Short Term Scientific Mission Report

DURABILITY OF BONDED-IN BFRP RODS IN IRISH TIMBER: PHASE 2

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PURPOSE OF THE SHORT TERM SCIENTIFIC MISSION

Despite much work being done in the last number of years on the behaviour of bonded-in rods little research has been carried out on their durability. Work at Queen's University Belfast (QUB) has focused on the behaviour of BRFP rods bonded-in to Irish grown Sitka spruce tested at ambient temperatures, however in order to fully realise the potential of this reinforcement method durability testing needed to be undertaken.

In Phase One of this STSM accelerated ageing by vacuum-pressure soaking was used to simulate the deteriorative effects of long term moisture ingress on a bonded-in rod connection. This vacuum-pressure regime is an extreme form of moisture cycling giving a worst case scenario representation. This second phase explores an alternative method of aging by cycling relative humidity which represents a more realistic exposure condition for structures designed for service classes 1 and 2.

Following a review of literature by both institutions in Phase 1, a cycling regime mimicking a typical Northern European annual relative humidity cycle was agreed upon with specimens being cycled through a minimum 65% RH and an upper limit of 90% RH at a constant temperature of 20°C. Phase 2 involved the testing of these specimens and the capacities of these aged specimens are presented in this report.

The durability performance of the bonded-in rods at both moderate and severe exposure conditions can be assessed to give a fuller picture of the impact of aging on bonded-in BFRP rods in Irish timber. This allows a better assessment of their suitability for applications such as reinforcement and repair.

SUMMARY OF PHASE ONE

The pressure regime used for aging in Phase 1 was adapted from prEN 16351:2013 - Annex D and BS EN 14080:2013 - Annex C Cl. C.4.4 and had been used previously at the host institute, NUIG, to investigate bond quality in CLT specimens (Sikora, Harte, & McPolin, 2014). Pull-out capacity of the specimens was then tested after being stored for 7 days in standard conditions of 20°C temperature and 65% relative humidity. Specimens were tested with a loading rate of 3mm/min in a Denison testing machine. Maximum pull-out load and failure method were recorded. Nine specimens were tested.

Average pull-out force recorded for the nine pressure soaked specimens was: P_{aged} = 39.1kN. This represented a 22% decrease in strength compared to samples tested at ambient temperature. The spread of results was found to be larger in the aged samples with twice as much variation seen than in the results of those tested at ambient temperature.

Figure 1: Delamination observed

Delamination was observed as the principal failure mode in aged specimens. This was characterised by debonding of the epoxy and the BFRP bar (Figure 1).

This ageing by pressure soaking gave some insight in to the impact of aging on the durability behaviour of bonded-in BFRP rods in very severe environments but in order to analyse durability behaviour of the specimens under more realistic conditions relating to service classes 1 and 2 a moisture cycling regime was established.

DESCRIPTION OF WORK CARRIED OUT AND KEY RESULTS OBTAINED

PART 1: ACCELERATED AGING BY MOISTURE CYCLING

Following installation of specimens in the variable climate chamber at NUIG in Phase 1 of this STSM, specimens were removed from the climate chamber, stored at standard temperature and relative humidity until their moisture content had regulated to 12 ±1% and tested to failure.

There are several test configurations seen in the literature that can be used to assess pull-out capacity of a rod bonded-in to timber. The pull-bending set-up was chosen for this study as it allows the effects of bending forces to be taken in to consideration along with axial forces in what is essentially a pull-pull type test. The system allows bending strength of the bonded-in rod connection to be evaluated by removing the timber in the section being loaded so that the only resistance is from the BFRP bars bonded-in to the timber. This type of pull-out test has been used successfully in investigating the bond behaviour between glulam elements and GFRP (Barros, Sena-Cruz, & Faria, 2001; Sena-Cruz et al., 2012).

EXPERIMENTAL PROCEDURE

MATERIALS

Class C16 Irish Sitka Spruce (Picea sitchensis), sourced from Balcas Sawmill, Co. Fermanagh, with a size of 75mm x 225mm sawn section was used. The C16 classification shows that the timber has a 5th percentile bending strength of 16N/mm^2 and a density of 370kg/m^3. Material testing verified these strengths but highlighted the high variability in the timber used.

12mm diameter Basalt Fibre Reinforced Polymer (BFRP) rods were used in this experimental programme. These rods were found to have a tensile strength of 920 N/mm^2 under a low loading rate of 0.2kN/s (Tharmarajah, 2010). Unlike steel or some other FRPs, no extensive cleaning of the rods was required prior to bonding as they are sand-coated which provides a good surface for adhesion.

A two-part thixotropic gap filling epoxy was used. This adhesive only flows under shear so is ideal for applications such as overhead beam repair, jointing overhead and such.

SPECIMEN PREPARATION

Moisture content of each sample was recorded during sample preparation and before testing using a handheld moisture meter. Moisture content was found to range from 9% to 11%, which corresponds to Service Class 1 (EC5, Part 1-1).

An auger drill bit was used to drill holes of 16mm diameter and 280mm length, thus producing a glueline thickness of 2mm all around the 12mm diameter rods. Guide blocks were used to ensure the holes were drilled accurately. The holes were drilled 42mm in from the specimen edge; this corresponds to an edge distance, *a =3.5d* where *d* is rod diameter.

The surface of the specimen around the drilled hole was sealed with candlewax to ensure that any glue overspill would not penetrate the sample and result in a false increase in strength around the hole.

The holes were 2/3rds filled with glue using a hose cut to the length of the drilled hole on the end of the nozzle of the glue cartridge to ensure that the glue filled all voids from the very bottom of the hole to the top.

Rods were twisted into place to allow any trapped air to be expelled and for the glue to fully coat the surface of the rods.

A device was used to hold the sample in place and ensure the 2mm bondline was maintained whilst drying. When the glue had hardened the steel hinges and strain gauges were fitted. The samples were then left until the glue had a minimum of 7 days to cure fully before testing.

CYCLING REGIME

The moisture cycling regime used was based on weather data gathered from a weather station based at NUIG. IT was agreed that standard temperature of 20° would be maintained and that relative humidity would cycle between a minimum of 65% and a maximum of 90%. Readings taken in the climate room are presented in Figure 2 below.

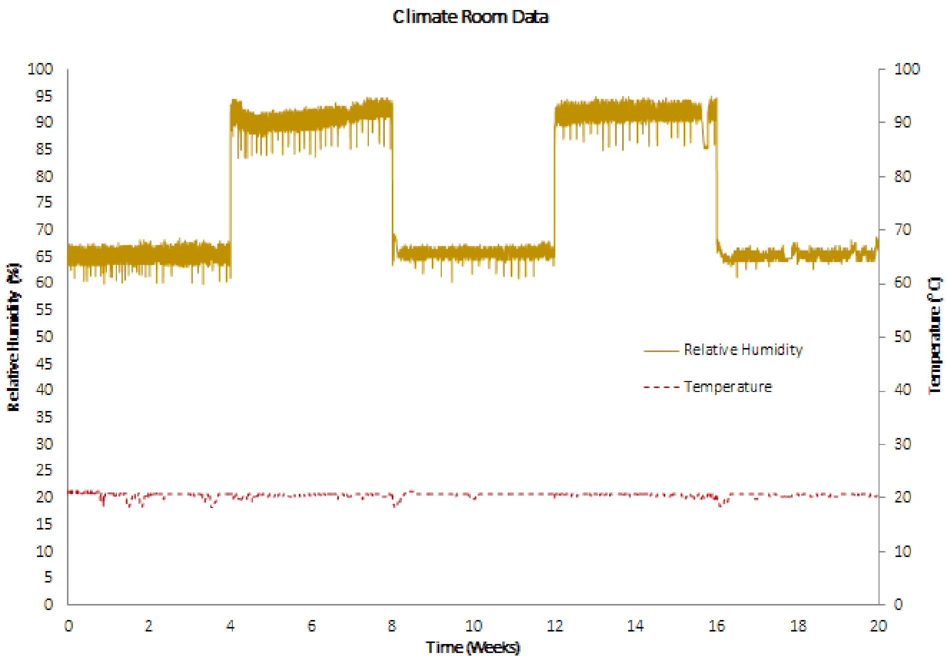

Figure 2: Climate Room Data

TEST SET-UP

The pull-bending test set-up requires a hinge system to be developed that can transfer load through the sample such that the bonded-in rod is under bending forces as well as axial forces. Figure 3 shows this pull-bending test set-up.

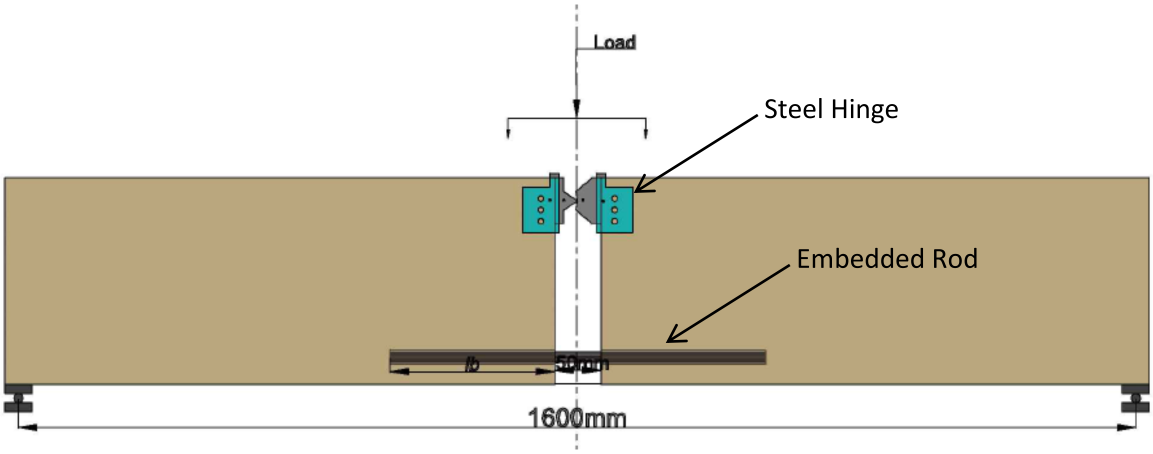

Figure 3: Pull-bending test set-up

A strain gauge was placed on the BFRP rod at mid-span on each sample to monitor the stress-strain in the rod as the sample is loaded. Samples were loaded at a stroke rate of 0.1mm/sec to failure.

Deflection at mid-span and net horizontal movement of the bar as the sample was loaded was recorded with transducers pictured in Figure 4.

Failure load was recorded when the sample could not take any additional load. The mode of failure was recorded also. Nine specimens were tested due to the high variability of the timber used.

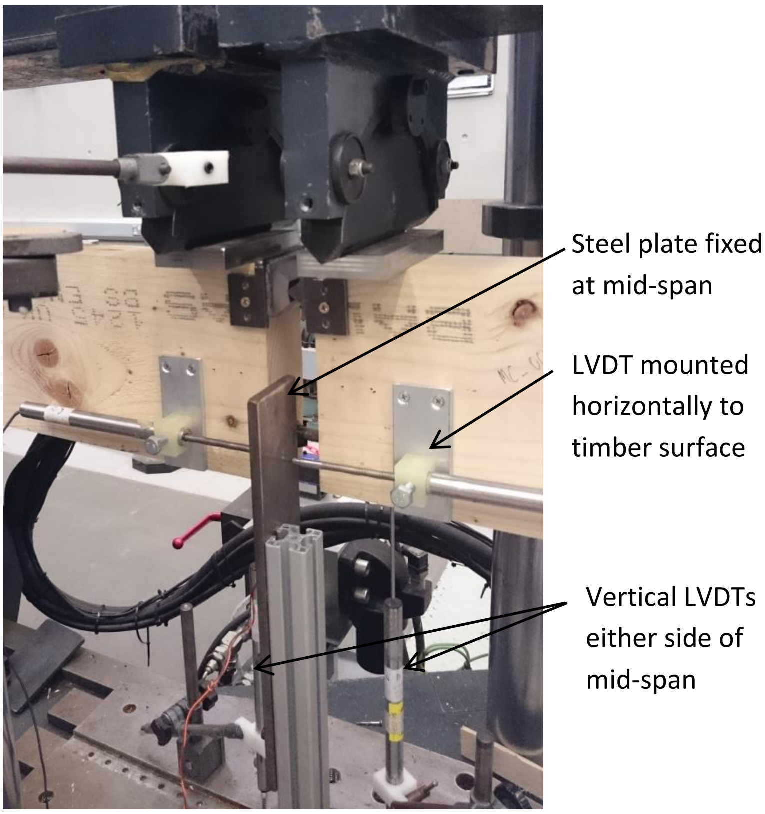

Figure 4: Instrumentation

SUMMARY OF KEY RESULTS

GENERAL

Average failure strength for the specimen set was recorded as 74.47kN. Two distinct failure modes were observed with the majority of specimens exhibiting failure in the timber around the bond (Figure 5) and only one specimen experiencing failure of the bond between the epoxy adhesive and the BFRP rod (Figure 6). These are denoted in Table 1 below as a timber pull-out or adhesive/rod failure.

Figure 5: Pull-out Failure

Figure 6: Glue/Rod Failure

Table 1: Summary of Pull-Bending Test

Specimen	Failure Strength (kN)	Failure Mode
MC01	65.94	Pull-out
MC02	82.47	Glue/Rod failure
MC03	80.54	Pull-out
MC04	73.44	Pull-out
MC05	77.71	Pull-out
MC06	88.40	Pull-out
MC07	69.47	Pull-out
MC08	65.80	Pull-out
MC09	66.50	Pull-out
Average: 74.47 kN, Standard Deviation = 7.77kN		

INFLUENCE OF AGING

When compared with similar specimens tested in ambient conditions no significant loss of strength was observed. Aged specimens had average failure strength of 74.47kN whereas non-aged specimens failed at an average of 75.44kN. Variation within the samples sets was 0.11 and 0.10 respectively confirming that aging for a short time period does not have a detrimental impact on the bond strength.

Comparing failure modes for the two sample sets it was observed that the failure mode also remained unchanged after short-term aging with 83% of the entire specimens tested failing with a pull-out in the timber as was expected.

Suggested future work would be to observe the pull-out strength after a longer period of moisture cycling using the method outlined above.

PART 2: VACUUM-PRESSURE LOADING

Vacuum-pressure loading is a method of rapid accelerated aging whereby a specimen is submerged in water, a vacuum formed and then a pressure applied such that the specimens become fully saturated. The specimen is then removed from the pressure vessel and dried for a set time period.

Following an in-detail review of the data obtained during Phase 1 of this STSM an inconsistency was identified in the resulting relative moisture contents of the specimens after being dried for the specified time period. In order to assess if this had an impact upon the strength of the specimens a repeat test was performed with nine specimens, this time dried to a specific relative moisture content rather than for a set time period. Moisture content was defined by weight of the specimen after drying relative to the original specimen weight. Two moisture contents were specified so as to examine the variation within and between specimens of these, namely, 125-130% and 135-140% by weight. These moisture contents were chosen to provide two distinct points for comparison of strengths and were achievable within the time frame of the STSM, on an average 125% was reached with 30hrs drying at 60°.

EXPERIMENTAL PROCEDURE

Dimensions of the specimens remained the same as those from Phase 1. All nine specimens consisted of a 12mm diameter BFRP rod embedded 280mm in to the centre of a piece of solid C16 timber of size 75x225mm and length 300mm. Each specimen had a glueline thickness of 2mm. Rods protruded 150mm from the face of the timber and had an epoxy plug of 100mm length to enable the specimen to be gripped easily in the jaws of the testing machine.

Similarly to Phase 1, the pressure regime used was adapted from prEN 16351:2013 - Annex D and BS EN 14080:2013 - Annex C Cl. C.4.4, one cycle was performed as detailed below:

- Submerge in water between 10 and 20 °C ensuring that all end-grain surfaces are exposed to the water
- Vacuum at 700 – 850 kPa for 30 minutes
- Pressurise at 500 – 600 kPa above atmospheric pressure for 2 hours
- Dry until specimens reach a moisture content by weight of 125-130% or 135-140%

Pull-out strength of the specimens was tested immediately when the required moisture content by weight was reached.

Considering the specimen dimensions which were limited by the dimensions of the pressure vessel, the pull-out method used was a direct push-pull test. Specimens were tested with a loading rate of 3mm/min in a Denison testing machine. Maximum pull-out load and failure mode were recorded.

RESULTS

The average pull-out strength recorded for the nine specimens was 44.4kN. Results obtained are detailed in Table 2.

Table 2: Summary of Vacuum-Pressure Aged Specimens

	Specimen	Weight after drying (%)	Failure load (kN)
Dried to 135-140%	20_01	141.6	35.92
	20_02	136.4	44.92
	20_03	135.6	48.85
	20_04	139.3	40.25
Dried to 125-130%	20_05	124.9	62.3
	20_06	125.0	44.08
	20_07	128.5	44.77
	20_08	124.8	39.96
	20_09	125.5	38.34

Comparing these results obtained to those from Phase 1, average strength was moderately higher with, F_{Phase1}=39.10kN and F_{Phase2}=44.4kN. When compared to similar specimens tested under ordinary conditions, an average loss of strength of approximately 10% is observed after aging suggesting that this reinforcement method will perform reasonably well over time.

INFLUENCE OF MOISTURE CONTENT ON STRENGTH

Moisture content was measured as a percentage weight compared to the dry weight of the specimen before vacuum-pressuring. As shown in Figure 7 no strong correlation was observed.

When looking at the spread of results within each of the groups of moisture content, least variation was observed in specimens from Phase 1 that had dried to 100-110% moisture content with cv_{100}=0.150. However again there was no obvious correlation between moisture content and variation.

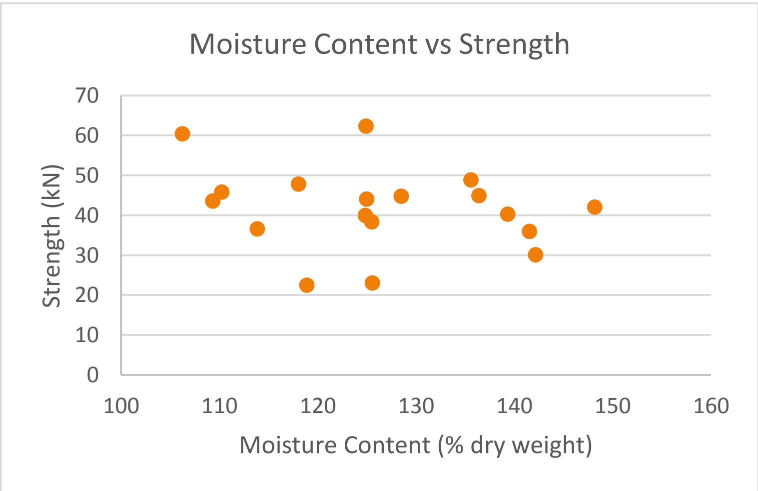

Figure 7: Influence of Moisture Content on Strength

FUTURE COLLABORATION AND DISSEMINATION

Links between NUIG and QUB have been reinforced through this STSM and it is hoped we will continue to share information on the work that is ongoing in each institution. Future work may include moisture cycling of specimens for a longer term to further investigate the durability behaviour of these bonded-in rods.

The results of the research carried out on this Phase of this STSM has been included in an abstract submitted to the Fourth International Conference on Sustainable Construction Materials and Technologies (SCMT4). This abstract has been accepted subject to review of the conference paper.

Research carried out over the two phases forms the basis of a journal paper currently in draft and will form a chapter of my PhD thesis.

OTHER COMMENTS

I would like to take this opportunity to once again thank COST FP1101 for the facilitating this research and enhancing my knowledge; Dr Annette Harte and her technical team at NUIG for being so accommodating and assisting me with the experimental aspects of this research; and my own supervisor Dr Danny McPolin of Queen's University Belfast for allowing me the time away from the university to carry out this STSM.

REFERENCES

Barros, J., Sena-Cruz, J., & Faria, R. (2001). Assessing the embedded length of epoxy-bonded carbon laminates by pull-out bending tests. Retrieved from http://repositorium.sdum.uminho.pt/handle/1822/12845

Sena-Cruz, J., Branco, J., Jorge, M., Barros, J. A. O., Silva, C., & Cunha, V. M. C. F. (2012). Bond behavior between glulam and GFRP's by pullout tests. *Composites Part B: Engineering*, *43*(3), 1045–1055. doi:10.1016/j.compositesb.2011.10.022

Sikora, K., Harte, A. M., & McPolin, D. (2014). Bond quality of cross-laminated timber from Irish Sitka spruce. In *Civil Engineering Research in Ireland 2014*. Belfast, N. Ireland. Retrieved from http://www.irishtimber.org/uploads/1/9/2/0/19209479/sikora_et_al__bond_quality_of_clt_from_irish_sitka_spruce_ah.pdf

Tharmarajah, G. (2010). *Compressive Membrane Action in Fibre Reinforced Polymer (FRP) Reinforced Concrete Slabs*, PhD Thesis, Queen's University Belfast.