

LICONS Final Technical Report Summary

Task 4: Design Optimisation

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TRADA Technology Ltd**

Task 4.1: Validate design models

This task involved the assessment and validation of various proposed design expressions for the prediction of the strength of bonded-in FRP rods. The task included the prediction of the pull-out behaviour of (a) rods bonded parallel to the grain and loaded parallel to the grain, and (b) rods bonded parallel to the grain and loaded perpendicular to the grain (carried out as part of Task 2.3). A design expression for determining the optimum depth of a counter-bore, used in cases where anchorage lengths were presented as part (c).

- (a) OBU undertook a preliminary investigation into various aspects of bonded-in rods, which was reported in *Task 4.1: Report Preliminary test series - Experimental verification of design procedures*. This included investigations into tension-tension vs. tension-compression tests methods, and a modified GIROD specimen configuration. This was completed in March 2004 and provided insight and direction for the following main experimental work. *Report Task 4.1: Main test series - Verification of design calculations* was completed in April 2005. This involved an extensive experimental programme that investigated the application of thermoplastic FRP rods bonded into various timber species using two very different gap-filling adhesives. Various design expressions were compared against the experimental findings and a number of important conclusions were highlighted. Notably, the failure mode of the pull-out specimens was found to be different depending on the bonded embedment length. Predictions borne out of the researcher's findings were very good and matched that of the large test beams investigated in Task 5. Worryingly, many of the proposed design expressions over predicted the pull-out strength. Also in contrast to previous work undertaken in the GIROD project, timber density was shown to have a significant effect on pull-out performance. There appears to be much needed work yet to be done before robust design expressions can be used with confidence.
- (b) Legnodoc srl carried out experimental tests on specimens manufactured by OBU that were similar in material and form to that tested in (a) except the loading was applied perpendicular to the grain, in general accordance with EN 383, which was completed in March 2005. The tests results formed part of *Task 2.3: Laboratory tests – Embedding tests according to EN 383*. These confirmed that the

standard could be used for FRP rods. It also concluded that timber density had a significant effect on strength.

- (c) Work on the optimum depth of a counter-bore, introduced in cases where only short anchorage lengths can be used, was carried out and a paper was presented at the Euradh 2005 conference in Oxford, UK, on the 7th-9th September 2005, entitled '*An analytical method for the determination of end-of-hole profiling in bonded-in rod connections for structural timber*'.

Task 4.2: Consideration of abnormal conditions

The most significant and detrimental abnormal condition was determined by the project partners to be that of high temperatures. Fire was also considered early on in the project but the lack of available facilities curtailed this line of investigation. LNEC produced a report that included (a) the effect of temperature on epoxy adhesives, (b) the effect of temperature gradient on bonded timber elements and (c) glue-line temperature prediction.

- (a) A set of experimental tests was carried out to provide some additional understanding into the influence of temperature (22°C to 80°C) on the behaviour of two construction-type epoxy adhesives.

The results obtained showed that epoxy adhesives soften and lose strength at relatively low temperatures. These results lead to the conclusion that epoxy repaired timber, under the action of fire or under high service temperatures, could be potentially hazardous. Thus, it would appear that any rehabilitation and/or repair of timber structures involving structural epoxy adhesives should always take into consideration the service temperature effect on the adhesive performance.

- (b) A set of experiments was conducted to investigate how effective the protection of the timber offered against excessive heating of the bondline in a joint inside a structural timber element. The investigations were performed using a specimen designed to simulate the common situation where two timber beams are connected by means of a bonded in rod, made of either steel or glass fibre reinforced polymer (GFRP). Three wood species were used to assess the effect of timber species on temperature, i.e. spruce, pine (with low, medium and high density) and a tropical timber, and two different timber covers were studied. The rods were tested (a) partially exposed and (b) fully hidden, allowing in (a) the evaluation of direct exposure of the rod to the environment temperature and its influence, if any, on the glue line temperature evolution. The temperature cycle used consisted of triangular temperature variation within a time span of 24 hours, ranging from 23°C at 50% of relative humidity to 80°C at 25% RH.

From the results obtained it could be seen that the temperature in the glue line follows closely the temperature of the surrounding environment. The resulting data showed the existence of a small damping of maximum and minimum temperature relatively to external ambient temperature (2°C or 3°C for the specimens with smaller cross section and ~10°C for the ones with the larger cross section). The temperature damping was observed both during the heating and cooling phases, and depended mainly on the heating rate and from the timber cover (both in the transverse and longitudinal directions). Pronounced phase shifts (from 1 to 2.5 hours) were also observed during the testing. Notably, the phase shifts and temperature damping were more-or-less independent of wood species and of rod type.

It was concluded that the service temperature to which the timber structures are exposed strongly influences the temperature reached inside the bonded elements and at the glue line. Because of this, although the service temperature, even in extreme conditions, is unlikely to lead to degradation of the timber structural elements, or, reinforcing elements, it may limit the performance and durability of bonded structural joints where adhesives exhibiting low glass transition temperatures are used. This preliminary work, therefore suggests, that the maximum in-service temperature could well be experienced at the glue line, depending on timber cover thickness, and thus dictates the minimum glass transition temperature of the proposed adhesive.

- (c) In order to predict the heating of the glue line for other heating rates and cross sections, a 2-dimensional FE model was used. The influence of the timber cover was also evaluated through the numerical model, and three timber covers were used to calculate the temperature damping and the phase shift.

A good agreement of experimental and theoretical data was obtained. The numerical simulation allowed the prediction of the temperature developed in the glue line for different timber covers in this simple geometry, the model used was a 2-dimensional model. To evaluate more elaborate repair geometries that could be used in bonded repair systems it was suggested that a three dimensional transient model would be more appropriate in order to obtain good predictions of the temperature gradients achieved in service conditions.

Task 4.3: Construction of full-sized mechanical tests with reference to varying timber species

OBU and TRADA Technology provided the main input into the development of the joint configurations and parameters to be investigated in the main test series. The main material parameters included combinations of two or four rods, or, two or four plates. The variations in joint configurations included

right-angled or sloped butted timber and also gap-filled or not filled at the butted joint. LNEC proposed two loading configurations: four-point flexure (constant moment) and three-point flexure (induced shear). Details of the joint configurations and material parameters are given in the output reports from Task 5.

Task 4.4: QC test development

Rotafix Ltd provided the main input into the chosen QC test methods for on-site acceptance of bonded-in rods. These included (a) an *in-situ* thermal measurement of the state-of-cure of the adhesive used on-site, (b) compressive lap shear tests on timber blocks bonded on-site to assess adhesion and shear capacity, and (c) an *in-situ* load verification on the actual bonded-in rod configuration. The proposed QC methods were evaluated as part of tasks 8 and 9. LNEC conducted tests on the thermal (exotherm) measurements of a number of commercial gap-filling epoxy adhesives.