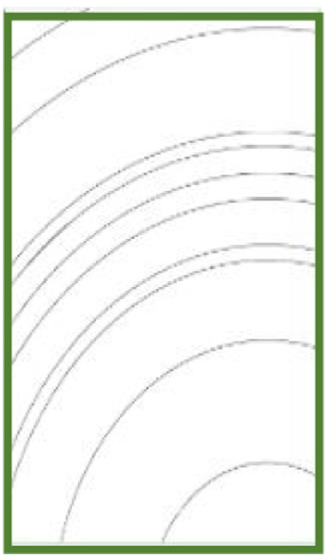


Map 20. Grain distribution model.

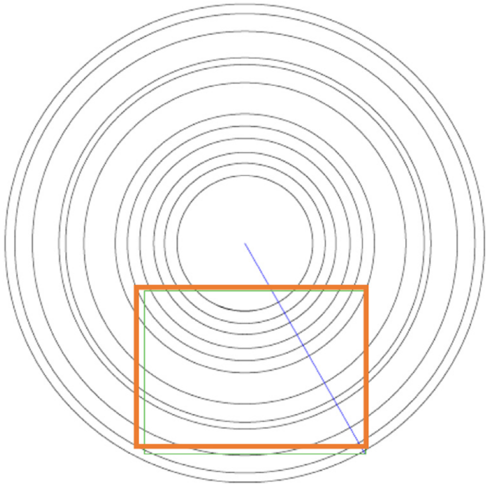
Wood is a hygroscopic construction material. Hygroscopic is the property of wood to invite moisture from the surrounding atmosphere. The motivation for moisture entering into the mass of wood is due to the desirability of water molecules by the hydroxyls mainly on cellulose. This results in a monomolecular layer of water formed and detained by these hydroxyls with sturdy hydrogen bonds. After formation of this layer it creates an effect in pushing apart chains of cellulose molecules in the amorphous regions and between the crystallites of the micro fibrils. Then wood starts to swell [17]. When it releases the wood starts to shrink. This phenomenon affects toward the mechanical property of the particular timber within its entire service life (Map 27).

The wood movement is highly influenced by grain orientation. Subsequently, wood absorbs water when the relative humidity increases and loses water when the relative humidity decreases. With this phenomenon when wood absorbs moisture it swells and as it loses moisture it shrinks. This swelling and shrinking varies across the three main planes of the wood grain: tangential, radial and longitudinal. The swelling or shrinking of longitudinal grain is so small, that it can be ignored and assume that there is no wood movement along the length. These timber structural components have highlighted that the cross-grain behavior of wood can be vital to safety and serviceability of the structure (Map 28).

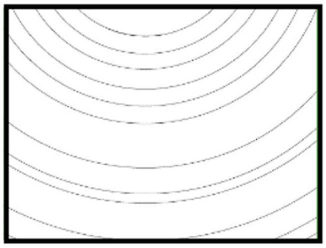
Generally, deflection of any bearers or beams depends on its support configuration, and its loading configuration: the amount and the position of the load, the span of the bearer or beam, the size and the shape of its cross section and the nature of the construction materials. The placement of the structural components with reference to grain orientation has influenced to avoid long-term deflection. Also, the medieval constructors have sawn the bearers with a larger depth than its width



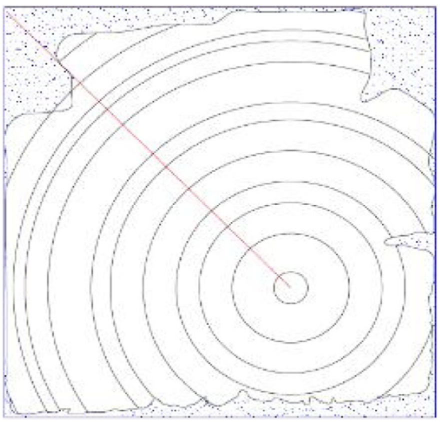
Map 21. Type B.



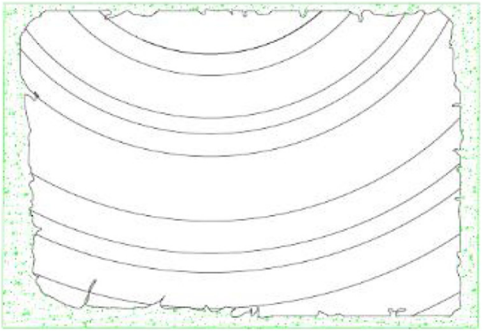
Map 22. Grain distribution model.



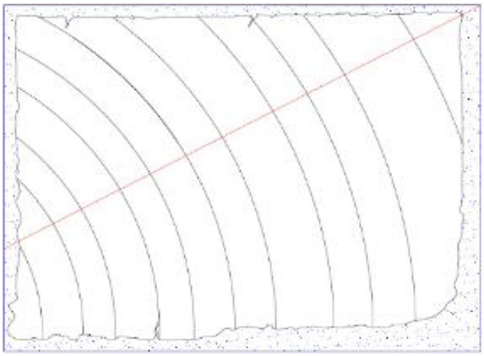
Map 23. Type A.



Map 24. Type B.



Map 25. Type C.

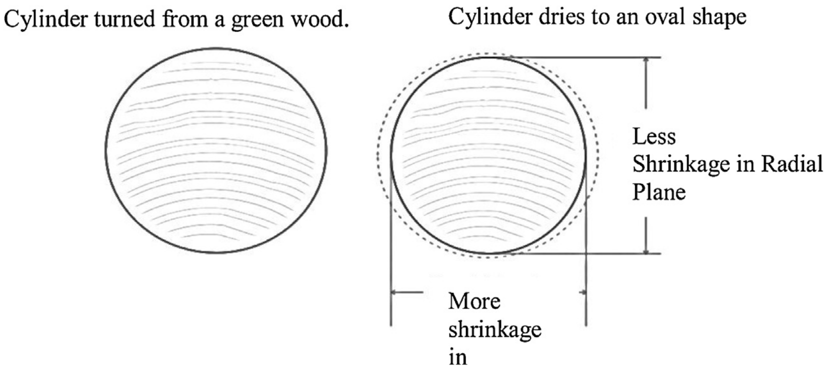


Map 26. Type D.

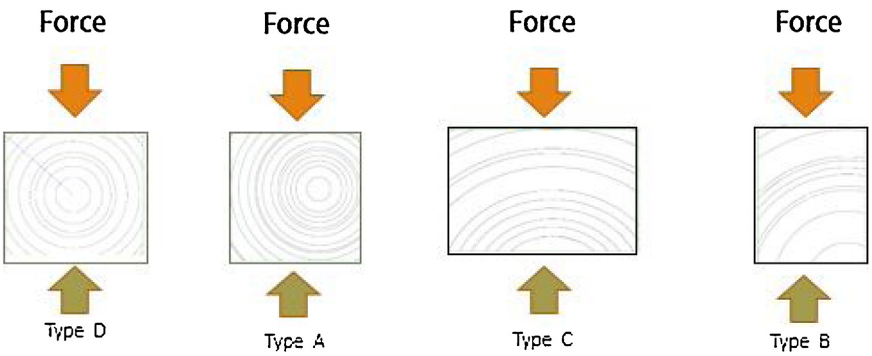
Map 27. Shrinkage in the tangential plain.

within the construction to overcome the deflection. All structural components applications were done in a way which the force attends parallel to the grains or the annual rings, where the radial plane shrinkage is very less and the effect toward the load is very less. Further, it is clear that medieval constructors were knowledgeable on the deformation caused by the shrinkage and swelling precisely through experience. Hence observations and analysis highlighted that the majority of the components were sawn as the curves orient concentric to the opposite of the force applied (Map 29,30).

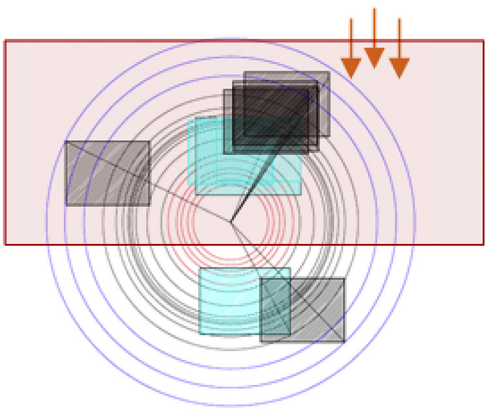
Grain orientation is important for three reasons. The direction of the grain affects the amount of deflection that occurs when loads are applied. It compromises on load bearing ability. Load bearing timber is stronger when forces are applied parallel to the grain than when force is applied perpendicular to the grain.



Map 28. Force applied on the identified model types.



Map 29. Sawn log distribution corresponding to the center (*Rukula Ambalama*).



Map 30. Characteristic shrinkage and distortion of wood (curatorial care of wooden objects, NPS Museum handbook Part 1, pp. N6).

Construction material assessment and the structural assessment of *Ambalam* structures with a history of more than 50 years is also the first step toward an intervention that itself range from mere preservation of an artistic artifact to the full rehabilitation of a structural function and materials unique to Sri Lanka. Medieval constructors had a vast knowledge through experience on construction material manipulation on specific materials resembling timber. Revealing the adequate knowledge utilized within the practice of construction field in a tropical country with reference to living sources creates a database of material history of more than 50 years exposed to nature. Therefore, this study creates access to researchers to approach construction materials in a novel way in future.

Conflict of interests

M.S Mendis , R.U Halwatura, D.R.K Somadeva, R.A. Jayasinghe, M Gunawardana declare that no conflict of interest.

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