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Assessment of structural performance of Accoya® wood for GluLam fabrication

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ABSTRACT: Accoya® GluLam beams were specified for use as an external foundation support detail for an innovative low carbon affordable home in the Scottish Highlands. This detail was identified in collaboration with Neil Sutherland Architects (NSA) LLP where the use of Accoya® GluLam would result in enhanced performance in exposed conditions. The Accoya® GluLam provides support to the superstructure formed from offsite fabricated closed panels therefore reduced movement over time due to moisture fluctuations was identified as a key design consideration in order to ensure serviceability criteria are met. Due to the nature of Accoya® (acetylated timber) a test programme was developed to determine its mechanical properties for specification as a structural component both in isolation and in combination. In order to assess the long term performance of acetylated GluLam a number of beams are currently being monitored using in-situ monitoring equipment over a minimum period of 12 months.

KEYWORDS: Acetylation, Durability, Mechanical Grading, Glue Laminated Timber, Post Completion Monitoring.

1 INTRODUCTION

The purpose of this research project was to determine the mechanical properties of Accoya® Pine via acoustic and structural testing in order to assess its feasibility as a structural component. A further objective of the research was to determine the viability of producing Accoya® Glue laminated (GluLam) timber for structural application.

A specific end application of the Accoya® GluLam, following on from this feasibility study, would be in a bespoke foundation detail specified by Neil Sutherland Architects (NSA). The Accoya® GluLam would act as a replacement to solid larch beams that are exposed to service class 2 or 3 conditions. Increased movement over time due to moisture fluctuations was identified as a key design consideration hence Accoya® is the ideal product for such an application given its increased stability and durability. Benefits of this detail include; reduced build time, reduction in carbon emissions and improved tolerances.

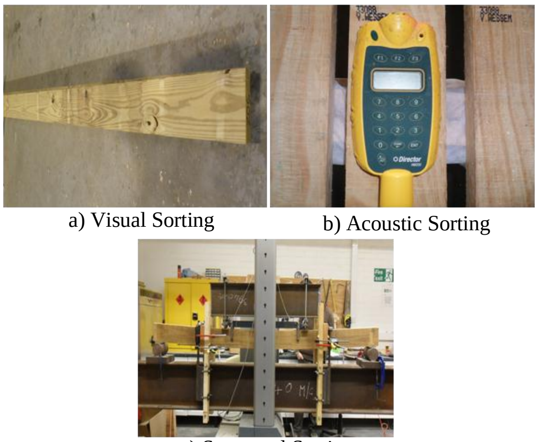
2 LAMELLA PRESELECTION AND QAULITY ASSURANCE PROCESSES

2.1 GENERAL

Glue laminated timber, commonly referred to as GluLam, (strength graded timber lamellas bonded together to form a sizeable structural component) has a wide range of structural applications, ranging from beams to columns to truss members. In this particular case the end application was the use of Accoya® GluLam in bespoke foundation detail for NSA. Therefore, the structural properties of the material to be used in the GluLam fabrication had to be quantified via both a destructive and non-destructive method and the validity of the quality assurance (QA) demonstrated. As a result of this a rigorous quality assurance (QA) process was undertaken as part of the study in order to:

- Determine the feasibility of using Accoya® for structural application
- Provide a method for optimising the resource available
- Provide all necessary information required for academic rigour

The QA process consists of 3 key principles which include visual, acoustic and structural sorting at varying stages of the GluLam fabrication process.



a) Visual Sorting b) Acoustic Sorting

c) Structural Sorting

Figure 1: *Lamella sorting process*

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2.2 VISUAL SORTING

Each piece of timber was visually assessed and correspondingly graded for structural purposes in accordance with BS EN 4978:2007 (1). The standard specifies the permissible limits for two visual strength grades, general structural grade (GS) and special structural grade (SS), timber that did not meet the specification for either (GS) or (SS) was rejected and not used in fabrication of the GluLam beams.

2.3 ACOUSTIC SORTING

Acoustic technology is widely acknowledged as an accurate and efficient non-destructive method to determine wood quality (2) (3). Acoustic sorting was carried out using a Hitman HM200 which is a handheld tool capable of quantifying Modulus of Elasticity (MoE) in bending a key mechanical wood property, quickly and accurately without causing damage to the sample.

In order to determine the MoE of a piece of timber using the Hitman HM200 the length, density and sonic velocity of the piece must be determined and Equation 1 applied. Therefore, each piece of timber was weighed using platform scales capable of measuring lengths of timber accurate to 3 decimal places and the sonic velocity (V), when excited using a standard hammer, was measured by the acoustic sorting kit.

$$MoE = \rho_k * (V)^2$$

Where;

ρ_k is the density of the piece in (kg/m^3).
V is the sonic velocity in (km/s).
MoE is the stiffness in (N/mm^2).

Equation 1 - *Acoustic Grade MoE Calculation*

The information from this process is as contained in Figure 2 and it is demonstrated from the MoE values obtained that there is a relatively large degree of variability ranging from C45 and above to C16 and lower in some cases.

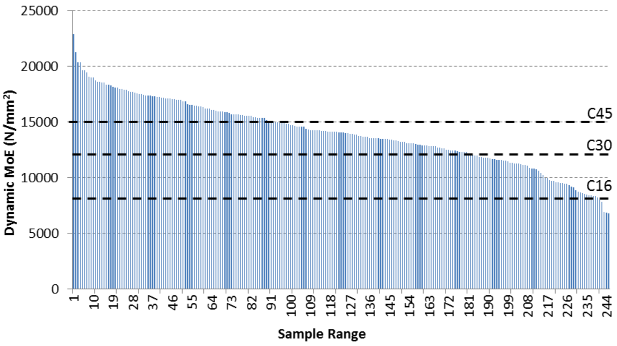


Figure 2: *Acoustic MoE (Individual lamellas)*

In total 245 lengths of Accoya® Pine were acoustically graded, each piece of timber was then classified in accordance with BS EN 338 – "Structural Timber Strength Classes" (4). This allowed timber with higher strength class to be specified for the outer lamellas of each beam and lower strength class for the inner lamellas optimising the available resource. It should be noted at this stage that boards which were acoustically sorted with a dynamic MoE greater than or equal to the equivalent C40 (as defined in BS EN 338) were designated for fabrication of the GluLam beams for NSA.

2.4 STRUCTURAL LAMELLA ACOUSTIC SORTING VALIDATION

In order to validate the acoustic sorting process a range of samples were selected and structurally graded in accordance with BS EN 408:2003 (5), this validation process is critical, particularly when considering modified timber. In total 50 pieces of timber were tested, this sample range covered both high grade (C50) timber and lower grade (C18) timber as determined by the acoustic sorting process.

Each piece of timber was loaded to failure in accordance with BS EN 408 (5) and contained in Figure 3 are the load displacement plots of the varying samples.

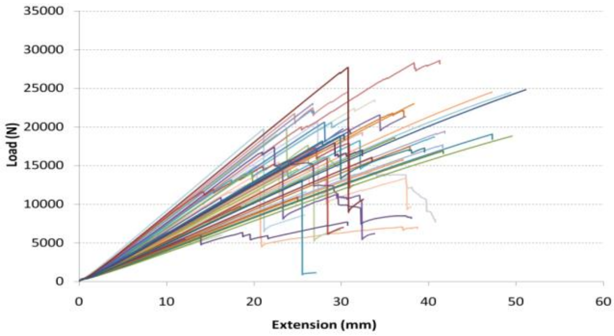


Figure 3: *Load vs. Extension curves – Individual lamellas*

It is clear from this that there is a large degree of variability (both in stiffness and in the max load sustained) in the structural behaviour of the timber samples selected for testing as would be expected given the pre-selection process ensuring a range in quality for validation purposes.

Figure 4 shows the dynamic MoE results from acoustic analysis compared relative to both the global and local MoE as determined from the structural sorting process. When considering the correlation of determination (R^2) values of 0.9455 and 0.9261were obtained for both global and local MoE respectively.

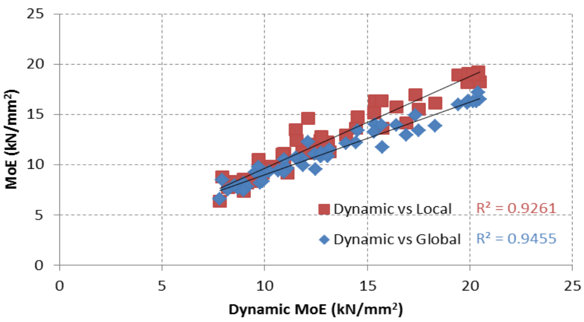


Figure 4: Static MoE vs. Dynamic MoE

Figure 5 shows the static and dynamic MoE values obtained for a range of samples from which it is clear that there is a large degree of variability. From the structural tests carried out it is evident that the timber selected would meet the required properties to be graded C24 however, implementation of the acoustic sorting process would allow timber with equivalent MoE of grade C24 up to and including C50 to be pre-selected if necessary (if stiffness in bending is taken as the main selection criteria).

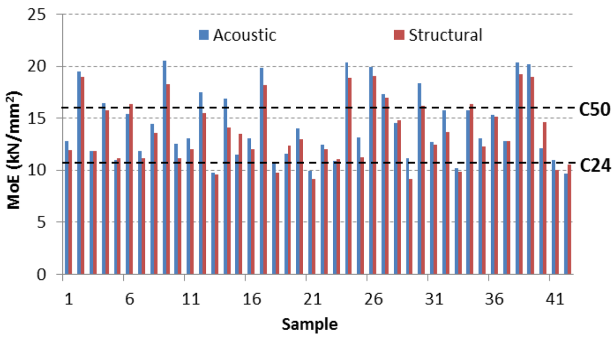


***Figure 5:** Accoya SYP equivalent grade (based on MoE values)*

2.5 STRUCTURAL LAMELLA FAILURE MODE CLASSIFICATION

Individual lamellas tested were classified through visual inspection on completion of the tests according to failure types as presented in Figure 6 by Bodig and Jayne (6). As a result of this it was identified that the majority of samples failed in a diagonal failure mode (1) evidence of which is shown in Figure 7.

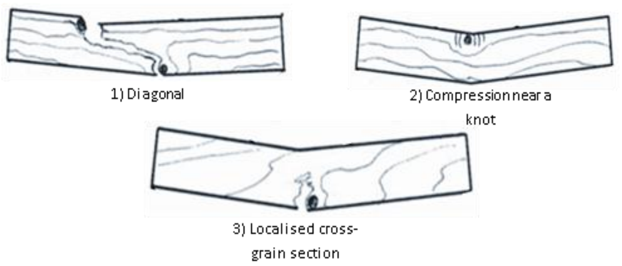


***Figure 6:** Failure types of clear wood in bending with span parallel*

a) 174 (1) b) 227 (1)

Note: (1) Refers to the mode of failure as defined by Bodig & Jayne (6)

***Figure 7:** Structural testing of lamellas – failure modes*

Of the individual lamellas tested it was noted from the visual sorting process that the majority of samples contained few defects and there was a large variation in the growth rate of each sample. The positioning and size of defects within the timber sections would have an impact upon the failure mode. Knots tend to cause grain variation with larger knots exaggerating this further. Timber with large knots subject to bending will therefore tend to fail quicker and in a more brittle fashion due to tension perpendicular to the grain taking place.

GluLam offers the opportunity to reduce the impact of defects on the structural performance through re-engineering the product. In order to take advantage of this the flaws within the timber must be situated away from areas of high bending stress, primarily the top and bottom chords of the beam at mid-span positions. A further re-engineering technique that would enhance this is the utilisation of finger jointing of shorter sections containing minimum flaws. Re-engineering therefore offers the opportunity to enhance the structural performance and optimise the use of resource if applied correctly and with adequate QA.

3 GLULAM STRUCTURAL TEST PROGRAMME

3.1 INTRODUCTION

Following this initial test programme and given its inherent structural properties, increased durability and dimensional stability it was identified that Accoya® GluLam (produced from Accoya® Pine) would be an appropriate solution for use as an external foundation detail for a number of low carbon dwellings in the Scottish Highlands (Dunsmore House).

In order to determine the mechanical properties of Accoya® GluLam and assess its feasibility for application as a structural component a further programme of work including; glue line bond strength tests and full-scale 4 point bending tests were carried out in accordance with the relevant standards. Due to the accuracy of results obtained from the initial test programme acoustic analysis was carried out on each of the test beams as well as those specified for application within Dunsmore House.

3.2 STRUCTURAL PERFORMANCE TESTING OF GLULAM BEAMS

A total of 15 GluLam beams were fabricated from 5 laminations of 38mm × 125mm for test purposes. The total beam dimensions were 185×125×3650mm. Fabrication of the GluLam beams was carried out at Norbuild in controlled conditions and the adhesive used was Purbond HB S309 (7).

a)Lamella segregation b) GluLam pressing

***Figure 8:** Fabrication of GluLam Beams*

BS EN 14080 (9) gives characteristic material properties for homogenous and combined GluLam and it is stated that in order to meet the requirements of a GL28 (combined) beam the central lamella should be strength class C24 or above and the outer lamellas of minimum C30. It is also stated that in order to meet the requirements of a GL32 (homogenous) beam the lamella should be of strength class C35 or above. Taking this into consideration a number of homogeneous and combined beams were specified during fabrication and Table 1 contains the make-up of the beams themselves optimising the use of material available.

Table 1: *GluLam lamella make-up*

Lamella as per Figure 8	Accoya® Pine - GluLam				
	Beam 1-2	Beam 3	Beam 4	Beam 5-11	Beam 12-15
1	C35	C30	C27	C35	C35
2	C35	C30	C27	C30	C27
3	C35	C30	C27	C24	C24
4	C35	C30	C27	C30	C27
5	C35	C30	C27	C35	C35
Note: Strength classes based on dynamic MoE from acoustic sorting					

In order to determine the strength and stiffness properties of each beam a series of structural tests were carried out in accordance with BS EN 408 (5). Four point bending tests were carried out which allowed the critical structural parameters for beam design to be determined, global and local MoE in bending, Bending Strength. At the time of testing the 'Single span method' was adopted in order to determine Shear Modulus (G). The average local and global MoE, Bending Strength and Shear Modulus results for each of the beams are compared relative to the minimum requirements for GL grades according to BS EN 14080 (9) in Figure 9, Figure 10, Figure 11 respectively.

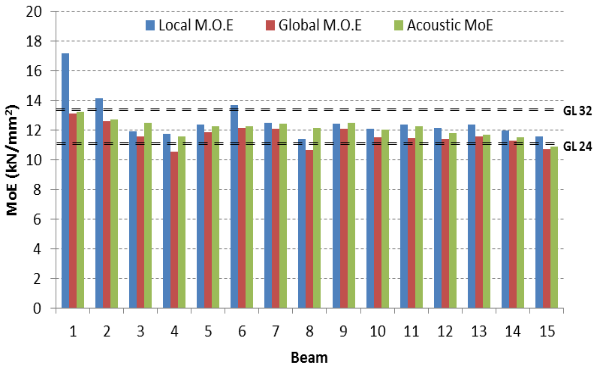


Figure 9: *Individual Beam Local MoE Comparison to GL Requirements*

Figure 9 demonstrates that when considering the local MoE in bending all of the beams meet the required stiffness properties for GL24 and in most cases GL28 is achieved. When considering the homogenous GluLam beams (Beam 1 and 2, as shown in Table 1) both beams meet the required stiffness criteria to be classified GL32 which is in line with the guidance given in BS EN 14080.

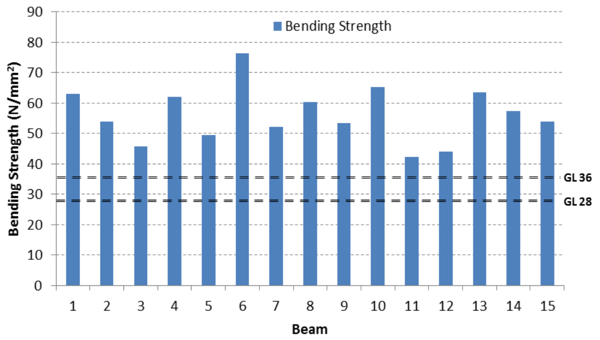


Figure 10: *Individual Beam Bending Strength Comparison to GL Requirements*

Figure 10 shows that the all of beams comply with the Bending Strength requirements for GL36 - this is due to the nature of GluLam where the bending strength of lower grade solid section timber is enhanced due to the redistribution of stresses to stronger timber sections.

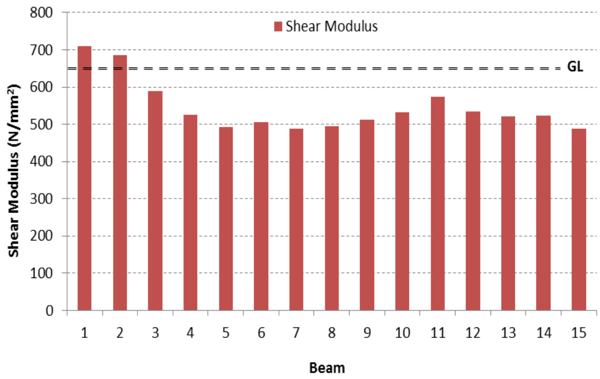


Figure 11: *Individual Beam Shear Modulus Comparison to GL Requirements*

When considering the Shear Modulus Figure 11 shows that a number of the beams did not meet the required value as stated in BS EN 14080, however, the 'single span method' is not without problems and has since been replaced. In order to determine a more representative value for shear modulus of Accoya® Pine further research is currently planned using the 'torsion test method' as prescribed in the revised standard.

Given that bending stiffness is generally the most critical factor in beam design (depending upon the load span conditions) a GluLam member fabricated using Accoya® Pine could feasibly be pre-selected using the methods described in this study to produce a GluLam product that meets the equivalent requirements of GL24, GL28 and perhaps GL32. As previously noted timber which returned a dynamic MoE value equal or greater to C40 was specified for fabrication of the beams for Dunsmore House and had this material been incorporated in the test programme the overall strength and stiffness values would have increased.

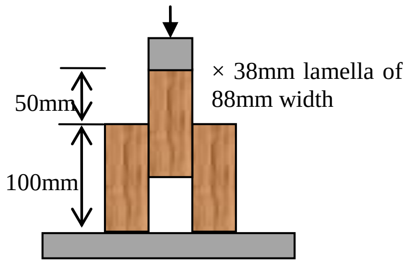
3.3 GLUE LINE BOND STRENGTH TESTS

Visual inspection of the beams after testing revealed that in the majority of cases failure was caused by tension in one of the bottom laminations, this type of failure can be seen in Figure 12.

Figure 12: *GluLam Failure modes*

There were no signs in any of the beams of failure occurring due to delamination in the glue line. However, as part of the QA process it was deemed necessary to carry out a further program of tests to assess the glue line bond strength by means of bond strength tests.

The current standard EN 14080:2009 (9) is a draft, therefore the test method prescribed is not current beyond April 2009 and an up-to-date version of the code was unavailable at the time of writing. It is understood that the current method within the code is not without problems and given that it induces eccentric loading of the joint it would provide a conservative estimation of the bond strength. Therefore, for the purposes of this exercise a "bespoke" test set up as shown in Figure 13 was employed.



Note: load applied in the direction of the end grain

Figure 13: *Glue line bond shear strength*

In order to determine the glue line bond strength a number of samples were tested as shown in Figure 13 - each sample was loaded at a constant rate till failure occurred. After testing each sample was visually assessed (Figure 14) and an estimated percentage wood failure to the nearest 5% recorded.

Figure 14: *Bond strength failure modes*

BS EN 386:2001 (10) gives guidance for the minimum wood failure relating to the shear strength. It is evident from the information provided that as the shear strength increases the wood percentage failure is seen to decrease. BS EN 386 also gives a calculation method to determine the minimum wood failure based on the average shear strength, when comparing this value to the average result from visual assessment (Figure 15) there is a difference of only 3.25%.

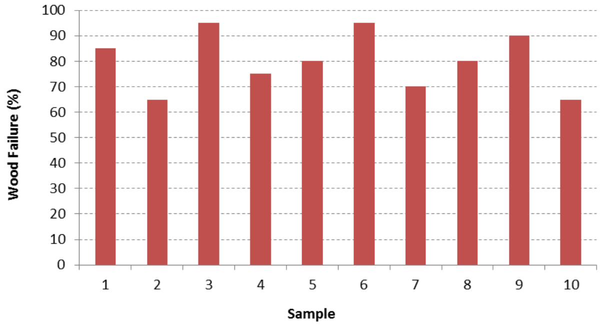


Figure 15: *Wood percentage failure – GluLam beams*

Figure 16 shows the comparison of samples when considering the calculated shear strength from which it is clear that there is a degree of variability – max value 9.29 N/mm^2, min value 5.41 N/mm^2 and a mean value of 6.75 N/mm^2.

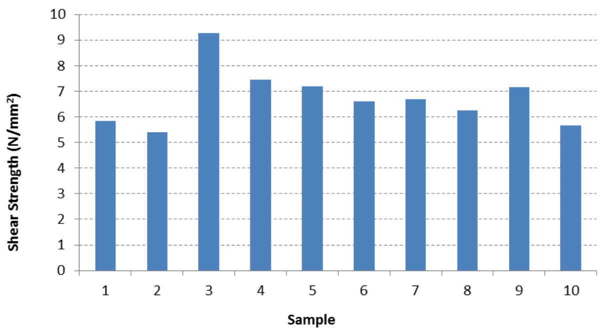
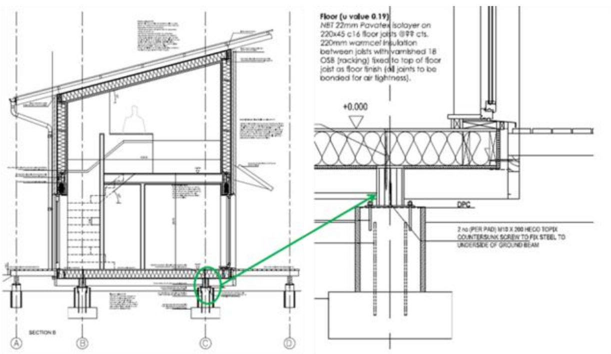


Figure 16: *Shear Strength – GluLam beams*

4 DUNSMORE HOUSE – GLULAM

Based on the findings of this study a number of Accoya® Pine GluLam beams have been specified for use as an external foundation support detail as shown in Figure 17.



Note: Stainless steel fixings must be specified for use with Accoya Wood

Figure 17: *Dunsmore House – foundation detail*

As previously stated timbers that returned a dynamic MoE value greater than or equivalent to 14000 N/mm^2 from the acoustic sorting process were segregated and specified for fabrication of the beams for Dunsmore House. Each beam was fabricated based on the architect's specification and subsequently acoustically graded to ensure that they comply with the minimum engineer's requirements, GL28. Results from acoustic sorting of each beam are given in Figure 18 from which it is evident that each beam returns a dynamic MoE greater than the equivalent stiffness value of GL32 as stated in BS EN 14080.

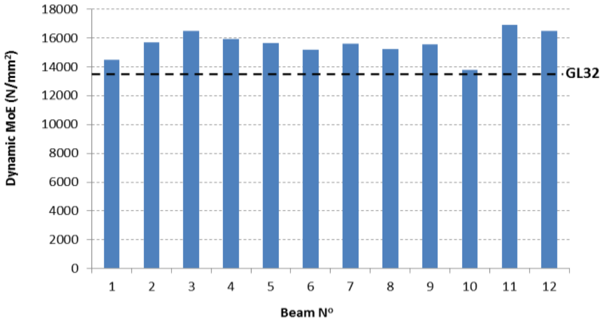


Figure 18: *Dunsmore House – Acoustic GluLam analysis*

In order to assess the long term effects on the structural performance of Accoya® GluLam a number of the beams at the homes in the Scottish Highlands (Figure 19) are currently being monitored using post completion measurement techniques (including vibrating wire strain gauges) over a period of 12 months.

Figure 19 - Accoya® Glulam in-situ

Given that this is an on-going assessment limited results are available. The construction of this semi-detached dwelling utilises two main building materials – one fabricated using Scots Pine, the other Sitka Spruce. Two beams were chosen for in-situ monitoring for each house type and Figure 20 shows the strain gauge data to date for each beam.

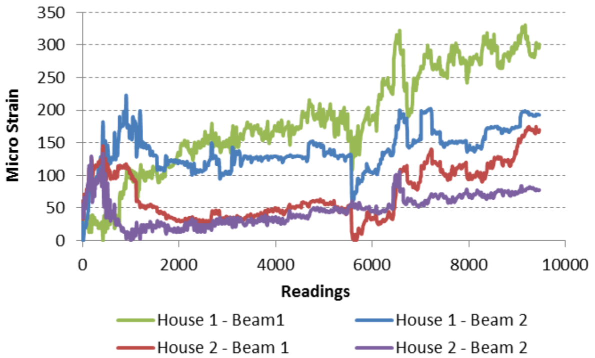


Figure 20: *Dunsmore House – post completion monitoring*

In-situ monitoring began once each of the foundation support beams were installed and has continued throughout the construction period which explains the constant increase in strain. Scots Pine is typically denser than Sitka Spruce hence the strain for House 1 is greater in comparison to House 2.

5 SUMMARY

Based on the findings of this study GluLam fabricated from Accoya® Pine is viable when considering the key structural performance criteria tested. To an extent the sample range for this study was limited but it demonstrates that through appropriate visual and acoustic sorting Accoya® Pine can be segregated to produce a GluLam product fit for structural applications particularly where durability and moisture movement are major design considerations.

Further to this it demonstrates that pre-selection and optimal specification of material through acoustic and visual sorting allows the production of at least GL24 and up to GL32. If the relatively higher grade material can be selected, segregated and optimally specified during the GluLam fabrication process applying appropriate sorting techniques then the available resource can be better utilised thus adding value.

Post completion monitoring is currently underway and is anticipated to run for a minimum of 12 months at which point the data will be reviewed and further analysis made to the long term effects of Accoya® Pine GluLam.

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