Characterisation of OSB properties for application in gridshells

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Received: 7 June 2016 / Accepted: 27 January 2017 / Published online: 6 February 2017
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Abstract In order to establish the viability and efficiency of orientated strand board (OSB) for use in bending active gridshells, the relevant material properties need to be established. Standard test methods for OSB assume the material will be used in large panel form. However, gridshells are made from long, relatively narrow and thin strips. To characterize the material properties of OSB for use in bending active gridshells, bending, torsion and compression tests were carried out to determine material strength and material stiffness properties. Test methods different to those in the standards were developed. Relatively high variations were observed in the material properties compared to those given in the standards. In addition, relatively high variations in product thickness were also observed in OSB sections. The variation in material and section properties identified should be considered when formulating design rules. This study shows that, in addition to a thorough understanding of the overall structural behaviour, in order to use OSB in bending active gridshells, application-specific material tests need to be carried out.

Keywords Gridshells · Orientated strand board · Bending active · Material properties · Mechanical testing

1 Introduction

Timber has been used in construction for thousands of years, in many shapes and forms. 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. The most common commercial timber produced in Ireland is Sitka Spruce and has a typical timber strength grading of C16. This is a fast growing timber which, in a solid timber form, possesses many of these defects and as a result is of poor structural quality [1]. In recent years, the use of engineered timber products has become more common in structural applications. The general principle behind engineered timber is to spread the defects out over a number of layers or particles so that the probability of having a large defect in any one cross section is reduced. As a result, a material with enhanced and less variable properties is achieved. Oriented strand board (OSB) is one such engineered timber product that has become commonly used in the construction sector since the late 1970s [2]. It is the only engineered structural timber product manufactured in Ireland and is made using Sitka Spruce or Lodgepole Pine conifers from managed plantations in Ireland [3]. OSB is a low-cost commercially manufactured wood-based panel of standard dimensions 2440 mm × 1220 mm and ranging in nominal thickness from 6 to 25 mm [4]. These standard panels are typically cut from a master panel,
which could be from 4 to 9 times the standard panel size or cut from a continuous panel. OSB is used extensively in furniture, non-structural applications such as site hoarding, display stands, sheds, shelving, and structural applications such as roofing generally and wall panels in timber frame housing. While further load bearing applications such as I-beams using OSB came on the market in 1990 [5], most structural applications still use whole or close to whole panels.

Shell structures are inherently efficient in their structural performance as they utilise both bending and membrane action to transfer forces. This results in high span-to-thickness ratios [6]. Gridshells can be thought of as discrete or discontinuous shell structures. A gridshell, similar to a continuous shell, is a structure that gains its strength and stiffness through its double curvature configuration. Gridshells are made from elements that have one dominant dimension, so timber is naturally a suitable material for gridshells. A timber gridshell enables doubly curved structures to be formed from a set of straight, prefabricated components of identical cross-section. The double curved surface means that individual laths being shaped like an arch will, like any arch, experience axial forces when loaded normal to its curvature. Also, like any arch, even an arch that has a funicular form with respect to permanent loads, in so far as the load arrangement may vary, bending stresses will in general arise, particularly where concentrated loads occur. Furthermore since a gridshell surface is doubly curved, where laths cross some compatibility of slope will tend to be enforced. This means that a change in slope of one member will give rise to a corresponding change in twist of the crossing member. Therefore gridshells subject to variable loading will, in general, experience axial, bending and torsional stresses. The development of computer methods for modelling complex three-dimensional structures can facilitate designers in using this challenging structural form. The availability of engineered materials further facilitates designers in achieving complex geometries providing the corresponding stiffnesses are available for the analytical model since gridshells are highly indeterminate forms.

Bending active gridshells are generated by bending a flat grid composed of initially straight members to form a shell-like curved surface. “Bending active” refers to the way in which the gridshell is formed; “Active” means that a bending pre-stress is generated during the forming (or form finding) process. Steel gridshells, in contrast, may be formed from unbent short straight lengths (or lengths curved by cold rolling) welded in situ to generate a curved surface free of bending stresses prior to loading. This type of gridshell is termed bending in-active [7]. Gridshells represent a state of the art in structural timber engineering. They are uncommon and difficult to engineer. Examples of large scale bending active timber gridshells include the Multihalle in Mannheim [8], the Weald and Downland Museum [9], and the Savill Garden centre [10] (Fig. 1). A smaller scale example is the Chiddingstone Orangery gridshell [11]. Notably, the majority of bending active gridshells were constructed from solid timber sections. This results in a high cost arising from the need for small, solid, defect-free timber sections. The solid timber used was specially selected from the forestry from a visual inspection of size appropriate trees, then, defects in the sawn timber are identified, removed and the defect-free pieces finger jointed together. The average defect free piece for the Savill garden gridshell was only 600 mm long [10]. Therefore, 10,000 finger joints were required to produce 6 m long defect free pieces, which were then scarf jointed on site to create lengths in excess of 25 m. The processing cost must be added to an initial high base cost for the actual material. This high cost is a barrier to the commercial use of timber gridshells. In more recent years, alternative engineered materials have been used in the construction of gridshells, including bending active gridshells such as cardboard tubes [12] and glass fibre reinforced polymer (GFRP) [13].

Engineered materials allow material properties to be optimised for a specific application. OSB is
proposed as a potentially suitable low cost engineered material for bending active gridshells. This paper focuses on the bending, torsion and compression properties of OSB relevant to bending active gridshells. The standard material property testing approaches are modified from those described in the testing standards to take account of the particular design requirements of bending active gridshells. The research reported here is part of a research programme that will examine the time dependent behaviour of both OSB generically, OSB in a bending active mode, OSB in a multi-layer configuration and the associated time-dependent connection behaviour. This research is concerned to establish the appropriate short term behaviour properties for gridshell applications. The specific objectives of the research are therefore:

- To develop material testing procedures appropriate for bending-active gridshells.
- To determine the short-term characteristic properties of OSB in bending, torsion and compression relevant to its use in bending active gridshells.
- To establish and analyse the variation in material properties of OSB.
- To establish and analyse the variation in section properties of OSB.
- To assess the suitability of OSB for bending active structures.

2 Materials and methods

The relevant standard for establishing OSB material properties for structural design is [14]. The typical end use of a standard panel is as large panels in walls, floors and roofs. The stipulated test specimen width is 300 mm for flexural tests, which reflects the assumed end uses in wide panel form. However, for bending active structures such as gridshells, the proposed end use requires narrow strips (50–100 mm). The property data generated from the standard tests will, necessarily, be the average of the property across the 300 mm tested width and the variability in the data among individual specimens will reflect this averaging effect. As may be seen in a number of the precedents referenced above, in gridshells the structural element may be only 50 mm wide. This is to facilitate the support of doubly curved surfaces clad with thin sheets. Therefore the material properties generated from standard test specimens may be on the unsafe side as the properties of locally weaker zones will not be identified by the standard test. If specimens with a smaller width are tested, local property variations can be identified. Consequently, a higher variability in the material property test data may be anticipated. Therefore, a modified testing approach must be used in order to determine the material properties using test specimen dimensions that are representative of the proposed end use. In this study, the short-term material properties only are considered although further research is ongoing to study time-dependent effects.

Commercial OSB was sourced from a local producer and all the material had the same date stamp. The panels had dimensions of 2440 mm × 1220 mm × 8 mm. These standard panels were cut into 50 mm wide strips. The stiffness and strength properties in bending were measured using a four-point bend test. Tests were also carried out to determine the stiffness and strength properties in torsion and compression.

2.1 Specimen preparation and material evaluation

All test specimens were conditioned to dry conditions of 20 °C and 65% RH [15]. A number of preliminary tests were carried out to determine a suitable loading rate and to obtain preliminary estimates of the strength and stiffness. A good indicator of a material’s suitability for bending active gridshells is the ratio between its bending strength \( f_m \) and Elastic Modulus \( E_m \) [16]. The \( f_m/E_m \) ratio for the longitudinal direction (parallel to the longest panel dimension) was determined from [17] as 3.33 compared to 4.14 for the transverse direction (perpendicular to the longest panel dimension). The significance of these values is detailed in [18]. Additionally, in [18] the minimum radius of curvature achievable using members from the longitudinal direction was found to be 1.25 m compared to 0.96 m for the transverse direction. These values are considerably less than the minimum radius of curvature achievable with solid timber (3–5 m) using the minimum commercially available sections. This suggests that it may be possible to form a wider range of gridshells using OSB than is possible using solid timber. For a given gridshell, compared to members cut from panels longitudinally, OSB members cut from the transverse direction would require over double the number of joints to create sufficiently long lengths. In addition, transverse cut
members have a reduced strength. Albeit that the OSB members cut in the transverse direction would allow for smaller radii of curvature, in the context of using OSB for bending active gridshells on a scale similar to the built precedents mentioned, to minimize splice joints, the gridshell members should be cut from a panel in the longitudinal direction. Therefore, the principal tests were carried out on test specimens cut in the longitudinal direction. The geometry and moisture content of each specimen were also measured. All tests were carried out on a Zwick 100 kN universal testing machine.

2.2 Bending

To determine the bending properties of OSB a four-point bend test was used. The test setup was similar to that of [14] with proportional adjustments made to accommodate the smaller test specimens. Thus, the distance from the support to the nearest load roller and the distance between the load rollers are set to 16 times the specimen thickness. The load is applied at third points using 15 mm diameter rollers. The specimen is supported on 15 mm diameter rollers at a span of 384 mm (assuming 8 mm thickness). Figure 2a shows the modified apparatus for the four-point bend test which is used in this study.

The load is applied at a continuous rate, adjusted so that the maximum load is reached within $60 \pm 30$ s. The deflection measurements are taken with reference to the load points at the midpoint of the test specimen on the top face using a digital displacement transducer. Thus, it is the local modulus of elasticity in bending that is being derived from the measured deflections. The Elastic Modulus and bending strength are given in Eqs. 1 and 2 respectively in accordance with standard linear elastic small deflection theory [14].

$$E_m = \frac{(F_{40} - F_{10})L_1^2L_2}{16(u_{40} - u_{10})I}$$  \hspace{1cm} (1)

$$f_m = \frac{F_{\text{max}}L_2}{2Z}$$  \hspace{1cm} (2)

Where $E_m$ is the test specimen Young’s modulus in bending (called herein “the bending stiffness”), $F_{10}$ and $F_{40}$ are the values for force at 10 and 40% of $F_{\text{max}}$ respectively for the test arrangement shown in Fig. 2, $u_{10}$ and $u_{40}$ are the corresponding measured deflection increments, $f_m$ is the test specimen bending strength (expressed as maximum bending stress at failure), $F_{\text{max}}$ is the maximum test load reached at failure, $I$ is the second moment of area and $Z$ is the section modulus of the test specimen. $L_1$ and $L_2$ are as shown in Fig. 2.

The values for force and displacement are obtained from the force–displacement graph for each test.

2.3 Torsion

Because gridshells are doubly curved, gridshell members are subject to bending and twisting during forming. As a result, torsional moments are developed in the cross section. Therefore, in addition to flexural properties, the relevant torsional properties of narrow strips of OSB are required. Torsion causes shear stresses in the cross section. For solid timber the standards describe two methods to determine the shear properties in [19]: the torsion method and the shear field method. For this study the torsion method was used. As in [19] the test specimen were subject to torsion only (no bending), which directly determines the shear properties that are relevant to bending active structures. The test specimen length/width ratio stipulated in [19] was also used. The actual test setup in [19] is suitable for large solid timber sections. A diagram of the torsion test apparatus is shown in Fig. 2b. The specimen length is 19 times the largest cross sectional dimension. Thus for a section size of 50 mm $\times$ 8 mm a test length of 950 mm was used. The test specimen is clamped at the supports, which are spaced apart more than 16 times the largest cross...
sectional dimension and subjected to torsion along the longitudinal axis by a relative rotation of the supports. The rotation is measured between two templates that are spaced two to three times the specimen depth from the ends. This is to negate the effects of local crushing at the ends on the rotation measurements.

A vertical force applied by the testing machine is mechanically converted to a pure rotational torque, to which the test specimen is subjected until failure occurs. Similar to the bending test, the load is applied at a continuous rate adjusted so that the maximum load is reached within 60 ± 30 s. Following standard linear elastic theory the torsional stress and torsional stiffness are determined from Eqs. (3) and (4) respectively [20].

\[
\tau_{\text{max}} = \frac{3T}{bd^2} \left[ 1 + 0.6095 \frac{d}{b} + 0.8865 \left( \frac{d}{b} \right)^2 - 1.8023 \left( \frac{d}{b} \right)^3 + 0.9100 \left( \frac{d}{b} \right)^4 \right] \tag{3}
\]

\[
G = \frac{(T_{40} - T_{10})L}{K(\theta_{40} - \theta_{10})} \tag{4}
\]

\[
K = \frac{bd^3}{64} \left[ \frac{1}{3} - 0.21 \frac{d}{b} \left( 1 - \frac{d^4}{12b^3} \right) \right] \quad \text{for} \quad b \geq d \tag{5}
\]

Where \( \tau_{\text{max}} \) is the maximum torsional stress in a rectangular section of width \( b \) and depth \( d \) subject to a torsional moment \( T \), \( G \) is the material shear modulus (called herein “the torsional stiffness”), \( K \) is a geometry dependent section parameter, and \( T \) and \( \theta \) (rad) are the applied torque and associated angle of rotation respectively. The torsional strength corresponds to the maximum torsional stress calculated using Eq. (3) for the torque \( T \) applied at failure. \( T_{40} \) and \( T_{10} \) are 40 and 10% of the failure torque respectively while \( \theta_{40} \) and \( \theta_{10} \) are the corresponding measured angles of twist.

2.4 Compression

In contrast to bending and torsion material stiffness tests, no modifications are wanted to the compression tests set out in [14] as this test stipulates a test specimen width of 50 mm for OSB.

3 Results and discussion

The testing was carried out on specimens taken from 16 standard panels. A minimum of six test specimens from each panel were taken to determine the bending, torsion and compression properties along with moisture content and density. This is the minimum number of test specimens required according to [21]. Statistical analysis was carried out using the statistical software package SPSS. Goodness-of-fit tests (Shapiro–Wilk) were carried out and confirmed the hypotheses that each data set was normally distributed, \( (\alpha = 0.05) \). Due to the relatively small number of test specimens, a \( t \)-distribution was employed to calculate the characteristic properties. From this analysis, the 5th and 95th percentile values for both material stiffness and material strength were obtained (Table 1). The 95th percentile values for material stiffness are relevant to bending active gridshells as a high material stiffness will result in high stresses for a given curvature and therefore the anticipated upper bound material stiffness may be critical for establishing the ultimate design stress. The mean material stiffness value for bending obtained here is 14% greater and the 5th percentile material strength value is 26% lower than the standard values in [17]. The mean material torsional stiffness is 13% lower and the 5th percentile material torsional strength is 10% lower than the standard values in [17]. The mean material compression stiffness is 24% lower and the 5th percentile strength value is 21% lower than the standard values in [17].

The bending test results show a higher variability than that given in [17, 22]. The average Coefficient of Variation (COV) of the material bending stiffness of the OSB tested is 19.5%, compared with 9.1% from [17] and 12–14% from [22]. The bending test results from this study are compared with similar studies and the relevant product standards in Table 2. It can be seen that the material bending stiffness results in this study are higher than those of [22] and the material bending strength is lower. It is apparent, therefore, that an alternative test approach was justified as the results from [17] would result in unconservative design. The test methods used provide more representative property data for OSB cut in narrow strip form for use in bending active gridshells.
The lowest strength class of Irish Spruce solid timber commonly used is C16. Therefore this is the lowest strength class used for comparison purposes.

Table 3 compares the material bending stiffness and COV for OSB and solid timber [23]. The increase in COV between this study and that interpreted from [17] is a result of the reduction in test specimen width from 300 to 50 mm. However, this COV of 19.5% is similar to that of softwood solid timber from which the raw material in OSB was derived (&20%).

As mentioned in Sect. 2.1, 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 [18]. A material with a low stiffness and a high strength is required. Toussaint [24] uses a ratio of $f_m/E_m$ and normalises the data relative to C24 and D30 grades of timber. Lienhard [16] uses a ratio of $f_m/E_m$ with $f_m$ in MPa and $E_m$ in GPa. This ratio has advantages as it allows a direct comparison with the corresponding data for a wide range of other materials published by Ashby and Jones [25] and will therefore be the ratio used here. The ratio of material bending strength to bending stiffness of OSB may be compared with the same ratios for solid and engineered timber in Fig. 3. A material $f_m/E_m$ ratio lying along a steeper line is more suitable than one lying along a flatter line. Data points lying on the same line are of similar suitability as far as flexibility for forming is concerned. Therefore, we may say that OSB and Douglas C30 are of similar suitability for bending active gridshells whereas Spruce C16 is inferior to the OSB tested.

The test material was manufactured from Irish Spruce whose lowest commercially available strength class is C16. Therefore the engineered timber properties that relate to gridshell use have been improved by the manufacturing process. The test results are displayed in Fig. 3 along with data obtained from [16, 23]. The characteristic mean material stiffness values and the 5th percentile characteristic material strength values are plotted. The higher the $f_m/E_m$ ratio, the more suitable a material is for bending active structures. The $f_m/E_m$ test results may be compared with the OSB values from [17]. A line drawn from the origin through any data point has a constant slope equal to the $f_m/E_m$ ratio of that data point. A higher material bending stiffness and a lower material bending strength was measured for the OSB as part of this study as opposed to the values in [17]. As a

Table 1 Characteristic values for material stiffness and material strength based on experimental results

| Material Stiffness (MPa) | Material Strength (MPa) |
|------------------------|-------------------------|
|                        | $E_{0.05}$ | $E_{mean}$ | $E_{0.95}$ | COV (%) | $f_{0.05}$ | $f_{mean}$ | COV (%) |
| Bending                | 3492 (4190) | 5625 (4930) | 7758 (5670) | 19.5    | 13.3 (18) | 22.6       | 21.3    |
| Torsion                | 754 (918)   | 943 (1085)  | 1131 (1252) | 12.1    | 6.1 (6.8) | 8.4        | 16.5    |
| Compression            | 2257 (3230) | 2892 (3800) | 3527 (4370) | 13.3    | 12.5 (15.9) | 16.0       | 13.1    |

The corresponding values from EN 12369-1 are shown in parentheses.

Table 2 Comparison of bending results to standards and published work

| Source                  | $E_{mean}$ (MPa) | $f_{0.05}$ (MPa) | COV (%) |
|-------------------------|------------------|-----------------|---------|
| Present study 8 mm      | 5625             | 13.3            | 19.5    |
| Jin, Dai A 11.1 mm      | 4980             | 17.6            | 12      |
| Jin, Dai B 18.3 mm      | 4350             | 14.5            | 14      |
| EN 12369-1              | 4930             | 18              | 9.1     |

Table 3 Material stiffness (GPa) and COV (%) of select solid timber grades

|                  | C16 | C24 | D30 | D40 | OSB (EN12369) | This study |
|------------------|-----|-----|-----|-----|---------------|------------|
| $E_{min}$ (GPa)  | 5.4 | 7.4 | 9.2 | 10.9| 4.19          | 3.53       |
| $E_{mean}$ (GPa) | 8   | 11  | 11  | 13  | 4.93          | 5.75       |
| $E_{max}$ (GPa)  | 10.6| 14.6| 12.8| 15.1| 5.7           | 7.97       |
| COV (%)          | 19.7| 19.8| 9.9 | 9.8 | 9.1           | 19.5       |
result, an $f_m/E_m$ ratio of 2.4 is obtained. This further reinforces the need for the proposed alternative test methods to ensure a safe design.

In order to make a more informed decision on the suitability of any material for use in bending active gridshells, data additional to the $f_m/E_m$ ratio is required. The maximum achievable curvature (minimum radius) for a material is another essential parameter [18]. Using Euler–Bernoulli beam theory in Eq. (6), the bending radius of a member can be calculated as a function of the bending stress. By using the characteristic bending strength of a material $f_m$, the corresponding characteristic minimum bending radius $R$ of the member can be determined (7). Of course an appropriate partial safety factor would have to be determined to establish a suitable design value but the data detailed below nevertheless allows a valid comparison with other materials to be made.

\[
\frac{M}{I} = \frac{E}{R} = \frac{\sigma}{y} \tag{6}
\]

\[
R = \frac{Ey}{f_m} \tag{7}
\]

Given the already defined $f_m/E_m$ ratio, the minimum radius of curvature $R$ is also dependent on the depth $d$ of the section, $y = d/2$ for rectangular sections giving (8):

\[
R = \frac{Ed}{2f_m} \text{ (m)} \tag{8}
\]

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 using Eq. (8) to give the minimum radius of curvature for various timber materials. The selected section sizes for each material are based on the minimum (i.e. the most flexible) section sizes that are commonly available according to [26]. Based on the flexural test results, Fig. 4 compares the minimum radius of curvature of OSB with other engineered timber products such as plywood and Laminated Veneer Lumber (LVL) as

![Diagram showing comparison of typical structural timber products and minimum radius of curvature of different timber materials](image-url)
well as various grades of solid timber. It can be seen that the minimum radius achievable with OSB and plywood is considerably less than for LVL and solid timber. However it must be noted that the values used for plywood are based on those presented in [26], whereas data relevant to the current application would require tests to be carried on the plywood using a smaller test specimen width as outlined previously. The results indicate that by using OSB, gridshells with tighter radii of curvature can be achieved than is possible with a wide range of solid timber structural grades.

For design, in addition to the material strength and material stiffness properties the variation in these properties is required. The variation in material thickness is also significant for structural design because it affects the bending stiffness of an OSB section. Table 4 displays the mean, standard deviation and coefficient of variation of the thickness of all specimens tested. The results are based on an assumed normal distribution as before. High variability in section stiffness makes it more difficult to predict the actual behaviour of individual members. In addition to accounting for material property variations, any design rules would need to account also for this dimensional variation. As noted in [18], for bending active gridshells a higher than anticipated stiffness may be problematic as a higher pre-stress would be induced for a given curvature. Therefore, the design rules for a material with a higher thickness variation should stipulate lower limiting curvatures. Each thickness data point is the average of at least five measurements taken local to the data point. Additionally, the mean, 5th and 95th percentile values for density [27] and moisture content [28] are given in Table 4. These results are based on all test specimens being conditioned to 20 °C and 65% RH.

Wu and Suchsland [29] tested the effect of moisture on the flexural properties of commercial OSB for five different OSB products. It was concluded that the effect of moisture varies depending on the timber species used in the OSB. Taking the mean relationship between moisture content (MC) and bending stiffness and bending strength derived by Wu and Suchsland [29] the following linear regression models are obtained:

\[
\text{Material bending stiffness} = 6788 - 215 \cdot MC (\text{MPa})
\]

\[
\text{Material bending strength} = 39.792 - 1.022 \cdot MC (\text{MPa})
\]

The difference between the 5th and 95th percentile values (8.7 and 11.7%) for the moisture content of specimens used in this study is 3% points \((1.67 \times 2 \times \sigma)\). Using Eqs. 9 and 10, this difference in moisture content corresponds to a difference in the bending stiffness of 644 MPa and in the bending strength of 3.1 MPa. The difference between the 5th and 95th percentile values for bending stiffness and bending strength from this study is 4266 and 18.6 MPa respectively. Therefore, it can be stated that the effect of moisture content on the experimental results of this study accounts for 15.1 and 16.6% of the measured variation in bending stiffness and bending strength respectively. The measured COV for bending stiffness is 19.5% compared to 9.1% in the standards. The increase in variation (10.4% points) due to the moisture content accounts for 2.9% points. The remaining 7.5% points increase is assumed to be due to the modified test approach. It must be noted that the testing in this study was carried out in a controlled constant environment. Further research is needed on the typical environmental conditions a gridshell structure would be subjected to in order to fully understand the influence of moisture content.

### 4 Stress–strain behaviour

The experimental results for the stiffness and strength in bending are used to generate stress–strain material models for OSB. Figure 5 plots the bending stress–strain envelope for OSB with the mean, 5th and 95th percentile stress–strain curves indicated. This stress–strain envelope is derived by applying a best-fit polynomial function to the raw data. An idealised piecewise linear elastic model is also represented. The piecewise model is initially based on the slope of the

| Panel               | Mean | SD  | COV (%) |
|---------------------|------|-----|---------|
| Thickness (mm)      | 8.660| 0.615| 7.1     |
| Moisture content (%)| 10.2 | 0.9  | 8.9     |
| Density (kg/m³)     | 632  | 46  | 7.3     |
**Fig. 5** Experimental non-linear elastic and idealised piecewise linear elastic stress–strain behaviour of OSB in bending

![Graph showing experimental and non-linear elastic stress-strain behaviour in bending](image)

**Fig. 6** Experimental non-linear elastic and idealised piecewise linear elastic stress–strain behaviour of OSB in torsion

![Graph showing experimental and non-linear elastic stress-strain behaviour in torsion](image)

**Fig. 7** Experimental non-linear elastic and idealised piecewise linear elastic stress–strain behaviour of OSB in compression

![Graph showing experimental and non-linear elastic stress-strain behaviour in compression](image)
linear portion of the measured mean data (between 10 and 40% of $F_{\text{max}}$). The latter portions of the model are based on the linear portion of the measured mean data between 40 and 80, and 80 and 100% of $F_{\text{max}}$ respectively. A similar approach is adopted for the torsion and compression stiffness and strength properties (Figs. 6, 7). It has been shown that a piecewise linear elastic model is adequate for modelling the behaviour of bending active OSB gridshells [30].

5 Validation of results with a single curved beam

The load-deformation behaviour of a curved OSB beam is measured and compared against a computational model (MattGrid) for bending active gridshells. The computational model uses an iterative dynamic relaxation algorithm which is described in [30] and is based on the model described in [31]. A piecewise linear elastic material model based on the data reported herein was implemented. A test case of a pin-ended single lath of length 1.7 m was used, 50 mm in width and 8 mm in thickness (Fig. 8). The ends of the lath were forced towards each other to form a curve with a midpoint rise of 200 mm. The lath was then subjected to a load at the midpoint until failure. A total of 10 laths were tested. The mean results are shown Fig. 9 along with the predicted results from MattGrid. A 10% error bar is also plotted for the mean computational results. It may be seen that the experimental load-deformation results can be modelled (within 10%) by using the mean material and section properties of the OSB material from Sect. 3.

6 Conclusions

Modified material testing methods were developed to determine the bending, torsion and compression material stiffness and strength properties of OSB for use in the design of bending active gridshells. Using these modified tests the bending, material torsion and compression properties of a single commercial OSB product were investigated for 16 standard panels. A high variability in both stiffness and strength was identified. As noted in [18], this has implications for formulating design rules for bending active gridshells. However, the variability of OSB tested as part of this study is in line with the variability of softwood solid timber in the published standards. The increased variation is consistent with the reduced specimen dimensions used for testing compared to those in the relevant standard [17]. In addition to variation having an influence on design rules, creep relaxation cannot be overlooked for structures subjected to permanent loads. Further investigation is required to understand the effect of creep relaxation for bending active gridshells.

Furthermore, a study was carried out on the variation in thickness of the test specimens. A high variation in the thickness relative to the nominal product thickness was noted. This variation also needs to be taken into account when formulating design rules for bending active gridshells. The bending strength to bending stiffness ratio for this OSB material ($f_{\text{m}}/E_{\text{m}} = 2.4$) makes it suitable for use in bending active gridshells. Additionally, the low flexural stiffness allows this material to achieve smaller radii of curvature than is possible with solid timber sections.

Arising from this study, a suitable material model is being developed with a clearly defined envelope for...
use in form finding and load analysis software (MattGrid). It was shown that a piecewise linear elastic constitutive model using the mean material and section properties is adequate for modelling bending active gridshell members. Finally, the results of this study have been used in a computational and experimental study of a medium scale OSB gridshell (Fig. 10), the results of which are detailed in [32].

Acknowledgements This study was funded by the Irish Research Council EMBARRK 2012 initiative (RS/2012/280).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Picardo V (2000) Quantification of the yeilds of Irish grown Sitka spruce in the new CEN strength classes. COFORD
2. TECO (2011) OSB Guide. http://osbguide.tecotested.com/osbhistrory
3. O’Carroll J (2004) Uses of home-grown Irish timber COFORD Connects Note Dublin
4. SmartPly (2012) SmartPly OSB2 Datasheet
5. Fisette P (2000) Building and construction technology. http://bct.eco.umass.edu/publications/by-title/the-evolution-of-engineered-wood-i-joists/
6. Adriaenssens S, Block P, Veenendaal D, Williams C (2014) Shell structures for architecture: form finding and optimization. Taylor & Francis, Oxford
7. Lienhard J, Alpermann H, Gengnagel C, Knippers J (2013) Active bending, a review on structures where bending is used as a self-formation process. Int J Space Struct 28:187–196
8. Happold E, Liddell W (1975) Timber lattice roof for the Mannheim Bundesgartenscha The. Struct Eng 53:99–135
9. Harris R, Romer J, Kelly O, Johnson S (2003) Design and construction of the downland gridshell. Build Res Inf 31:427–454. doi:10.1080/096132103200008007
10. Harris R, Haskins S, Roynon J (2008) The Savill Garden gridshell: design and construction. Struct Eng 86:27–34
11. Carpenter Oak & Woodland (2013) Orangery Gridshell. http://www.carpenteroakandwoodland.com/
12. Paoli CCA (2007) Past and future of grid shell structures. Massachusetts Institute of Technology
13. Douthe C, Baverel O, Caron J (2006) Form-finding of a grid shell in composite materials. J Int Assoc Shell Spatial Struct 150:53
14. EN789 (2004) Timber structures - Test methods - Determination of mechanical properties of wood based panels
15. EN300 (2006) Oriented strand board (OSB): definitions, classification and specifications
16. Lienhard J (2014) Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein. Universitätsbibliothek der Universität Stuttgart
17. EN12369-1 (2001) Wood-based panels: characteristic values for structural design—part 1: OSB, particleboards and fibreboards
18. Collins M, O’Regan B, Cosgrove T (2015) Potential of Irish orientated strand board in bending active structures. Paper presented at the 13th International Conference on Civil, Structural and Environmental Engineering, London, March 14–15th
19. EN408 (2010) Timber structures: structural timber and glued laminated timber—determination of some physical and mechanical properties
20. Roark RJ, Young WC, Budynas RG (2002) Roark’s formulas for stress and strain. McGraw-Hill, New York
21. EN326-1 (1994) Wood-based panels: sampling, cutting and inspection—part 1: sampling and cutting of test pieces and expression of test results
22. Jin J, Dai C (2010) Characterizing variability of commercial oriented strandboard: bending properties. For Products J 60:373–381
23. Toussaint MH (2007) A design tool for timber gridshells: the development of a grid generation tool. Msc thesis Delft University of Technology. http://homepage.tudelft.nl/p3r3s/MSc_projects/reportToussaint.pdf
24. Ashby MF, Jones RHD (1999) Materials selection in mechanical design. Butterworth-Heinemann, Boston
25. Institution of Structural Engineers (2007) Manual for the design of timber building structures to Eurocode 5. Institution of Structural Engineers
26. EN338 (2009) Structural timber :strength classes
27. EN323 (1993) Wood-based panels: determination of density
28. EN322 (1993) Wood-based panels: determination of moisture content
29. Wu Q, Suchsland O (1997) Effect of moisture on the flexural properties of commercial oriented strandboards. Wood Fiber Sci 29:47–56
30. Collins M (2016) A computational and experimental study of Irish orientated strand board in bending active gridshells. University of Limerick, Limerick
31. Adriaenssens SML (2000) Stressed spline structures, Ph.D Thesis, Doctoral dissertation, University of Bath
32. Collins M, Cosgrove T (2016) Computational study of bending active gridshells (in preperation)