Bonded Fibre Reinforced Polymer Strengthening in a Real Fire

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BONDED FIBRE REINFORCED POLYMER STRENGTHENING IN A REAL FIRE

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ABSTRACT

FRP strengthening is critically dependent upon the bonding adhesive. The adhesive used is typically an ambient cure epoxy with a glass transition temperature as low as 60ºC. This paper describes the performance of bonded FRP strengthening within 'real' compartment fires, one of which was allowed to grow past flash-over (the Dalmarnock Fire Tests). The aim of these real fire tests was to compliment the laboratory-based fire tests on FRP strengthened members that are currently being undertaken at various research centres. Plate and near-surface-mounted FRP strengthening were applied to the ceiling of a concrete structure, and the FRP was protected using an intumescent coating and gypsum board protection, alongside FRP that was left unprotected. During the fire tests, temperatures and strains were recorded in the adhesive layer and inside the concrete slab. The tests demonstrated the vulnerability of FRP strengthening during a real compartment fire. The glass transition temperature was rapidly exceeded in the adhesive for all samples. The tests also demonstrated that NSM strengthening has superior integrity to plate strengthening during a fire, and that gypsum board fire protection can be used to reduce the temperature of the adhesive, hence slowing degradation of the FRP strengthening.

INTRODUCTION

The fire performance of bonded FRP strengthening has yet to be fully addressed (Porter & Harries, 2007). In July 2006, the BRE Centre for Fire Safety Engineering at the University of Edinburgh conducted fire tests in a cast in-situ concrete building in Dalmarnock, Glasgow (Abecassis Empis et al., 2007). The opportunity was taken to include bonded FRP strengthening within two full-scale compartment tests: Test 1, which was allowed to grow to post flash-over (the uncontrolled test); and Test 2, in which the ventilation was controlled to prevent flash-over being reached. Flash-over describes sudden spread of fire throughout a compartment, due to radiation feedback from the smoke layer and the walls of the compartment igniting the fuel and pyrolysed gases. Flash-over signifies the transition from a growing fire into a fully-developed fire. These are believed to be the first 'natural' or 'real' fire tests on FRP strengthening, all other reported tests having used furnaces that follow a prescribed time-temperature curve which can be quite different to reality (Drysdale, 1998).

It is the adhesive used to bond the FRP to the existing structure that is usually most critical during a fire. The glass transition temperature of a typical 2-part, ambient-cure epoxy adhesive is in the range 60ºC to 85ºC (Kodur et al., 2007), well below the temperatures expected in a compartment fire. The FRP component is often preformed off-site using different bonding adhesives that are post-cured to give a higher glass transition temperature, but this is not possible for the joint between the FRP and the substrate.

Current practice recognises that the fire performance of bonded FRP can be a concern. For example, UK design guidance states that "*Unless a rigorous analysis is undertaken it is sensible to neglect the strengthening from FRP in fire situations*" (Concrete Society, 2004). Neglecting the FRP strengthening may be acceptable if the FRP is not needed for the structure to carry the loads that are present during a fire scenario, which are lower than the ultimate load for which the strengthening is designed. Where FRP strengthening is designed to carry permanent loads, however, the strengthening could be required during a fire. This might occur where the dead load is increased by high density filing systems, or where FRP is used to carry the perimeter stresses around a new hole cut into a concrete slab to insert services. If the strengthening is required during a fire, the bonding adhesive must be insulated using a suitable protection system. Current guidance highlights the lack of knowledge on suitable protection systems: "*Regulations may require the application of an over-coat layer, which has been tested on the fully-cured composite system*" (Concrete Society, 2004). This is impractical for the design engineer who is working to a limited budget and timescale, and in lieu of properly developed protection systems may be tempted to use 'engineering judgement', adapting traditional insulation methods such as an intumescent coating or gypsum board insulation.

Recent research has started to address fire protection for bonded FRP. Furnace tests were carried out by Blondtrock *et al.* (2001) using combinations of gypsum board and mineral wool insulation. Barnes and Fidell (2006) report tests that used a proprietary cementitious fire protection, and supplemental bolted fastenings. Proprietary systems have been specifically developed to protect bonded FRP strengthening and these have been tested on columns and slabs (Kodur et al., 2007).

DESCRIPTION OF THE TEST ARRANGEMENT

The fire tests took place in the living rooms of two flats, part of a 23-storey residential building that was built in 1964. The layout of the compartment is shown in Figures 1 and 2a. The fire load consisted of office furnishings, and was dominated by a sofa placed towards the east of the compartment. In the uncontrolled test, the compartment was ventilated by an open door to the rest of the flat and the openings left by breaking windows during the later stages of the fire. During the controlled test the ventilation parameters were changed by remote control of the windows and door (Abecassis Empis et al., 2007).

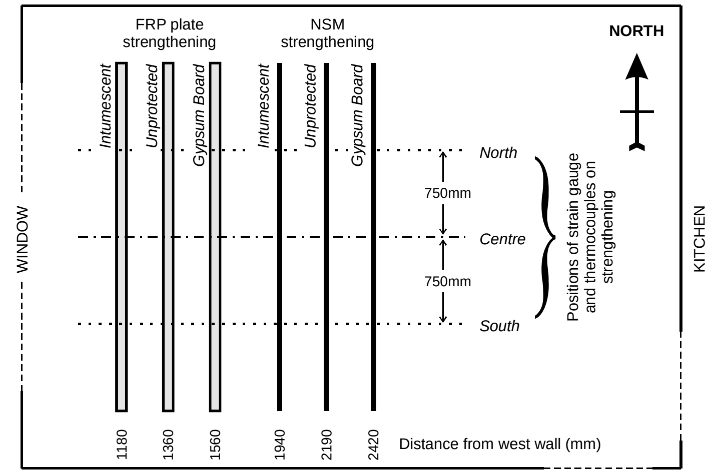
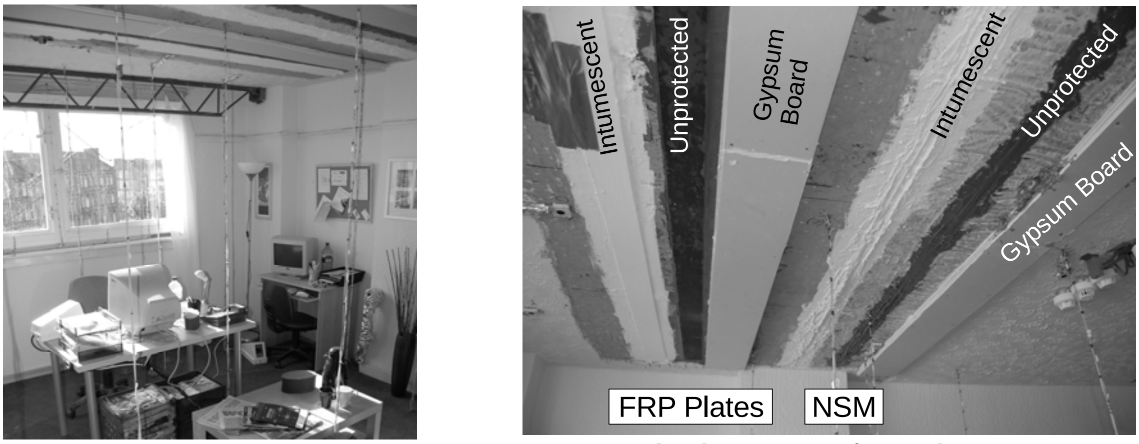


Figure 1. Schematic view of the strengthening.

Six strips of bonded FRP strengthening were installed in the compartment used in Test 1: three FRP plates and three near-surface-mounted (NSM) bars (Figures 1 and 2). The strengthening was installed by a contractor skilled in the application of bonded FRP and was completed 20 days before the fire test. The fire protection systems were installed by the University of Edinburgh. One of each type of strengthening was left unprotected, one painted with an intumescent coating, and one was protected within a gypsum board box. The gypsum board protection comprised two layers of 12mm board, spaced away from the bottom of the slab by a further two layers of board, placed to either side of the strengthening. The joints were staggered and the layers were sealed with an intumescent sealant. A single unprotected plate and unprotected NSM bar were installed in Test 2.



(a) Fire compartment, with FRP at top (b) The six strips of strengthening
Figure 2. The installed FRP strengthening and protection.

Intumescent coatings are intended for protecting steel members, not FRP. Their activation temperature is usually higher than the glass transition temperature of the adhesive. Despite this, the authors are aware of intumescent protection being specified for a bonded FRP project by design engineers (although this was changed before the scheme was implemented). The opportunity was therefore taken to demonstrate the performance of the intumescent protection during the Dalmarnock tests.

Table 1 gives the pertinent properties of the materials used in the Dalmarnock tests. Note in particular that the glass transition temperature of the bonding adhesive is given as ' ≥ 65ºC '. This is the manufacturer's quoted value, and is rather unsatisfactory. The authors intend carrying out further tests on the adhesive to determine the actual glass transition temperature.

Before installation, the FRP components in Test 1 were instrumented with strain gauges (attached to the upper surface of the FRP at the North, Centre and South positions shown in Figure 2), and thermocouples (placed within the adhesive layer at the same positions). The wires were led up through the concrete slab, with any holes filled using intumescent foam. A large quantity of additional instrumentation was used to record the progress of the fire and to monitor the structural response of the slab (Abecassis Empis et al., 2007).

Table 1: The FRP and protection materials. (Manufacturer's data sheet values).

Bonding adhesive	*Two component epoxy based adhesive*	
	Mechanical properties:	*E* = 10 GPa; Lap shear strength = 17 MPa
	Cure time:	Fully cured in 7 days
	Glass transition temperature:	≥ 65ºC
FRP plate	*Pultruded MM (medium modulus) CFRP plate with epoxy matrix*	
	Dimensions:	100 x 1.4mm
	Mechanical properties:	Tensile modulus = 170 GPa; Tensile strength = 3100 MPa
	Coefficient of linear thermal expansion:	0.6×10^{-6} /ºC
FRP NSM rod	*Pultruded CFRP rod with epoxy matrix*	
	Dimensions:	12mm diameter
	Mechanical properties:	Tensile modulus = 165 GPa; Tensile strength = 2500 MPa
	Coefficient of linear thermal expansion:	0.6×10^{-6} /ºC
Intumescent paint	*Thin film water borne intumescent coating*	
	Application:	2 coats by brush, estimated thickness 450μm
	Activation temperature	120ºC, from tests on the same material by Liang et al. (2007).

RESULTS AND OBSERVATIONS

The condition of the bonded strengthening after the uncontrolled fire (Test 1) is shown in Figure 3:

- The unprotected plate (Figure 3a) had completely separated from the concrete. Both the bonding adhesive and the matrix polymer had burnt away, leaving exposed concrete on the ceiling and the bare fibres exposed on the floor.
- The intumescent protected plate (Figure 3b) separated from the concrete, except for a short length at its southern end, where it remained bonded to the concrete. Away from this end, the matrix polymer had burnt away to expose the fibres. The bonding adhesive was charred, but remained on the ceiling.
- The gypsum-board protection was inspected after the tests, and was fully intact. When the board was removed (Figure 3c), the plate was fully bonded to the concrete, and there was no *visual* damage to either the plate or adhesive. (Unfortunately it was not possible to carry out mechanical tests to quantify the post-fire properties).
- The adhesive around the unprotected NSM bar (Figure 3d) had burnt away, leaving the FRP partially exposed.
- The intumescent coating over the NSM strengthening (Figure 3d) had activated. The strengthening beneath the intumescent was in place, although the adhesive was glazed and contained transverse cracks.
- The gypsum-board protected NSM (Figure 3d) remained intact, and the strengthening beneath was visually unaltered.

Figure 4 shows the temperatures recorded by the thermocouples in the FRP bondline for each type of strengthening and at each position (north, centre and south). Gas phase temperatures are included from a single thermocouple near the ceiling slab in the centre of the strengthened region, but it should be noted that the temperatures varied across the compartment. The figure indicates the major fire events: notably a growth period, ending with flashover at 5 minutes; and the fire was extinguished at 19 minutes (Abecassis Empis et al. (2007). The uncontrolled fire produced a peak heat release rate of 800kW.

(a) Remains of unprotected plate

(b) Remains of intumescent-protected plate

(c) Gypsum-board-protected plate
(protection removed after fire to expose plate)

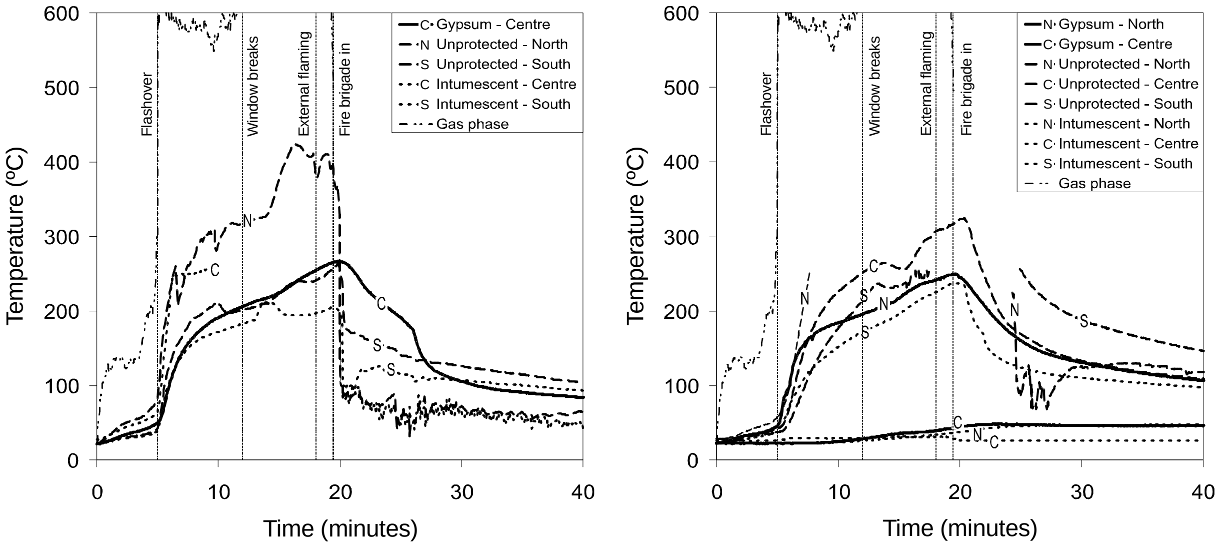
(d) NSM strengthening after the fire

Figure 3. The condition of the bonded strengthening after the fire.

A few thermocouples were inactive (and are not shown), and the readings for 3 NSM thermocouples (gypsum-C, intumescent-N and intumescent-C) are erroneous. In all cases the bondline temperature exceeded the glass transition temperature of the adhesive. As expected, the bondline temperatures are highest in the unprotected plates, but even with gypsum-board protection, the glass transition temperature was reached less than a minute after flash-over. This is more rapid than previous furnace-based research (eg: Blondtrock et al. (2001)), which suggest that it takes in the order of 20 minutes for a similar temperature rise (although the protection system is not directly comparable). Without further analysis of the gas-phase temperatures it is not possible to draw comparisons between the plate and NSM temperatures.

Figure 5 shows the strain gauge results. These are due to thermal expansion of the FRP, possibly in composite action with the concrete slab. The results have been corrected to remove temperature effects from (a) differential thermal expansion between the gauge and the FRP, (b) apparent strains due to electrical effects in the gauge and (c) variations in the gauge factor. The corrections are based on the bondline temperatures (Figure 4). If the thermocouple adjacent to the strain gauge was damaged, temperature data was taken from a different position in the same piece of strengthening. The temperature difference between the two locations was estimated by comparing gas phase temperatures, and the resulting uncertainty in the strain is indicated by the shaded regions in the figure. It is important to note that the strain gauges and gauge adhesive were only intended for use up to 200ºC, consequently the correction will not be accurate and there may have been slip in the gauge adhesive above this temperature. Hollow symbols indicate such points in Figure 5. The time resolution of the data is poor, and the negative strains for the intumescent-protected NSM are anomalous.

Nevertheless, the uncorrected strain evolutions in Figure 5 are useful. Separation of the intumescent plate from the concrete, for example, occurred about 10 minutes from the start of the test, but the plate remained in contact at the southern end (confirmed by Figure 3b). The gypsum board protected strengthening have complete strain traces. The negative strains for the north gypsum-protected NSM gauge suggest the FRP has slipped relative to the concrete slab due to adhesive viscosity at high temperatures, but solidified during cooling. Further work, however, is required to analyse these results.



(a) Plate Strengthening (b) NSM Strengthening

Figure 4. Bondline temperatures.

In the controlled fire (Test 2), gas-phase temperatures were significantly lower than during Test 1, and the fire was extinguished before flash-over was allowed to occur (Abecassis Empis et al., 2007). The unprotected FRP plate and NSM strengthening were *visually* unaffected by the fire: the colour had not changed, there was no sign of crazing of the adhesive, and the strengthening remained in place. (The test 2 strengthening was not instrumented).

The interpretation of test results herein is limited by the need for further work, which is being carried out in parallel to analysis of the structural data. This includes correlation of slab strain with the FRP strain, consideration of local variations in gas phase temperature, and determination of the time of separation events. Materials characterisation will be undertaken, and a thermal analysis of the protected strengthening carried out.

CONCLUSIONS

The fire performance of plate and NSM bonded FRP strengthening was investigated in a ‘real’, post-flashover fire. The results and preliminary analysis confirm the vulnerability of the bonding adhesive during a fire, the bondline temperature greatly exceeding the glass transition temperature in all tests (with and without protection). Furthermore, this temperature was reached far more quickly than furnace-based testing has suggested.

The unprotected and intumescent protected plate strengthening de-bonded early in the fire, the intumescent being ineffective due to an inappropriate activation temperature. The exposed bonding and matrix adhesive from these two plates burnt, and would have emitted toxic fumes. The NSM strengthening appeared to have superior fire resistance to the plate strengthening; whilst it was not possible to assess its mechanical performance the NSM strengthening did not debond. The surrounding concrete would be expected to draw heat away from the adhesive, but further analysis of the test data is required to investigate this. The gypsum board protected the FRP strengthening from visible damage; however, the glass transition temperature was exceeded. Consequently, the strength and stiffness of the adhesive layer would have been greatly reduced, affecting its ability to strengthen the slab.

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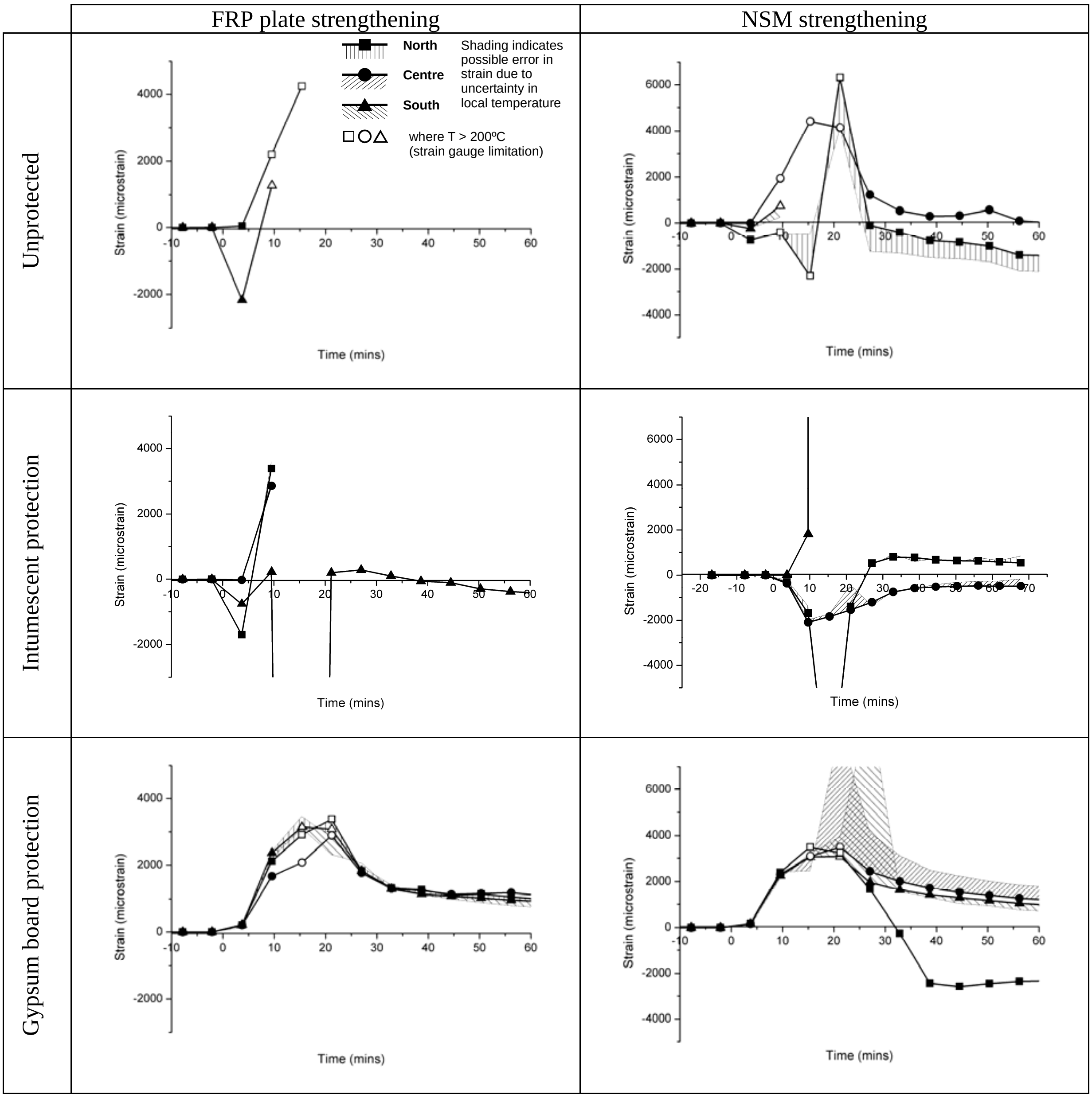

Figure 5. FRP strain measurements.

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