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Construction Material Selection Criteria for Timber Gridshell Application: A Literature Review

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ABSTRACT

Timber gridshells have the potential to be a sustainable and cost-effective solution for long-span applications and free-form architecture. Despite this, their overall use has been limited, and there is a lack of research focusing on their construction materials. This literature review aims to investigate timber gridshells and their construction materials to identify the criteria used in selecting suitable materials for gridshell applications. A review of peer-reviewed scientific articles, books, and theses was conducted to gather information on timber gridshells, construction materials used in gridshells, timber used in active bending structures, and building standards. The research findings identified six main factors that are important when selecting a suitable material for timber gridshell application: structural strength and strength grading, bending strength and behaviour, bending strength/bending elasticity ratio, durability, commercial availability, and cost. These findings are also discussed to identify the characteristics that make a material suitable for timber gridshell applications, depending on the gridshell's context, whether in a tropical or international context. This review serves as a necessary reference for architects and engineers when selecting materials for their timber gridshell projects, providing insight into the selection criteria for construction materials and sharing information on the material properties of suitable timber gridshell materials.

Keywords: Timber gridshell; construction material; material selection; selection criteria

INTRODUCTION

In recent years, the architecture and construction industry has shifted towards sustainable construction and building due to environmental and economic reasons. Designing structures with minimum use of resources and renewable materials can be a suitable option for achieving this goal. Timber gridshells offer a great combination for sustainable architecture, as wood is an important renewable material that has been used extensively in the built environment (Foliente 2000). Gridshells are also a great option for long span buildings, offering both aesthetic and structural benefits compared to other long span structures and shells (Malek 2012; Tayeb et al. 2015; Naicu et al. 2014; Fernandes et al. 2016; Science et al. 2003; Ghiyasinasab et al. 2017; Naicu 2012; Harris et al. 2003; Kuijvenhoven 2009). Due to their efficient use of material, single layer members, and openings, gridshells are lightweight and spacious structures that have a minimal footprint on natural resources (Malek 2012). Despite the advantages of using timber gridshells compared to other long span structures, a limited number of them have been built due to their complexity. This complexity is linked to the challenges of the design and formation process, including the size, design, construction material, technology, number of involved parties, construction skill sets, and construction experiences (Ghiyasinasab et al. 2017). The lack of information, tools, guidelines, and instructions to define the complexity of gridshells is also a major obstacle (Pirazzi & Weinand 2006). Previous research on timber gridshells has focused on the design and simulation process, while omitting construction materials and material selection (Malek 2012; Tayeb et al. 2015; Naicu et al. 2014; Fernandes et al. 2016; Science et al. 2003; Ghiyasinasab et al. 2017; Naicu 2012; Harris et al. 2003; Kuijvenhoven

2009). Some studies have mentioned construction materials as a part of their research, but none have studied it as a main focal point (Collins & Cosgrove 2016; Lienhard 2014; Pone et al. 2013). Furthermore, no previous studies have been conducted on timber gridshell construction materials in a tropical context. Therefore, this literature review aims to focus on timber gridshell construction materials and material selection in both international and tropical contexts.

FIGURE 1. Weald and Downland Gridshell
Source: Image credit:cc-by-sa/2.0 -Inside the Weald and... by Hugh Chevallier-geograph.org.uk/p/258909

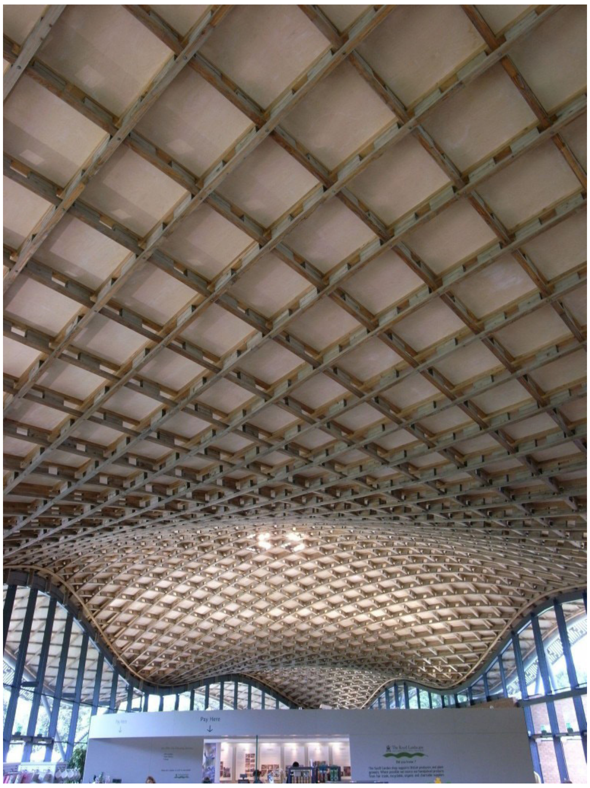

FIGURE 2. Savill Building
Source: CC BY-SA 3.0 - Interior of the wooden gridshell... by Oosoom - https://commons.wikimedia.org/wiki/File:Saville_ Building_roof_interior_long.jpg

Shell" and "reticulated shell" have been used to describe gridshells, these terms are more commonly used by scholars than by practising engineers (Malek, 2012). There is a debate about whether a gridshell should be defined according to its structural action or by its construction process (Malek 2012).

Dickson and Harris (2008) define a gridshell as "a three-dimensional structure that resists applied loads through its inherent shape. If regular holes are made in the shell, with the removed material concentrated into the remaining strips, the resulting structure is a gridshell." Gridshells can be divided into two main groups: bending active and bending inactive (Collins & Cosgrove 2016).

A bending active gridshell is a shell whose structural components must be deformed by bending to achieve the structure's final shape. Therefore, bending pre-stress is created in the members during forming (Collins & Cosgrove, 2016; Lienhard et al. 2013). On the other hand, a bending inactive gridshell is a structure whose structural components do not need to be deformed to create its shape.

According to Dyvik et al. (2021), there are three types of gridshells:

Bending active gridshells, such as the Mannheim Multihalle by Frei Otto, are among the most well-known examples (Happold and Lindil, 1974). Discrete or rigid gridshells, such as the British Museum Great Court and the Pods Sports Academy, are examples of this type (Sischka 2000).

Smooth gridshells made of pre-curved elements, such as steel or Glulam, such as the Centre Pompidou Metz, are well-known examples (Aguilar 2022).

METHODOLOGY

To better understand timber gridshells in construction and their material selection, peer-reviewed scientific articles, theses, and books were consulted. These sources provided information on timber as a construction material and gridshells as a structure. Specifically, the following questions were investigated:

1. What are the material selection criteria for timber gridshells? Are there any patterns or recurring factors in the materials selected for past timber gridshell projects?

2. What characteristics make a material suitable for use in timber gridshells?

To conduct this research, databases such as Science Direct, Researchgate, and Google Scholar were used to search for relevant literature. Articles were selected and analysed, and additional sources were found through their references. Multiple M.S. theses and Ph.D. dissertations related to timber and gridshells were also examined. Most of the selected articles were from the years 2000 to 2022 to ensure up-to-date information.

Through this literature review, definitions of gridshells and active bending structures, information about construction materials, and suitable materials for timber gridshell application were gathered. The importance of including not only literature related to gridshells and timber gridshells, but also relevant building and construction codes and references related to timber use in construction and material selection was also highlighted. By analysing both timber gridshell-related literature and building and construction codes, criteria for selecting materials for timber gridshells were identified.

The next step was to investigate the suitable timber gridshell materials with respect to their context. Figure 1 summarises the stages of literature review methodology.

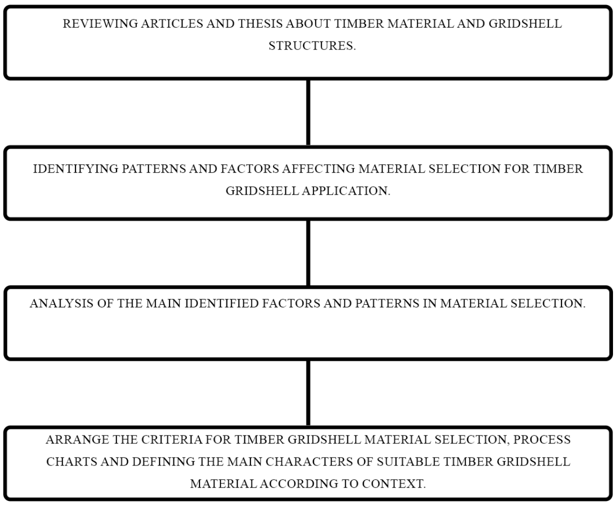

FIGURE 3. Stages of literature review methodology

FINDINGS

The literature review has identified six factors as criteria for selecting timber gridshell materials. These factors are: structural strength and strength grading, bending strength and bending behaviour, bending strength/bending elasticity ratio, durability, commercial availability, and cost. The criteria were identified by analysing both timber gridshell materials literature and timber construction codes. Table 1 provides a summary of the investigation on timber gridshell material selection criteria.

TABLE 1. Investigation on Timber gridshell material selection criteria

		Timber gridshell material selection criteria					
No	Reference	Structural strength and strength grading	Bending strength and bending behaviour	Bending strength/ bending elasticity ratio	Durability	Commercial availability	Cost
1	BS 5268 (2002)	x			x		
2	BS EN (1990)	x			x		
3	Ashby (1999)		x				
4	Eurocode 5 (1995)	x			x		
5	EN 338 (2003)	x					
6	EN 350 (2016a)				x		
7	EN 350 (2016b)				x		
8	Collins & Cosgrove (2016a)	x					
9	Collins & Cosgrove (2016b)		x				x
10	Tayeb et al. (2015)		x				x
11	Pone et al. (2013)		x		x		
12	MS 544 (2001)	x					
13	Lara-Bocanegra et al. (2020)	x	x		x	x	x
14	Lienhard (2014)		x				

STRUCTURAL STRENGTH AND STRENGTH GRADING

Strength grading involves arranging timbers with comparable mechanical properties into strength classes, which are characterised by a number of engineering design properties. This allows for the specification of a desired strength class and the use of its strength properties in design calculations. EN338 includes the mechanical property values for density, strength, and stiffness for the strength classes used throughout Europe (CEN 2003a; Moore 2011). The strength classes are named based on the bending strength properties. In the British standard BS 5268 Part 2, which is similar to the European standard and sets the tone for the international standard for wood grading, wood species are grouped into two main categories: coniferous or softwoods and deciduous or hardwoods. The strength grading in BS 5268 Part 2 ranges from C14 to C40 for softwoods and D30 to D70 for hardwoods. Table 2 illustrates EN 338 timber strength grading.

In Malaysian standards, the strength classes of tropical hardwood timber are categorised into two strength groups (SG): A to D, which are based on compression strength parallel to the grain (Table 3); and SG1 to SG7, which are related to grade stresses (Table 4) (Ashaari 2017).

Structural strength and strength grading are important in terms of the minimum structural strength required for each construction application. For example, C14 can be used for structural components, but C24 is used in structures that require high strength, such as roof trusses and floor systems (Wood Grades, n.d.). In Malaysian construction codes, the minimum strength class for structural and roof elements is required to be SG C or higher based on A to D classes, or SG4 or higher (e.g. SG3, SG2 and SG1) based on SG1 to SG7 classes (MS544: Part 2: 2001).

TABLE 2. EN 338 timber strength grading

Wood class	Characteristic Bending Strength(N/mm^2) (MOR)	Compression Parallel (N/mm^2)	Compression Perpendicular (N/mm^2)	Mean modulus of elasticity (N/mm^2)	Density (kg/m^3)
C14	14	16	2.0	7000	350
C16	16	17	2.2	8000	370
C18	18	18	2.2	9000	380
C24	24	21	2.5	11000	420
C27	27	22	2.6	11.500	450
C30	30	23	2.7	12000	460
C35	35	25	2.8	13000	480
C40	40	26	2.9	14000	500
C45	45	27	3.1	15000	520
C50	50	29	3.2	16000	550
D18	18	18	7.5	9.500	570
D24	24	21	7.8	10000	580
D30	30	23	8.0	11000	640
D35	35	25	8.1	12000	650
D40	40	26	8.3	13000	660
D50	50	29	9.3	14000	750
D60	60	32	10.5	17000	840
D70	70	34	13.5	20000	1080

Source: (EN 338 2003)

TABLE 3. Malaysian strength group based on compression strength parallel to the grain

Strength group		Compression strength parallel to the grain (N/mm^2)
A		Greater than 55.2 extremely strong
B		Greater than 55.2 extremely strong
C	C	27.6 - 41.4; moderately strong
D	D	Less than 27.6; weakest

Source: (MTIB, 2008)

TABLE 4. Malaysian timber strength grouping based on grade stress MS 544 part 2 (2001)

Wood class	Bending Strength (N/mm^2) (MOR)	Compression Parallel (N/mm^2)	Compression Perpendicular (N/mm^2)	Mean modulus of elasticity (N/mm^2)
SG1	26.5	22.5	3.74	18800
SG2	18.3	18.5	3.05	16800

continue ...

... cont.

SG3	15.9	14.1	2.09	14300
SG4	13.2	11.1	1.65	11000
SG5	9.5	8.5	1.14	9100
SG6	8.9	6.9	1.02	7300
SG7	6.5	5.4	0.62	6600

Source: (MS 544 part 2, 2001)

BENDING STRENGTH AND BEHAVIOUR

Elasticity is a material's ability to return to its original shape after minor deformations. However, when subjected to higher levels of stress, it may experience plastic deformation or fail (Kretschmann, 2010). The modulus of elasticity, or E, indicates a beam's ability to resist deflection or a column's ability to resist buckling (Kretschmann, 2010).

The modulus of rupture is a standard for timber strength that represents the maximum bending stress and strength of wood. It is influenced by the size of the beam and the method of loading (Kretschmann 2010).

The bending modulus of elasticity measures a material's resistance to bending deflection compared to its strength, while Young's modulus measures its resistance to lengthening or compressing under tension or compression (Cai & Ross 2010).

In isotropic materials, such as metals, the bending modulus of elasticity is similar to the compressive or tensile modulus of elasticity (Young's modulus). However, in anisotropic materials like wood, these scales may not be equivalent (Tsai 1979; Askeland 2017). When selecting a timber gridshell material for bending applications, elasticity, modulus of elasticity, and modulus of rupture are the most important factors to consider.

BENDING STRENGTH/BENDING ELASTICITY RATIO

When selecting a suitable construction material for active bending structures, the most important factors are bending strength (MOR), elasticity (MOE), and the combination of the two.suitable materials have a high MOR/MOE ratio (Lienhard 2014, Collins & Cosgrove 2016, Pone et al 2013). These materials should have a low elastic modulus (MOE) to allow bending with appropriate stress, and a high bending strength (MOR) to achieve tight curvatures (Collins & Cosgrove 2016).

For strained gridshell applications, species with good mechanical properties - especially high bending strength and modulus of elasticity - are suitable because a smaller radius of curvature can be used. These materials also enhance structural anti-buckling behaviour, which is usually essential in the design of bending active structures (Lefevre et al. 2015, Lara-Bocanegra et al. 2020).

Therefore, it can be concluded that a certain level of modulus of elasticity is desirable in timber gridshell materials - not too high that bending into shape becomes difficult, but not too low that the structure would face buckling.

DURABILITY

Natural durability is related to the inherent natural resistance of wood counter biological degradation (e.g. fungal decay and insect attacks) ((Taylor et al. 2002, EN 350, 2016).

There are five classes that describe natural durability which are the following:(1) very durable; (2) durable; (3) moderately durable; (4) slightly durable; and (5) not durable (EN 350, 2016). Table 5 shows the EN 350 durability classes.

In Malaysia, natural durability is determined based on the performance of wood in "graveyard testing". This method involves burying test-sticks measuring 50 mm x 50 mm x 600 mm in a test ground and monitoring their performance over several years under specific conditions to group them according to their natural durability (Ashaari, 2017). Another method of testing the natural durability of wood is through accelerated laboratory exposure to deteriorating fungi (Findlay 1985; Ashaari 2017). This testing method involves exposing blocks of wood measuring 20 x 20 x 20 mm to worsen fungus and calculating the weight loss of the specimen after 16 weeks of incubation. This test uses four classes of degradation (Ashaari 2017).

TABLE 5. EN 350 durability classes

Durability class	Service life (years)
Class 1	Very durable more than 25 years
Class 2	Durable 15 to 25 years
Class 3	Moderately durable 10 to 15 years
Class 4	Slightly durable 5 to 10 years
Class 5	Non durable less than 5 years

TABLE 6. Natural durability classes in Malaysian standard based on (Findlay, 1985)

Classification	Service life under Tropical conditions (years)	Temperate conditions (years)
Very durable	More than 10 years	More than 25 years
Durable	5 to 10 years	15 to 25 years
Moderately durable	2 to 5 years	10 to 15 years
Non durable	Less than 2 years	5 to 10 years

COMMERCIAL AVAILABILITY

To minimise the budget of a project and offer options for choosing a suitable timber gridshell, there should be ease of access to construction materials in terms of transportation, information, and data. Hence, established and commercially available materials that are readily available and abundant can be a valuable option for timber gridshell material to save time, money, and for environmental and sustainability reasons.

The budget of a construction project can be divided into two parts: construction materials budget and labour costs (AGHAZADEH et al. 2019). When building an economical project, building materials cost can be decreased by using available and sustainable materials (AGHAZADEH et al. 2019, Fallah 2005). It is advised to use components already available in the construction industry that are affordable (Tayeb et al. 2015). The material selection challenges related to commercial availability are the lack of suitable timber products that are easily accessible on the market and the lack of timber with superior mechanical properties.

COST

The Malaysian hardwood species discussed are based on data from the Forest Research Institute of Malaysia (FRIM), Malaysian Timber Industry Board (MTIB), and Malaysian Timber Council (MTC). The prices of Malaysian hardwood, including light, medium, and heavy hardwoods, range from 1,200RM (mixed lightwoods) to 3,400RM per cubic metre, except for Chengal, which is priced at 9,000 RM to 12,000 RM. "Durable" species like Nyatoh wood start from 1,412 RM, while "Very durable" species range from 2,500 RM to 3,400 RM. For context, these prices are for green and dried timbers with high density and durability. Species like Balau, Giam, and Resak are very durable with excellent mechanical properties and density, and their prices range from 2,500 RM to 3,400 RM, with an average price of 3,200 RM.

In comparison, the prices of American woods range from 782 RM (173 USD) to 4,464 RM (988 USD) based on 2020 prices (Luppold & Bumgardner, 2021). The Durable and Very durable species' prices start from 3,434RM. However, most of these species are not durable, except for White Oak and Walnut, which are the most expensive at 3,434RM and 4,464RM, respectively. The American species discussed are FAS (first and second grade wood, which are the highest hardwood and timber grades in the US), Green timbers of White Oak, Red Oak, Hickory, Yellow Birch, Hard Maple, Soft Maple, Beech, Sweetgum, Ash, Basswood, Aspen, Yellow Poplar, Walnut, and Cherry.

DISCUSSION

TIMBER GRIDSHELL SELECTION CRITERIA

The use of timber to explore material complexity in gridshells is a rarely discussed topic in literature (Charest et al. 2019).When selecting a suitable material for gridshells, structural strength classes can be a useful starting point. It can be difficult for architects and engineers to survey all timber species on the market or available for construction use, making strength classes a handy tool. This is because a material can be selected based on the required strength class needed for the project, instead of a specific wood species. Strength classes are also important because some construction codes, such as the Malaysian construction code, require a minimum strength class for structural and roof elements. The most important mechanical properties of wood are bending strength (MOR), modulus of elasticity, and density (Moore, 2011), which are used to identify the timber's strength class according to EN 338 (CEN, 2003a). In terms of material selection for a timber gridshell application, bending strength (MOR) and modulus of elasticity (MOE) are the main factors to consider for bending behaviour. Using materials with high MOR and MOE is essential for gridshells, making hardwood species with optimal properties a great potential solution (Lara-Bocanegra et al. 2020). Hardwoods have high bending strength and modulus of elasticity, while still offering good bending capacity.

In timber gridshell examples, Western hemlock was selected for the Mannheim Multihalle structure because it has a very straight grain, allowing long finger-jointed laths and minimising the number of connections (Lara-Bocanegra et al. 2020). Green oak was selected for the Weald and Downland gridshell since it has good bending capacity and is cheaper than dry oak (Lara-Bocanegra et al. 2020). In temperate conditions, most of the selected materials are moderately durable, since the selected timber species are softwoods. In tropical conditions, exposed timber has a short product life, and materials selected for timber gridshell applications should be at least durable, and preferably very durable. The bending strength/bending elasticity ratio is a critical factor in material selection criteria for gridshell applications, but it should not be the only parameter. Sometimes materials can have a high bending strength/bending elasticity ratio but exhibit low bending strength and low bending elasticity. To solve this, bending strength and bending elasticity should be considered individually first. Then, if bending strength is high and bending elasticity is low, the bending strength/bending elasticity ratio should be considered and compared between different materials. Therefore, the overall blend of properties is more important than an individual aspect of mechanical behaviour for selecting suitable materials (Lienhard 2014).

SUITABLE MATERIALS FOR ELASTIC GRIDSHELL APPLICATION

Different architectural and structural applications have varying requirements for suitable materials. Durability is important in temperate conditions, but it becomes a vital factor in tropical conditions, especially if the material is exposed. Composite materials, which are harder than wood but have comparable forming ability (Kotelnikova-Weiler et al. 2013), provide new opportunities for gridshells. Glass Fibre Reinforced Polymer (GFRP), for example, enables more flexibility with bending and stronger structures that are less affected by buckling (Tayeb et al. 2015). Since composite materials are industrially produced, their mechanical properties are consistent, unlike wood, which is anisotropic and has varied arrangements (Charest et al. 2019). Timber gridshells must demonstrate their architectural relevance and ecological advantages to compete against synthetic materials (Charest et al. 2019). According to Kotelnikova-Weiler et al. (2013), the best suitable materials for elastic gridshells are GFRP, Natural Fibre-Reinforced Polymer Composites (NFRP), and wood. GFRP and NFRP have similar shaping ability to wood while being three times stronger than wood. They have similar strength to each other, and their price is comparable. The maintenance cost of composite materials is cheaper than that of wood. However, composite materials have a greater impact on the environment than wood (Kotelnikova-Weiler et al. 2013).

In tropical contexts, if hardwood is sustainably grown, locally sourced, and very durable species are commercially available at economic prices, then hardwoods have no competitors and have many advantages except for the high maintenance price over the long term. Using natural materials,particularly wood, displays local ecology and enriches the sense of place as opposed to synthetic materials (Charest et al. 2019). In temperate conditions, since hardwood species are expensive and most of the grown wood is softwood, wood products made of softwoods would be an appropriate option, as long as they are properly treated. Composite materials can also be a good option, but they are not as environmentally friendly as wood. Also, since gridshell aims to be a sustainable and environmental project that uses a minimum amount of materials and leaves a minimal footprint on the environment, composite materials will face the challenge of becoming more eco-friendly to be a proper gridshell material.

CONCLUSION

This paper investigates the most important criteria for selecting a suitable material for timber gridshells and elastic gridshells, and identifies the characteristics that make a material suitable for gridshell applications. The study concludes that there are six criteria that should be considered when selecting a timber gridshell material: structural strength and strength grading, bending strength and bending behaviour, bending strength/bending elasticity ratio, durability, commercial availability, and cost. These criteria provide general guidelines for material selection. In addition to these criteria, the characteristics that make a material suitable for a specific gridshell project can vary depending on the project's requirements, and are influenced by factors such as budget, climate, function, aesthetics, overall context, and available local materials. The study concludes that hardwood is a suitable option as a gridshell material due to its high bending strength and balanced modulus of elasticity, which ensures anti-buckling and bending capacity during the gridshell forming phase. Additionally, many hardwoods are naturally durable, which is important if the material will be exposed or the gridshell will be outdoors in tropical conditions. Composite materials are also an option that has been used recently in gridshells and has suitable properties as a gridshell material.

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DECLARATION OF COMPETING INTEREST

None

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