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Potential of Irish Orientated Strand Board in Bending Active Structures

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Abstract**—**To determine the potential of a low cost Irish engineered timber product to replace high cost solid timber for use in bending active structures such as gridshells a single Irish engineered timber product in the form of orientated strand board (OSB) was selected. A comparative study of OSB and solid timber was carried out to determine the optimum properties that make a material suitable for use in gridshells. Three parameters were identified to be relevant in the selection of a material for gridshells. These three parameters are the strength to stiffness ratio, the flexural stiffness of commercially available sections, and the variability of material and section properties. It is shown that when comparing OSB against solid timber, OSB is a more suitable material for use in gridshells that are at the smaller end of the scale and that have tight radii of curvature. Typically, for solid timber materials, stiffness is used as an indicator for strength and engineered timber is no different. Thus, low flexural stiffness would mean low flexural strength. However, when it comes to bending active gridshells, OSB offers a significant advantage. By the addition of multiple layers, an increased section size is created, thus endowing the structure with higher stiffness and higher strength from initial low stiffness and low strength materials while still maintaining tight radii of curvature. This allows OSB to compete with solid timber on large scale gridshells. Additionally, a preliminary sustainability study using a set of sustainability indicators was carried out to determine the relative sustainability of building a large-scale gridshell in Ireland with a primary focus on economic viability but a mention is also given to social and environmental aspects. For this, the Savill garden gridshell in the UK was used as the functional unit with the sustainability of the structural roof skeleton constructed from UK larch solid timber being compared with the same structure using Irish OSB. Albeit that the advantages of using commercially available OSB in a bending active gridshell are marginal and limited to specific gridshell applications, further study into an optimised engineered timber product is merited.

Keywords**—**Bending active gridshells, High end timber structures, Low cost material, Sustainability.

I. Introduction

GRIDSHELLS are doubly curved structures, constructed from initially straight elements that resemble shell structures. Shell structures are inherently effective in their structural performance leading to high span to thickness ratios. They inherit their strength and stiffness from their three dimensional geometry and curvature. Large open plan spaces can be created with a minimum amount of material. Gridshells represent a state of the art in structural timber engineering, which are difficult to engineer. There are two principle categories of gridshells, classified as bending active and bending inactive gridshells. The term bending active means that the structural elements have to bend considerably to give the structure its shape, a type of bending pre-stress [1]. Alternatively, bending inactive describes a structure whereby the structural elements do not need to bend to give the structure its shape. A typical bending inactive structure would be a truss, portal frame and a geodesic dome. The majority of bending inactive gridshells have been constructed from steel whereby the structure is comprised of numerous straight elements each inclined at a different angle to its adjacent element to give the structure its curved shape. Bending active gridshells on the other hand are not all that common, however a number of them have been constructed such as the Multihalle in Mannheim [2], the Weald and Downland Museum [3], and the Savill Garden centre [4] (Fig. 1). Notably, the majority of bending active gridshells is constructed from solid timber sections. However, there was a high cost associated with these gridshells because solid timber was used. Many natural defects such as knots, splits and grain discontinuities occur in solid timber. These defects become critical when using small sections, as the defects do not scale with section size. Therefore, the solid timber material used for the gridshells mentioned in [2]-[4] had to be specially selected from the timber available. For the latter two gridshells described in [3] and [4], from the lengths of sawn timber, the defects were identified, removed and the defect free pieces finger jointed back together. The average defect free piece was 600mm with the distances to be spanned for the Savill garden gridshell being 90m and 25m [5]. The time and labour required to carry this out led to a high processing cost along with an initial high base cost for the actual material, which is unsuitable for the sustainability of these structures. However, in more recent years, alternative engineered materials have been used in the construction of gridshells, more so for bending active gridshells such as cardboard tubes [6] and glass fibre reinforced polymers (GFRP) [7].

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Fig. 1 Savill Garden Gridshell

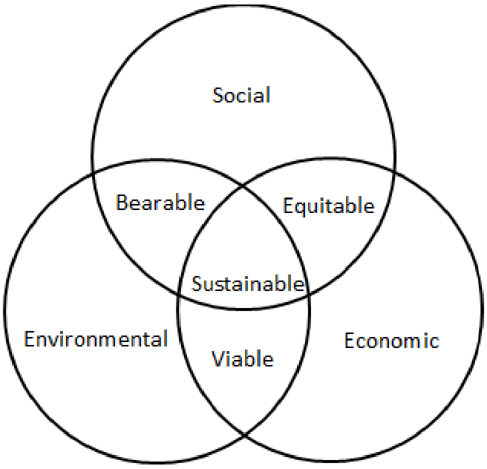

Fig. 2 Three pillars of sustainable development

The reason for the shift towards engineered materials is to do with the fact that their material properties can be optimised for a specific application. Therefore the question is can a form of engineered timber be more suitable than solid timber for use in bending active gridshells. The primary novelty of this study is to identify the potential for an Irish timber for use as the structural elements in bending active gridshells. Irish timber is fast growing similar to timber in Scotland and other temperate climate. Hence, the material properties and ability to source defect free solid timber are poor. In order to use successfully Irish timber for gridshells, an engineered timber product is proposed. As there is no structural plywood manufactured in Ireland, the next logical material of choice is Orientated Strand Board (OSB). OSB is a mass produced, sustainable Irish timber product and it uses *100%* of the raw material in its manufacture. It is low cost, has a low flexural stiffness and a considerable reduction in the number of defects than with solid Irish timber.

Another way that OSB can be evaluated for use in gridshells is to consider its sustainability. Sustainability can be broadly defined as:

"Sustainability encompasses the simple principle of taking from the earth only what it can provide indefinitely, thus leaving future generations no less than we have access to ourselves." [8]

In the context here of assessing the potential of Irish OSB for bending active structures, sustainability is mentioned with a strong emphasis on economic factors. A preliminary sustainability study is carried out to investigate the sustainability of an OSB gridshell verses a solid timber gridshell. A complete study would be based on the three pillars of sustainable development, environment, economics and social, which are identified in Fig. 2.

Additionally, for the sustainability of buildings a fourth indicator needs to be looked at which is the building regulations. The economic and environmental indicators will be assessed quantitatively (although with limited and proxy data) while the social indicator and the building regulations will be assessed qualitatively.

This paper details a comparative study of OSB verses solid timber in terms of structural and material properties that are unique to bending active gridshells. The unique gridshell properties outlined by [1] and [9] are revised here with respect to OSB. In addition, a preliminary sustainability study is carried out which determines the sustainability of an Irish OSB gridshell verses one using imported solid timber with a primary focus on economic factors. This overall study is focused on identifying the potential of OSB for use in high-end structural applications such as bending active gridshells. The specific objectives of this study are:

- To identify the unique characteristics associated with bending active structures that have implications for design.
  - E/fm ratios
  - Flexural stiffness of available sections
  - Variability
- To investigate if an engineered timber is more suitable and sustainable than solid timber for bending active gridshells.
- To assess the sustainability of constructing a large scale gridshell in Ireland using two specific timber products (native and non-native) in terms of reduced environmental and social impacts with lower costs.

The results presented here are based on short term cold bending, thus no long term material behaviours such as creep and stress relaxation are accounted for, neither are improved bending techniques such as steam bending.

II. Comparative Study

A. Stiffness vs Strength Ratio

A key indicator of a given materials suitability for use in bending active structures such as gridshells is its ability to bend with relative ease without breaking. Thus, a material with a low stiffness and a high strength is ideally suited. Reference [9] uses a ratio of E/f_m and normalises the data to C24 and D30 grades of timber. Reference [10] uses a ratio of f_m/E with f_m in *MPa* and E in *GPa*. This ratio has advantages as it provides a direct comparison to other materials as used by [11] and will be the ratio used in this study. By comparing the ratio of bending strength and bending stiffness of OSB with solid timber and other engineered timber products, it can be seen that OSB has an acceptable ratio when compared to solid timber. The data used for this ratio was obtained from [10] and

[12]; they are based on mean stiffness values. Fig. 3 compares the strength and stiffness of various species and grades of timber. The higher the f_m/E ratio the more suitable a material is for use in bending active structures. If a line is drawn from the origin through the OSB data point it directly bisects the solid timber into hardwood and softwood. This means that OSB (manufactured from a softwood timber) in terms of the f_m/E ratio is more suitable for bending active gridshells than any softwood solid timber.

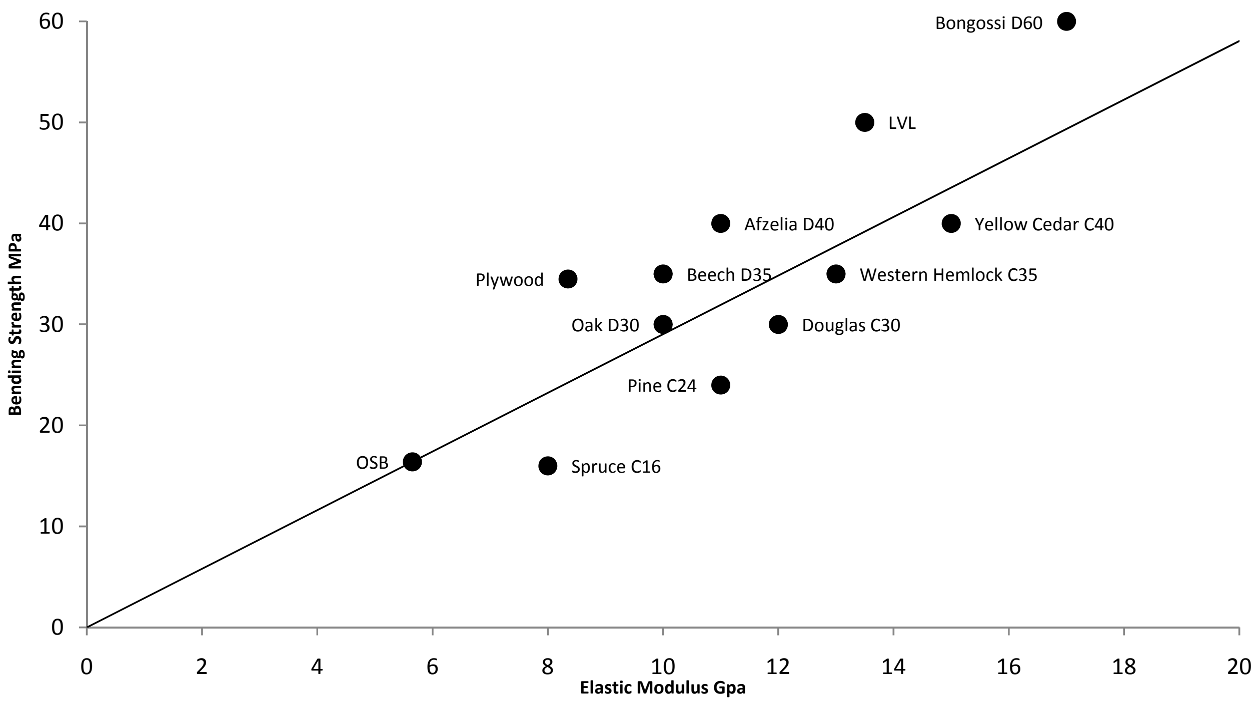

Fig. 3 Comparison of typical structural timber and timber products

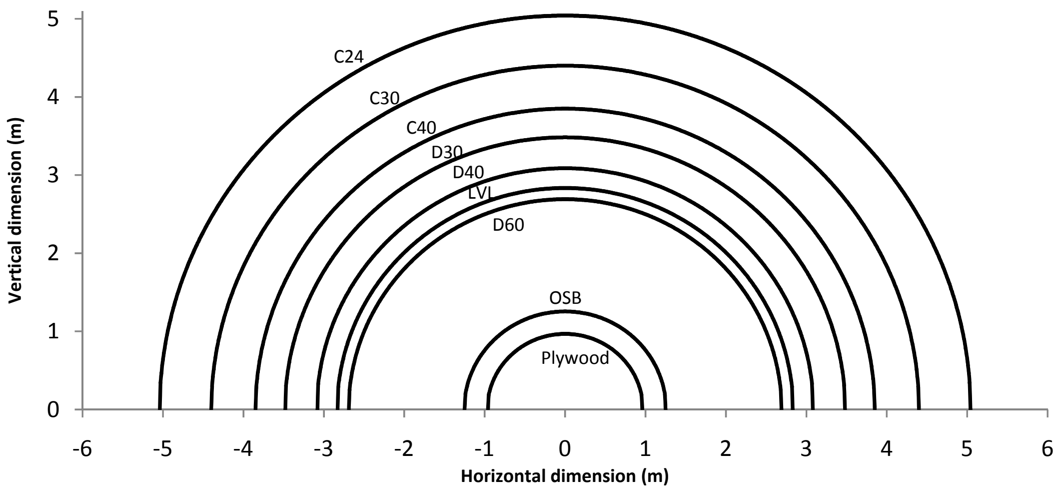

Fig. 4 Maximum curvature of different timber materials. The legend is displayed in a descending order of radius of curvature

B. Section Flexural Stiffness

The *fm/E* ratio is not enough to be able to make an informed decision on a suitable material for use in bending active gridshells. The maximum curvature (minimum radius) that a length of material is able to form to is another essential parameter. Using Euler-Bernoulli beam theory (1) the bending radius of a member can be calculated as a function of the bending stress. By using the maximum bending stress of a material f_m, the minimum bending radius of the member can be determined (2)

$$\frac{M}{I} = \frac{E}{R} = \frac{\sigma}{y} \quad (1)$$

$$R = \frac{Ey}{f_m} \quad (2)$$

Given the already defined f_m/E ratio, the minimum radius of curvature is also dependent on the depth d of the section, $y=d/2$ for rectangular sections giving (3):

$$R = \frac{Ed}{2f_m} \quad (3)$$

Therefore, in selecting a material for use in gridshells the available section sizes of that material must be taken into account. A comparison has thus been made which adapts the previous f_m/E ratio to include the section size giving the minimum radius of curvature for various timber materials. The selected section sizes for each material are based on the minimum section sizes that are commonly available according to [13]. Fig. 4 shows the maximum curvature of OSB verses other engineered timber products such as plywood and LVL as well as various grades of solid timber. It can be seen that the maximum curvature achievable with OSB and plywood is considerably greater than for LVL and solid timber, which indicates that smaller spanning gridshells can be developed with adequate curvature subject to strength and stiffness requirements.

C. Multi-Layer Gridshells

In order for gridshells to span further distances, issues around stiffness need to be overcome as small sections are used to achieve the required curvature. The solution to this is to increase the number of layers of the same small section, which was the technique adopted for the gridshell exemplars mentioned previously. During the forming of the gridshell, the layers would be uncoupled therefore forming multiple single layers simultaneously. Once the required section has been achieved, the layers were then locked together at the nodes and shear blocks were introduced to permit shear transfer though the layers. This gave the structure greater strength and stiffness in the out of plane direction.

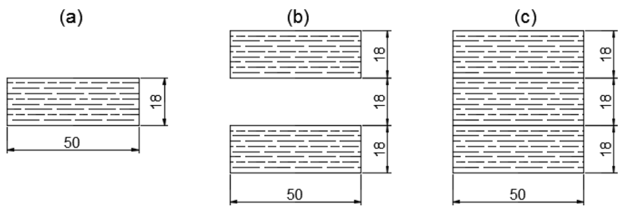

Fig. 5 Dimensions of gridshell layers, (a) single layer, (b) double layer without shear blocks, and (c) double layer with shear blocks

TABLE I
FLEXURAL STIFFNESS GRIDSHELL LAYERS

	Case	I	EI	Times stiffer
a)	Single Layer	2.43E-08	137	-
b)	Double Layer w/o shear blocks	6.318E-07	3570	26
c)	Double Layer w shear blocks	6.561E-07	3707	27

By analysing the section of a single layer (S.L.) verses a double layer (D.L.) a significant increase in stiffness is observed. Here a rectangular section of *50 mm* wide (*b*) and *18 mm* thick (*d*) was analysed for a single layer, a double layer with a shear block and a double layer without a shear block (Fig. 5). Given that each case is made from the same material, the flexural stiffness EI is only varied by I, the second moment of area of the section. Using the equation for the second moment of area, $I=(bd^3)/12$ and applying the parallel axis theorem the flexural stiffness of each case is given in Table I. The elastic modulus E was taken as 5650 N/mm^2. It can be seen from these results that there is a considerable increase in flexural stiffness of the double layer section when compared to the single layer section (*26 times stiffer*).

D. Variability in Material Properties

With bending active gridshells, we are also concerned about the maximum bending stiffness of a particular grade of timber or timber product. In the design of timber structures, the general stiffness requirements for a given material are to be suitable to limit deflection of a structural member. This often governs the design process over strength requirements. For a single structural member such as a beam in bending, Reference [14] suggests that E_{min}, the minimum characteristic flexural modulus of elasticity, be used in design calculations for deflection. However, for structures composed of multiple elements such as a floor diaphragm E_{mean}, the mean characteristic flexural MoE, can be used subject to sufficiently close spacing to allow load sharing. Recalling that for a bending active structure the ability of the material to achieve a desired curvature is fundamental to the structures implementation. Therefore, we are now also concerned with E_{max}, the maximum characteristic flexural MoE. This is a unique characteristic in the design of bending active structures. Overlooking this characteristic may result in premature failure of the structure during construction and erection process. The requirement to consider this leads on to the requirement of fully understanding the variability of material properties in order for an efficient and predictable design. E_{max} is not accounted for in the current standards. However, given that the mean and minimum stiffness is based on a form of the normal probability distribution [15], the maximum stiffness can be derived (4). Along with driving the maximum stiffness, the coefficient of variation (COV) can also be derived.

$$E_{max} = E_{mean} + (E_{mean} - E_{min}) \quad (4)$$

The COV is determined as the ratio between the mean and the standard deviation, σ/μ. The maximum stiffness and COV were derived for the solid timber sections of Fig. 4 and displayed in Table II. Also displayed for reference purposes are the minimum and mean stiffness's. All stiffness values displayed are parallel to the grain direction.

TABLE II
MAXIMUM STIFFNESS (GPa) AND COV OF SELECT SOLID TIMBER GRADES

	C24	C30	C40	D30	D40	D60	OSB
Emin	7.4	8	9.4	9.2	10.9	14.3	4.19
Emean	11	12	14	11	13	17	4.93
Emax	14.6	16	18.6	12.8	15.1	19.7	5.7
COV (%)	19.8	20.2	19.9	9.9	9.8	9.6	9.1

This now creates an envelope for the material stiffness for which can be used when making design decisions. In light of this unique characteristic, there is a specific implication for using OSB and other wood-based panels for bending active gridshells. The change in the end use of OSB from its implicit use in the standards needs to be understood along with the implications of doing so. For the determination of characteristic material properties in terms of bending, the standards [16] suggest a test specimen width of *300 mm*. This width has an averaging effect of the material properties over a narrower width, thus implying that the end use of the product as defined by the standards is close to that of the full sheet. In contrast to this, the end use of the product for bending active gridshells is narrow strips of approx. *50-100 mm*. Therefore, there is less of an averaging effect for the material properties resulting in a higher variability but closer to what is expected in reality for bending active gridshells. A different material testing strategy needs to be developed to account for the deviation from the standards in terms of the end use of the product. This is further discussed along with experimental results in [17]. This also has implications for the way in which the design codes and product standards are developed if the design of bending active gridshells is to become standard practice.

III. SUSTAINABILITY OF IRISH OSB VERSES UK LARCH

The second part of this study is to investigate the sustainability of using Irish OSB verses imported UK larch for the structural members in a bending active gridshell. The research question being answered here is, is using engineered Irish timber in a gridshell more sustainable than using imported solid timber.

A. Functional Unit

In order to answer this question an existing gridshell, the Savill garden gridshell, will be used as the functional unit. To investigate whether Irish OSB is a more sustainable material for gridshells, this building will be assessed by firstly replicating it in Ireland using the same material (UK larch) and then replacing the larch that makes up the roof structure with an equivalent quantity of OSB to give the structure the same strength and stiffness. The sustainability of each will be assessed using straightforward indicators primarily concerned with the economy and the environment but also with a mention to society and building regulations.

B. Straight forward Indicators

As mentioned previously, the sustainability study is based on the three pillars of sustainable development. The primary indicator for this study is economy (cost). This includes the volume of material, time, processing and transportation. The environmental indicators include the energy inputs for each process, emissions, water and waste. The social indicators include health and safety, aesthetics and the potential for Irish industry. The building regulations would include policymaking, legislation and governance. These indicators are more clearly represented in Table III.

TABLE III
OUTLINE OF THE INDICATORS IN THIS STUDY

Item	Assessment	Indicator	Unit
Economic	Quantitative	Vol. of material	m3
			€
		Time	€
		Labour	€
		Transport	€
		Processing	€
Environmental	Quantitative	Embodied Carbon	kg CO_2/kg
		Embodied energy	MJ/kg
Social	Qualitative	Irish Industry	-
Building Regulations	Qualitative	Compliance	-

C. Definition of Boundary

In order to assess sustainability, a clearly defined boundary needs to be established. Hence, the longitudinal (Life Cycle) boundary established for this study will be from the harvesting of the timber in the forestry up to the construction of the structural roof skeleton. Further clarifications on the transverse boundaries will be established as each indicator is discussed.

The longitudinal boundary for the assessment of sustainability of a gridshell constructed from imported UK larch has the following steps:

- Harvest from forest
- Transport to sawmill
- Saw into laths
- Transport to processing facility
- Finger jointing
- Transport to site
- Scarf jointing
- Construct gridshell

In addition, the associated boundary using OSB has the following steps:

- Harvest from forest
- Transport to factory
- Process into sheets
- Saw into strips
- Transport to site
- Splice jointing
- Construct gridshell

D. Assumptions and Data Gaps

The sustainability of the building in service is outside the scope of this study. However, it is thought this would not differ significantly for both buildings. As both roofs are externally clad identically, they are expected to have the same life expectancy.

E. Assessment and Results

The manufacturing process of OSB starts with the transportation of the whole logs to the mill wood yard where they are sorted. The logs are fed through the debarker to remove bark, which is later used as fuel in the mill's energy supply. The entire debarked logs are then cut into strands of precise dimensions. The strands are deposited into wet bins and then dried until the appropriate moisture content is reached. The strands are then blended with resin binders and a small amount of wax, which improves the efficiency of the resin binder and enhances the panel's resistance to moisture and water absorption. From here, the strands go through the forming line where cross directional layers are formed then pressed under high temperature and pressure to form a rigid, dense master panel of OSB. Finally the master panels are cooled, cut to size, grade stamped, stacked in bundles and shipped [18].

For the imported larch gridshell, *400* trees were specially selected from the Crown Estate's commercially managed woodland in Windsor Great Park. These trees were then transported to the sawmill which created *35km* of laths in *6m* lengths. Visual grading sorted the high grade from the low grade. A GreCon Dimter OPTICUT 101 mechanical saw was used to cut out the defects. The average defect free piece of timber was *0.6 m* in length. The defect free pieces were then finger-jointed back together using a GreCon Dimter SUPRA finger-jointing machine. A total of *10,000* finger joints were required to create *10 km* of high grade defect free timber in *6 m* lengths. The glue used was a water based PUR glue. A total of *10 km* of low-grade timber and *10 km* of high-grade timber were created and transported to site. The high-grade timber was further processed into *260* continuous single pieces each up to *35 m* in length using *1000* scarf joints with a *1:7* slope. The characteristic bending strength of the larch used was $35\ N/mm^2$. The completed section of the gridshell was a double layer of laths *80 mm* wide x *50 mm* thick with shear blocks in between creating a total section depth of *190 mm*. Given this information, a C30 timber is assumed, the moment resistance of the section is *12.9 kNm* and the flexural stiffness *EI* of the section is $450\ kNmm^2$. The total volume of larch harvested was $140\ m^3$, from which only $80\ m^3$ was used in the actual building. No data was available on where the waste material was used.

An equivalent composite section using OSB requires four layers of *90 mm* x *40 mm* laths with shear blocks in between creating a total section depth of *280mm*. This gives a moment of resistance of the section to be 13.4 kNm and the flexural stiffness *EI* of the section is $662\ kNmm^2$. This is double the amount of layers required than the larch gridshell, thus *20 km* of OSB would be required for the gridshell laths along with an estimated *15 km* for shear blocks and splicing. A total volume of OSB material is $126\ m^3$. Given that all of the harvested material is used for the production of OSB, makes it an efficient method. The depth of the OSB roof assembly is *47%* more than the depth of the larch assembly (Fig. 6). As this is only a marginal increase in terms of the overall scale of the building, it is assumed that it does not have any implications for the assessment of this sustainability study.

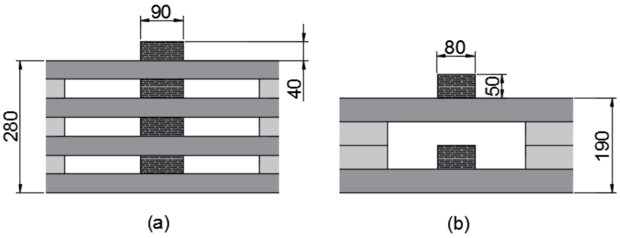

Fig. 6 (a) OSB layers and (b) Solid timber layers

1) Economical Assessment

Although no clear data was available on material costs, it is evident that the high quality larch members that were handpicked and processed into defect free lengths would have a very high cost if required for a similar project in Ireland. Additionally, the transportation cost is also deemed higher due to the specialised nature of the material being imported. Therefore the locally sourced, OSB can be produced at a considerably lower cost making it a more beneficial material in terms of economics.

2) Environmental Assessment

The environmental assessment of both structures will be assessed in terms of energy and CO_2 release for the various stages of the process. These stages are fabrication, transportation, construction, maintenance and demolition/end of life. Proxy data was sourced in terms of embodied energy (*MJ/kg*) and embodied carbon ($kg\ CO_2/kg$). The embodied energy takes into account the energy required for extraction of the raw materials, processing and manufacture, transport to site and constructed as the finished building. Carbon dioxide emissions associated with this embodies energy is the embodied carbon.

The larch was classified as a general timber with an embodied energy of 8.5 MJ/kg and embodied carbon of 0.4 kg CO_2/kg. The OSB has an embodied energy of *9.5 MJ/kg* and an embodied carbon of $0.51\ kg\ CO_2/kg$. The total energy consumption and CO_2 emission figures are calculated from this data and are presented in Table IV.

TABLE IV
TOTAL ENERGY AND CO2 RELEASE FOR LARCH AND OSB

	Larch	OSB
Energy (MJ)	477	658
CO2 release (t CO2)	30	35

From this data, it can be seen that larch solid timber has less of an impact on the environment than OSB. This is presumably due to the processing, whereby the OSB requires resins additional pressure and heat inputs to form the product. Solid timber only requires sawing and drying, this was the assumption made here that the larch was a standard solid timber. However this was not the case for the Savill garden gridshell, the lengths of timber are further processed using pressure and glue to create defect free laths. Therefore, though not stated here, it is assumed that the total energy and CO_2

release for modified larch timber is close to if not greater than that for OSB.

Both structures are constructed similar whereby the first layer is lifted into position and additional layers added until the structure is complete. As the structure is relatively lightweight when compared to structures of a similar size made from steel or concrete, it is expected that the impact of the construction phase is low in the overall assessment. It is thought that the construction of the OSB gridshell make take longer due to the extra number of layers. However, this can be offset by lifting all layers together with the joints unlocked to allow sliding between the layers. In addition, the impact of transport will have an effect on the results as the two products are sourced from two completely different locations, one of which crosses international boundaries.

3) Social Impact

The social aspects of the sustainability of the two building types are assessed qualitatively. Using OSB is positive from an Irish point of view. The OSB material is 100% Irish. The timber is locally sourced from sustainably managed forests, and processed into OSB in Ireland. This has positive potentials for the Irish industry, benefits the local economy and creates jobs. Whereas the Larch timber for the original Savill Garden gridshell was sourced in the UK and has to be imported at a cost for use in Ireland.

4) Building Regulations

Given the fact that the same functional unit is used for both building types and the only variation is the type of timber product used for the structural roof skeleton, both building types would have to comply with the exact same building regulations. Therefore, no comparison can be made in this regard.

IV. Further Work

The lack of data made difficult any meaningful quantitative analysis. However, the preliminary study (both material property comparison and sustainability) has shown that there is a potential for OSB to be used in bending active gridshells. OSB was identified to be more suitable for smaller scale gridshells than solid timber, thus putting a restriction on its use. In order to gain a more complete insight into limitations of OSB for use in bending active structures, the following list of items must be addressed:

- A more complete sustainability study that will encompass the entire life cycle (cradle to grave) of OSB and solid timber.
- A single normalized index ('Suitability Index') depicting the suitability of OSB and solid timber across various spans.

A qualitative suitability index is shown in Fig. 7 that compares the suitability of OSB and solid timber for different gridshell spans. The intersection at *'A'* is the limiting threshold whereby above this OSB is not a suitable timber material for gridshells. Furthermore, once these limitations have been established and quantified, work can begin on optimizing the OSB material through the manufacture process to expand the threshold for OSB gridshells.

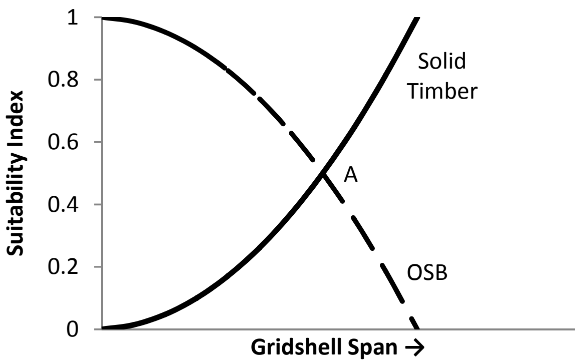

Fig. 7 Qualitative suitability index of OSB compared to solid timber for increasing gridshell spans

V. Conclusion

Engineered timber is a more suitable and cost effective material for use in gridshells. Here an Irish engineered timber product in the form of OSB compared against solid timber and other engineered timber products under three main headings that are relevant to gridshells. It was concluded that OSB is suitable for use in gridshells, notably smaller span gridshells with high curvatures.

A preliminary sustainability study was carried out to compare using Irish OSB against imported larch for a large scale gridshell constructed in Ireland. This preliminary study concluded that in terms of environment and building regulations both material were quite similar. On the other hand, in terms of economics and society OSB has a more positive impact than imported UK larch.

Given that OSB is manufactured from fast growing softwood, the renewability of the forestry has a shorter time period as compared to the solid larch used in the Savill garden gridshell.

Overall, this paper successfully outlines to the wider timber community of the potential of a substandard timber product in the form of OSB as a replacement to the high cost solid timber products previously used in state of the art timber structures such as gridshells.

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