

UNDERSTANDING THE COMPATIBILITY OF UK RESOURCE FOR DOWEL LAMINATED TIMBER CONSTRUCTION

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ABSTRACT: Dowel Laminated Timber (DLT also known as Brettstapel) is a technique of constructing large-scale solid timber panels for use as structural or non-structural elements. The technique utilizes smaller sawn timber sections mechanically fixed together with timber dowels by means of moisture movement. Moreover, as DLT utilizes locally sourced material and does not include adhesives it can be considered a natural low carbon value engineered product.

This paper presents the findings of an industry and academic collaborative project to determine the viability of producing DLT from UK Larch given the spread of Phytophthora Ramorum (commonly referred to as Ramorum disease). The work undertaken evaluated:

- The compatibility of Larch resource with the production method including a review of supply chain considerations in Scotland.
- Timber-dowel-timber connection research to determine optimized configurations relative to panel load span conditions.
- Structural appraisal of DLT systems for use in flatwise orientations for floor panel specification.
- Determination of intermediate floor panel to wall detailing in accordance with Eurocode 5.
- Appraisal of DLT panels trial in a new build project as floor panels.

Keywords - Brettstapel, product development, in-situ testing, engineered wood products

1 INTRODUCTION

Advances in the understanding of timber has enabled a large variety of engineered wood products (EWPs) to be developed. EWPs exploit the inherent mechanical properties whilst reducing any natural variations in strength and stiffness that may exist within timber. Many EWPs are produced using adhesives to create a uniform bond between individual pieces of timber to allow for, larger sizes, more efficient section shapes and greater reliability to be created. However, the use of adhesives reduces the overall environment impact credentials and often require a high level of capital investment for fabrication.

One EWP, which can avoid the use of adhesives, is Brettstapel also known as Dowel Laminated Timber (DLT) or Dowel-lam. DLT is produced by stacking a series of rectangular timber sections (laminations) and joining them together using hardwood dowels that are set through perpendicular to the centre of the laminations. The fixity between the laminations is created by inserting the hardwood dowels (between 12-24mm diameter) at a lower moisture content than

the surrounding laminations and the in service moisture equilibrium. The moisture differential created between the two timber types causes the hardwood dowels to swell securing the laminations together to form a solid timber panel.

Concerns have been raised about the suitability of the home-grown UK resource to provide the quality and quantity required for high quality timber products (Moore *et al.* 2008). The Centre for Offsite Construction + Innovative Structures (COCIS) at Edinburgh Napier University in conjunction with MAKAR Construction Ltd undertook a pilot study to understand and assess the available homegrown UK timber resource for use within DLT panels and the strength and stiffness characteristics of DLT panels formed from UK larch. Finally a pilot project which utilised homegrown larch DLT as an intermediate floor panel was also realised and the preliminary findings of the Post Occupancy Evaluations (POE) are reported.

The pilot project can provide a 'benchmark' for the technical information needed to overcome the environmental, organisational and technical challenges associated with its implementation of the DLT systems by:

- Demonstrating the benefits of producing a solid timber panel from locally sourced timber and creating information that could be used for a future Environmental Product Declaration (EPD);
- Allowing the design to be structurally certified using available knowledge from test work undertaken;
- Implementing a quality assured fabrication process with acoustic grading technology to ensure it is of the standard necessary satisfying the engineering specification; and
- Evaluating the performance of the product in-situ.

2 DLT Resource Selection and Performance Criteria

2.1 Dowel and lamella resource selection

The main criteria for the production of DLT from UK home-grown timber resource is the availability of the material for the laminations and the dowels with required associated material characteristics. Although, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), is the most abundant available softwood species available of use in EWPs accounting for approximately 50% of the UK softwood resource (FC, 2015a) Larch (*Larix decidua*) was the resource considered within this study for lamella material. Although Larch only represents 8% of all conifer timber volume it is being actively felled to contain the spread of Phytophthora Ramorum (commonly referred to as Ramorum disease). It is estimated that 6000 ha (approximately 1,200,000 m³) of standing trees will be removed, generating around 240,000 m³ of sawn larch (Moore, 2015). This represents a 7% increase in the amount of UK grown softwood coming into the market from 2015 levels, creating industry pressure to develop scenarios for its use (FC, 2015b).

Typically in European DLT production European beech is used for the dowels but little is known about the suitability of other hardwood species within a DLT panel. Beech represents a mere 5% of entire hardwood available in the UK, other hardwoods including oak (16%), sycamore (8%) and ash (12%) represents a far

greater proportion of the available hardwood (FC, 2015). Whilst there is a small precedence for using cleft oak dowels in traditional post and beam framing within the UK (Shanks & Walker, 2005), there are currently no hardwood saw millers producing dowels at any significant scale. The precedence set in mainland Europe was therefore followed but other hardwood species required to be considered due to their prevalence in the British Isles.

2.2 Supply chain integration

DLT development will need to (initially at least) be able to integrate into the existing upstream supply chain and adapt to the material that is readily available, in this instance Larch, in order to be cost competitive. In this regard it is common practice in the UK to select material from stock timber sizes referred to in BS EN 336:2003 (BSI, 2003) as 'target sizes' which are available in a number of differing cross sections and alternative finishes (Table 1). The finish of a piece of timber in this instance refers to its tolerance class: tolerance class 1 (T1) is normally for rough sawn timber and tolerance class 2 (T2) for timber that is planed or machined. For DLT construction a regularised T2 section of timber is necessary to limit gaps between the laminations and provide a uniform bearing area at points of support.

Table 1. Common target sizes for sawn UK timber tolerance class (T2), from BS EN 336 (BSI, 2003)

Thickness mm	Width mm								
	72	97	120	145	170	195	220	245	295
35		✓		✓	✓	✓	✓		
44	✓	✓	✓	✓	✓	✓	✓	✓	
60				✓	✓	✓	✓		
72		✓		✓	✓	✓	✓	✓	✓
97		✓		✓		✓	✓	✓	✓
145				✓					✓

For dowel production the researchers were unable to source the required amounts of hardwood dowels (at approximately 20mm diameter) using the UK grown hardwood resource. A selection of hardwood dowels from the UK resource were therefore produced from pre-dried (to approximately 6% moisture content) prismatic blanks by using a spindle moulder and a bespoke jig. The piece had to be manually inserted into the spindle moulder in two stages to shape both halves of the section, often this did not align completely creating a non-uniform cylindrical cross-section along its length. On average the dowels produced by this method had a tolerance of $\pm 10\%$ from the target diameter of 20.5mm, the level of tolerance achieved meant that dowels also had to be sourced from Europe where the dowels are created using a dye cut process to ensure uniformity.

2.3 Physical Mechanical Properties

The physical and mechanical properties of a piece of timber is dependent on a variety of parameters that include type of species, site location, moisture content, duration of load and the presence of defects within the timber (Moore *et al.*, 2008). For DLT manufacture the laminations are required to be kilned dried to a moisture content of $12\pm 2\%$ and the dowels to much lower levels so that they expand and lock the system together after fabrication. However, timber in the UK is typically dried down to a target value of $\approx 18\%$ moisture. When kiln drying resource to low levels of moisture content issues with the dimensional stability are exacerbated. With respect to DLT lamella production the key areas of concern when considering timber distortion are; box, spring, twist and cup. This is particularly important considering EWP production given the amount of allowable distortion in a timber lamination is smaller than the visual override requirements stated in EN 14081-1 (BSI, 2011).

Research into the use of UK larch is lacking and no compendium exists for their properties beyond what was stated in Lavers (1969). The Centre for Wood Science and Technology (CWST) at Edinburgh Napier University conducted a large testing program on UK Larch for the purpose of assigning grade settings. From these results it was shown that the greatest potential yield for UK Larch was to grade the material as C22 for commercial production. The characteristic values of larch shown in Table 2 indicate that UK larch is equivalent strength classification grade of C20 but has the density of grade C35 in accordance with BS EN 338 (BSI, 2009).

Table 2. Characteristic values for UK larch (CWST, 2015)

Strength Properties			
Characteristic bending strength	$f_{m,k}$	21.2	N/mm ²
Mean bending strength	$f_{m,mean}$	39.1	N/mm ²
Stiffness Properties			
Mean elastic modulus	$E_{0,mean}$	9.57	kN/mm ²
Density			
Characteristic density	ρ_k	406	kg/m ³
Mean density	ρ_{mean}	494	kg/m ³

Hardwood dowels are normally used to join the stacked softwood lamella because of their higher ratio of moisture movement and typically greater strength properties as compared to softwood laminations. The overall operation of a DLT panel will depend greatly on the adhesion that is provided when the pre-dried hardwood dowels expand as they reach moisture equilibrium with the surrounding lamellae. The static friction force created by this will be dependent on the static friction coefficient (μ_s) between the two elements and the normal forces being

exerted. The static friction coefficient (μ_s) between the timbers will differ due to the individual characteristic of that species of timber, the moisture content of the timber and the finish of both pieces of timber at the connection interface. For a general comparison between the species it can be assumed that the only variable is the normal force caused by expansion of the dowel. A simple comparative analysis of the dowel expansion was conducted on European sourced dowels by drying a selection of 20.75mm dowels in accordance with BS EN 13183-1 (2002). The dowel were then left in a service class 1 environment and the dimensions were measured at regular intervals to ascertain moisture expansion across the two transverse planes of timber (radial and tangential) and along the longitudinal plane. The results (see Table 3) indicate that the dowel with the greatest expansion ratio per percentage of moisture increase is beech, but ash and sycamore both exhibited marginally smaller expansion and should also be considered for DLT production due to their increased prevalence in the UK.

Table 3. Moisture expansion of selected hardwood species

Dowel species	Average Radial dimension changes			Average Tangential dimension changes			Overall dimension changes	
	Radial (mm)	%MC Diff.	%Dim/%MC	Tangential (mm)	%MC Diff.	%Dim/%MC	Average, both directions (mm)	%Dim/%MC
Ash	1.98	9.42	0.21	3.26	9.42	0.35	2.62	0.28
Beech	2.56	10.66	0.24	4.76	10.66	0.45	3.66	0.34
Sycamore	1.92	10.58	0.18	3.65	10.58	0.34	2.79	0.26

3 STRUCTURAL APPRAISAL OF SYSTEM

3.1 Dowel mechanical properties

A very simplistic appraisal of the dowel quality obtainable from the UK, was achieved through testing the UK resourced dowels in accordance with the 3 point bending test depicted in BS 373 (BSI, 1957). Twenty samples of each species were loaded tangentially across the grain to ensure lowest failure strength (Church and Tew, 1997) and the mean results from the preliminary appraisal are shown in Table 4.

Table 4. Dowel bending test strength and stiffness results summary

Dowel species	Mean dowel diameter, d_{mean} (mm)	Mean bending stress, $f_{m,mean}$ (N/mm ²)	Mean, Modulus of Elasticity E_{mean} (N/mm ²)	Mean bending strength, $M_{y,mean}$ (kNmm)	Mean density, P_{mean} (kg/m ³)
Ash	21.57	127.05	9825	125.12	588
Beech	21.36	129.13	10492	123.62	666
Sycamore	21.52	108.39	8032	106.06	593

3.2 Connection tests

A series of double shear connection tests were conducted parallel and perpendicular to the grain on UK sourced 140mm wide x 30mm thick regularised larch with a selection of different European sourced hardwood (ash, beech and sycamore) 20.75mm diameter circular dowels. Before testing was undertaken all the larch and hardwood dowels were stored in a climatically controlled store at 20±3 °C and 65±2% relative humidity for two weeks prior to the start of testing. Each test was loaded monotonically across the entire width of the sample in accordance with the loading procedure in BS EN 26891 (1991) and the geometric considerations in EN 1380 (2009), there were 4 test samples for each species. For these initial tests the slip of the connection was measured only using platen displacement and the connection was terminated when significant failure occurred or 15mm slip was reached.

Table 5 depicts a comparison of the mean stiffness and strength characteristics of the connection using different species configurations. No one species combination creates a compelling argument to be considered over another and the precedence in Europe should be considered for the production of pilot panels.

Table 5. Comparative analysis of the connection tests

Lamination Species	Dowel Species	Connection Orientation	Maximum average load (kN)	Slip Modulus (kN/mm)
Larch	Ash	Parallel	12.67	4.29
		Perpendicular	11.27	3.13
	Beech	Parallel	14.84	4.73
		Perpendicular	10.97	3.07
	Sycamore	Parallel	11.12	3.81
		Perpendicular	7.81	2.49

3.3 DLT System Structural Appraisal

To fully understand the structural performance of the DLT panel a series of fullscale panel's tests were conducted. The panels consisted of 140mm deep by 300mm wide and 2520mm long Larch dowel-lam panels joined together with 20mm diameter Beech dowels at 300mm centers. A subset of 100 dried and regularised larch lamellas utilized for production were acoustically categorised utilising a handheld (Brookhuis MTG960) resonance grading machine based on the Edinburgh Napier determined grade settings for UK larch (CWST, 2015). The larch was graded as C22 or above for 95% of samples.

A series of four point bending tests were conducted (shown in figure 1) on five full size panels to determine the local, global modulus of elasticity (MOE) and the bending strength of the panel in accordance with EN 408 (BSI, 2010b). The DLT panels were orientated in a flatwise orientation to represent a typical floor span and were loaded across their whole width loaded at a constant rate of 0.08 mm/s ensuring that failure of the panels was reached within 300 seconds.

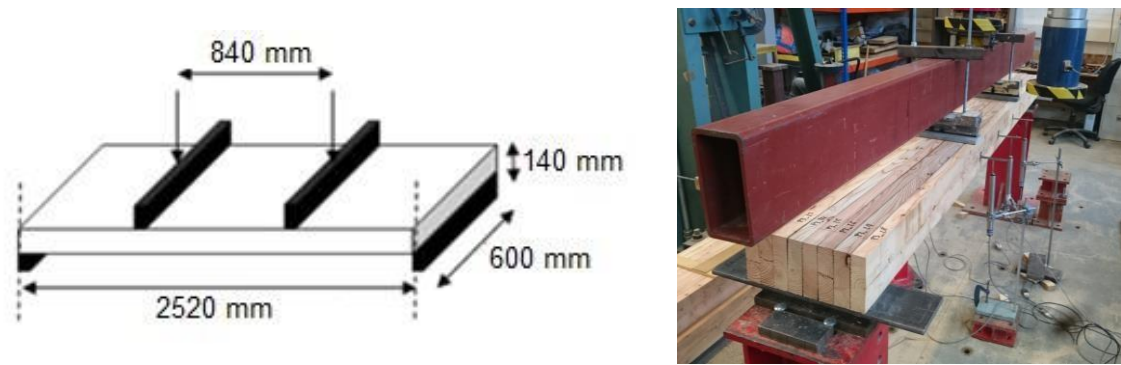


Figure 1. Four point bending test arrangement

The load deformation of the panel tests illustrate the behavior of dowel-lam under load conditions (Figure 2) and the results from the four point bending test on UK larch are shown in Table 5. The irregularity of the load deformation curves suggest that some laminations within the system are weaker than others and as they break (mostly due to tension failure in the lower edge of the panel, initiated at locations with noticeable macro defects such as knots or areas where large slope of grain were apparent) the stress is being transferred through the dowels to the neighbouring lamination and the panel is still capable of taking the load before complete failure occurs.

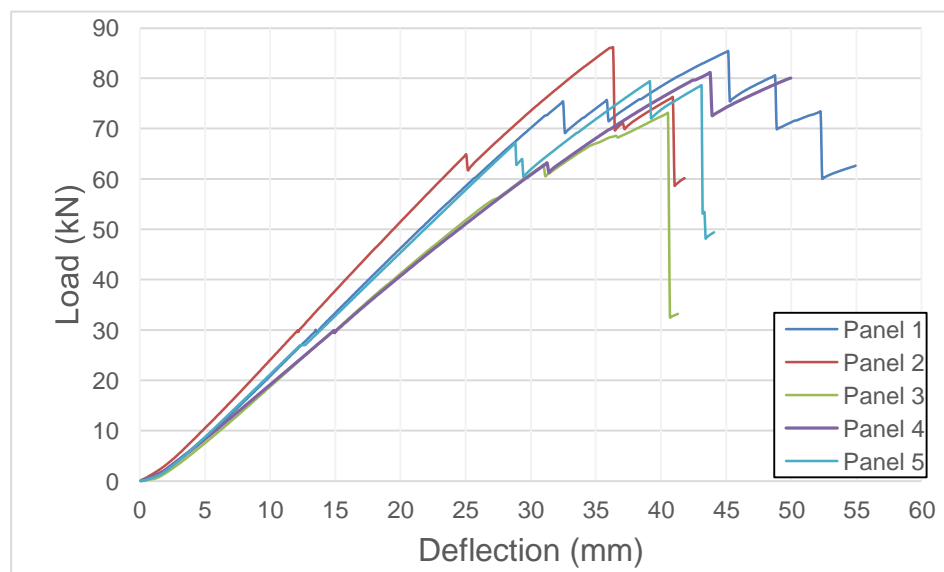


Figure 2. Typical load vs. deformation curve for UK larch DLT panels

Table 5. Summary of bending tests results

Species	Local MOE (N/mm ²)	Global MOE (N/mm ²)	Bending Strength (N/mm ²)
Larch	10484	9671	33.9

There is an expectation that higher values for strength and stiffness properties will be achieved for the panel than mechanical properties of the individual planks owing to the dowels transferring more stress to stiffer, stronger planks. Test results have shown that bending strength of the dowel-lam panels was higher

than what can be expected for C22 grade timber. However, in EC5 section 6.6 (BSI, 2004) the system strength factor for a mechanically fixed laminated plate is limited to 1.1. From the limited amount of tests conducted on UK produced panels, it seems likely that the European guidance for an enhancement factor can be followed. Similar to standard timber floor construction, serviceability is typically the limiting condition. Vibration checks must be carried out in accordance with EN 1995-1-1 and the relevant National Annex.

4 FLOOR PANEL TO WALL DETAILING TO EC5

The information ascertained from the resource and supply chain compatibility research and structural appraisal process was utilised to specify DLT floor panels for a new build project by MAKAR Construction in Fortrose, Northern Scotland.

4.1 Manufacture and Storage Considerations

The DLT panels were manufactured with the timber laminations at a moisture content as close as possible to be expected in service moisture equilibrium to avoid excessive shrinkage. Consideration was given to the storage of the panels prior to installation and during erection to avoid excessive moisture movements occurring. The moisture variations that will occur naturally within an internal environment will cause the timber to swell by small amounts. The movements that occur across the width of the panel will be exacerbated because of its solid formation; therefore the fixing and detailing around the edge of the panel need to be considered carefully.

4.2 Details and Connections

The main issue with connections is related to the nature of DLT being a series of planks, which are only connected by a dowel. These planks may be as little as 20mm thickness so direct fixing into a panel may occur at a joint between planks and have little strength. Hence typical connections use angled fasteners. The fixing of any sheathing then requires extra consideration to maintain edge distances. This can be achieved by using wider planks on each edge of each panel and these should be coordinated with the sheathing so that the nailing lines in the sheathing correspond to these thicker planks. This requires good coordination with the fabricators.

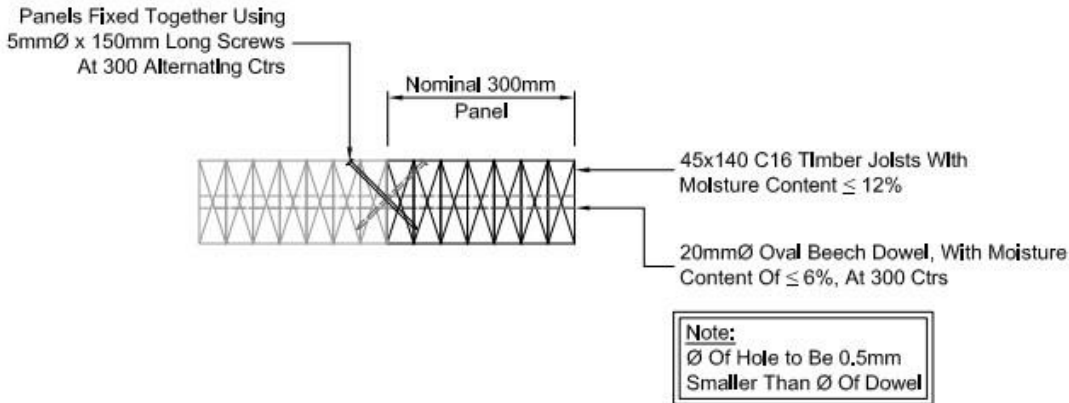


Figure 3 - Connection detail between individual dowel-lam panels

Connections between individual DLT floor panels of up to 600mm width are typically made with self-drilling screws installed at an angle of 45° in pairs (Figure 3). Laps may be used in order to ensure a flat surface for floors. Several panels may be fabricated prior to delivery to site.

In balloon construction the DLT panels can bear directly onto ledger plates that are fixed back to noggins within the timber panel or directly into the head plate of the panel (see figure 4). In platform frame construction the DLT floor can simply bear directly onto the head of a panel and the timber walling can be built directly from it, if excessive amounts of cold bridging is a consideration the floor deck can be set on the internal edge of the panel and a rim beam can be used on the outer edge of the panel to form a cavity that can be filled with insulation.

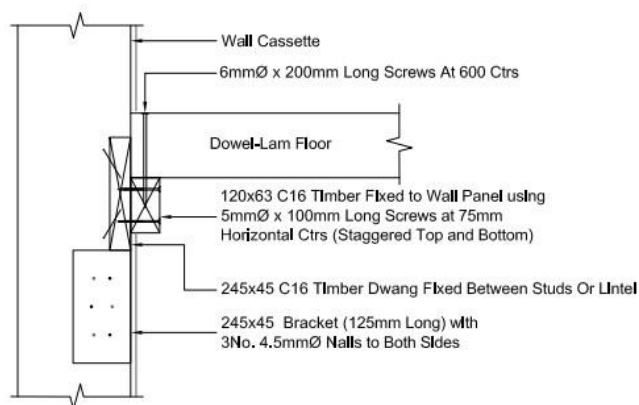


Figure 4 – DLT panel to timber wall panel detail

Figure 5 demonstrates an intermediate UK larch DLT panel, installed in the pilot project, here one edge of the panel is free to move as swelling occurs. Often where the panel runs parallel to the walling an expansion joint should be allowed to accommodate any swelling that could occur.



Figure 5 - Dowel-lam intermediate floor in practice

4.3 Post Occupancy Evaluation

The final stage of the research was to carry out a POE study on the pilot project that included a DLT suspended immediate floor (Figure 5). The study was conducted 4 months after the installation of dowel-lam panels. The performance of which were measured in-situ to ascertain the structural and thermal performance. The DLT floor, manufactured and constructed according to the

details indicated above, consists of 140mm deep by 300mm wide and 4190mm long Larch dowel-lam panels joined together with 20mm diameter Beech dowels at 300mm centers. Creating a floor of total area of 20 m². Moisture content measurement taken from 9 different locations at the underside of the floor gave an average value of 15%, which satisfactory considering that the house was not yet inhabited. Despite the significant loading that the floor was subjected to, the deflection did not exceed 5 mm throughout, which is 20% of allowable deflection for this sort of structure according to EC5.

In addition the building was subject to an air permeability and smoke pen test at second fix and at completion. A qualitative heat loss evaluation using infra-red thermography also took place to reveal any thermal bridging and envelope heat loss. The depressurisation and pressurisation air permeability tests performed at second fix revealed an average result of 7.16 m³/m².h@50Pa. Upon completion the house was re-tested and a final result of 5.25 m³/m².h@50Pa was obtained. Figure 6 shows how service penetrations and floor defects impacted on the results during the second fix testing.

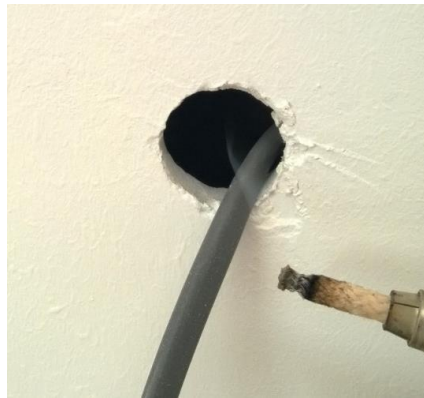


Figure 6. Smoke escaping into service penetration

Infra-red thermograms revealed consistency in the junction between the floor and the wall cassette, this connection has been identified to have an important impact on the thermal efficiency of the structure. Internally there aren't any low surface temperatures that would reveal thermal bridging or heat loss. Figure 7, shows a difference of 1 to 2°C between surfaces, observed particularly in the far right junction between two walls and the floor.

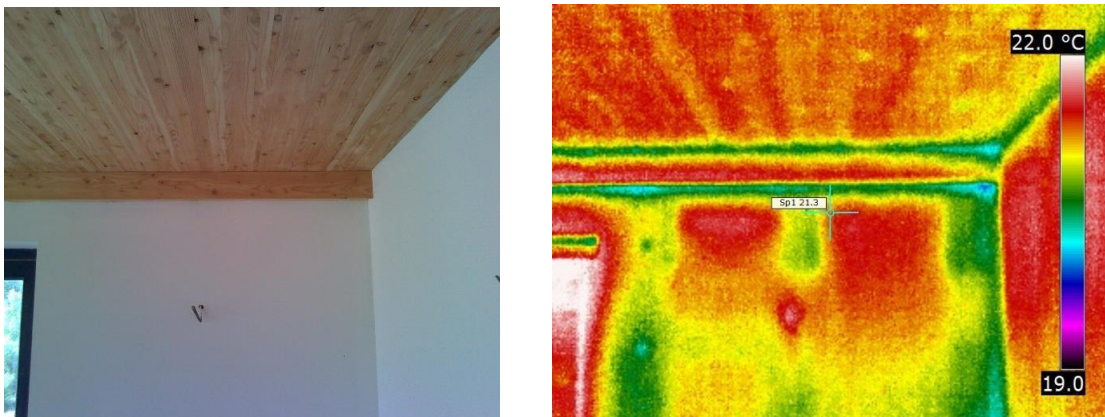


Figure 7. Infra-red thermography analysis in the junction between the dowel-lam floor and the wall cassette

5 CONCLUSIONS AND RECOMMENDATIONS

Overall the results have indicated that UK grown timber can be used in principal to manufacture DLT panels for floor construction. The creation of a DLT panel from the homegrown resources has shown that it elevates the strength performance of the raw resource beyond levels currently given in EN 1995-1-1. Much of the development of the panel will be to ensure cost certainty through all phases of the manufacture and design of the product, including distortion analysis to ascertain yields from drying to lower moisture contents and optimisation of the dimensions of timber for its production. Further research is on going into the embedment and expansion characteristics of UK sourced dowels, laminations and their combined embedment to optimise the panel construction using the UK resource. Vibrations in floors have not been investigated and these should also be taken into account for floor designs, hence future testing of dowel-lam should include the vibration checks to meet all the serviceability limit state criteria required by EN 1995-1-1 (BSI, 2004). With respect to the thermal performance, this small case study has been able to identify the benefits of a floor system into a closed panel wall. The whole-house air permeability tests provide a significant result in comparison with the best practice result required by the Scottish Building Regulations of $<7\text{m}^3/\text{m}^2.\text{h}@50\text{Pa}$ (SBS, 2015). Thermal bridging, partly evidenced in the infrared thermography, between walls and the floor have shown that little heat loss occurs, partly due to the attention to detail between the wall and floor connection.

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