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Published in:
Proceedings of the 4th Asia-Pacific Conference on FRP in Structures (APFIS 2013)

Publication date:
2013

FIRE PERFORMANCE OF BASALT FRP MESH REINFORCED HPC THIN PLATES

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ABSTRACT

An experimental program was carried out to investigate the influence of basalt FRP (BFRP) reinforcing mesh on the fire behaviour of thin high performance concrete (HPC) plates applied to sandwich elements. Samples with BFRP mesh were compared to samples with no mesh, samples with steel mesh and samples displaying a full sandwich structure. Final results confirmed the bond loss between concrete and BFRP mesh with temperature. The available void where the epoxy burnt away allowed the concrete matrix to release pressure and limit pore stresses, delaying spalling. It also reduced the mechanical resistance of the structure, since the ability of the mesh to bond on the concrete matrix was lost. A theoretical approach for numerical modelling is proposed based on the experimental observations. It describes the change of boundary condition at the vicinity of the mesh as an outer pressure dependent on a linear increase of the volume of melted epoxy and the outflow of moisture from the concrete matrix. It was concluded that the use of a BFRP mesh to reinforce HPC exposed to fire reduces the mechanical strength despite a beneficial effect related to spalling.

KEYWORDS

Basalt FRP, thin plates, sandwich elements, high performance concrete, fire testing, modelling.

INTRODUCTION

Sustainability of the built environment has become a major concern of the building industry drawing attention to reducing material consumption and improving heat insulation and durability. Thin high performance concrete (HPC) plates (30mm) used to frame an insulation layer in sandwich panels provide solutions to such challenges (Gara *et al.* 2012), allowing for thicker insulation and thinner load-carrying structure than conventional elements. Moreover their light weight enables transporting more elements at a time. To ensure structural robustness and safe transportation and handling on site basalt fibre reinforced polymers (BFRP) mesh with epoxy as a matrix is introduced in the concrete plates. FRPs are preferred over steel for their small dimensions, low weight, high strength and superior durability properties (Urbanski *et al*. 2013). Basalt fibres present alkali and weathering resistance similar to that of glass fibres (Wei *et al*. 2010) and a higher fire endurance and residual strength at high temperature than carbon fibres (Sim *et al*. 2005), hence the choice of basalt over more expensive carbon or aramid FRPs. The fire safety of such elements remains a challenge because of the spalling behaviour of HPC at elevated temperatures (Phan *et al.* 2001, Hertz 2003) which has also been observed in previous testing within the scope of this research. Triggered by internal pore pressure rise from water vapour accumulation in the low-permeability HPC in combination with thermal stresses, a fracture process leads to concrete spalling. In the presented research it is hypothesised that the presence of a FRP mesh can potentially impact the fire resistance of such elements, due to its influence on permeability and mechanical behaviour. This paper presents a preliminary study regarding the influence of basalt FRP mesh on fire-induced spalling behaviour when cast into HPC thin plates. An experimental program is conducted to verify the initial assumptions presented in the hypotheses section. Based on this work, an approach to model the temperature and pressure profiles is presented as a numerical assessment of the fire behaviour of HPC including a BFRP mesh.

HYPOTHESES

The influence of the BFRP mesh on HPC in fire depends on its contact interface with concrete. If the contact surface does not present gaps or voids, the mesh will act as a vapour transport barrier increasing the pressure build-up at the boundary with concrete due to the pressure-proof epoxy coating. This will enhance the spalling probability along the plane where the mesh is located. If voids are created at the interface by the epoxy coating melting at elevated temperature, space would be available for pressure to be released and avoid build-up, in which case the concrete would benefit from the mesh on a fire point of view.

EXPERIMENTAL WORK

An experimental program has been conducted to verify the above hypotheses, providing preliminary experimental data on the influence of the mesh with respect to spalling and place a foundation for a numerical model. Thermocouples were placed through the thickness of the concrete samples including the location of the BFRP mesh. A first set of samples focussed on the comparison between steel mesh and BFRP mesh (Set 1), and a second set of samples on the comparison between BFRP reinforced concrete and concrete alone (Set 2). Both tests involve HPC of 100MPa in compressive strength and cured under the same conditions, sealed in tight plastic sheets for 28 days. The tests were carried out on the same furnace controlled by the same operator. The fire load followed the standard ISO834 curve and the samples were laid horizontally above the furnace to expose one side only. Mineral wool from Rockwool served as insulation to keep the rest of the sample cold. The mesh used is a grid of 25x25mm, with approximately 5mm wide and 0.85mm thick BFRP cross sections.

The samples from Set 1 are 1660x710mm^2, representing a part of the load carrying back wall of the sandwich element and including insulation and a structural rib but omitting the front plate (Figure 1). The structural rib acts as a vertical stiffener in the sandwich element. The HPC was cast in a single batch and hardened in ambient conditions for 28 days. The parametric variation in the test series concerns the mesh in the plate (either of steel or BFRP) and the reinforcement in the rib, as outlined in Table 1. Thermocouples recorded the temperature through the thickness of the plate and in the rib during the 2h of fire exposure. LVDTs recorded the maximum displacement at mid-span. The initial moisture content was measured to be 5% per mass.

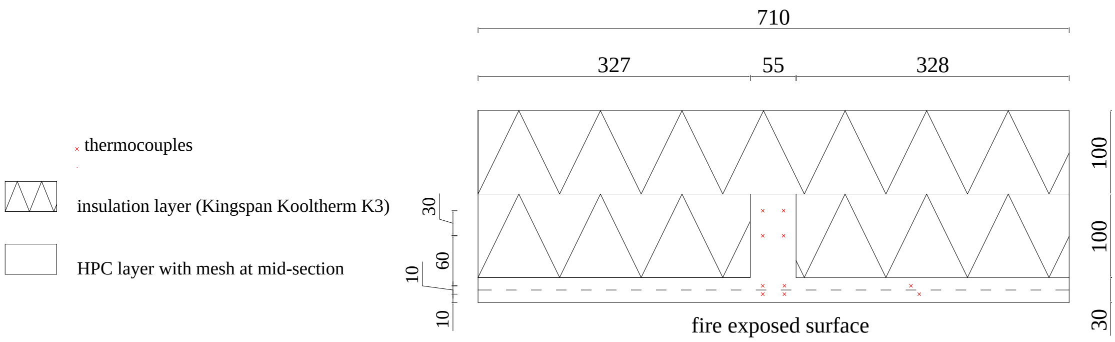

Figure 1. Cut of the samples from Set 1. All dimensions in mm.

Table 1. Description of test samples and test output

a. Test specimens from Set 1

Sample ID	Mesh	Rebar	Spalling	Mechanical failure
Set 1.1	Basalt	Yes	No	No
Set 1.2	Basalt	No	No	Yes
Set 1.3	Steel	Yes	No	No
Set 1.4	Steel	No	No	No

b. Test specimens from Set 2

Sample ID	Thickness	BFRP Mesh	Spalling	Integrity kept
Set 2.201	20mm	No	Yes	No
Set 2.202	20mm	No	Yes	No
Set 2.301	30mm	No	Yes	No
Set 2.302	30mm	No	Yes	No
Set 2.201M	20mm	Yes	Yes	No
Set 2.202M	20mm	Yes	No	Yes
Set 2.301M	30mm	Yes	Yes	Yes
Set 2.302M	30mm	Yes	Yes	No

The samples from Set 2 are 540x540mm^2 and came in two thicknesses of 20 and 30mm. The HPC, different from the previous Set 1, was cast in several batches. The parametric variation concerns the thickness of plates and the presence of BFRP mesh as mentioned in Table 1. Thermocouples recorded the temperature through the thickness of the plate during the 40min test which corresponds to the necessary time to reach thermal equilibrium in such thin profiles. The initial moisture content was measured to be 4.75% per mass.

EXPERIMENTAL RESULTS AND DISCUSSION

The test output is presented in Table 1. A specimen is said to have passed the test when no spalling or mechanical failure occurred until thermal equilibrium. No spalling was observed on the samples from Set 1, but Set 1.2 failed mechanically. The specimen broke into two pieces at mid-span and fell in the furnace as the BFRP mesh was not able to withstand the bending of the plate. No steel-reinforced specimen failed. Observation of the inner structure of undamaged samples proved that the failure did not come from the basalt fibres since they were found intact. However it was also found that the epoxy coating burnt away leaving space between fibres and concrete. The failure of this specimen then lies in the low thermal resistance of the mesh due to the epoxy coating, providing reduced bond and low mechanical strength at high temperatures. Set 1.1 did not spall or break, showing that steel reinforcement is necessary.

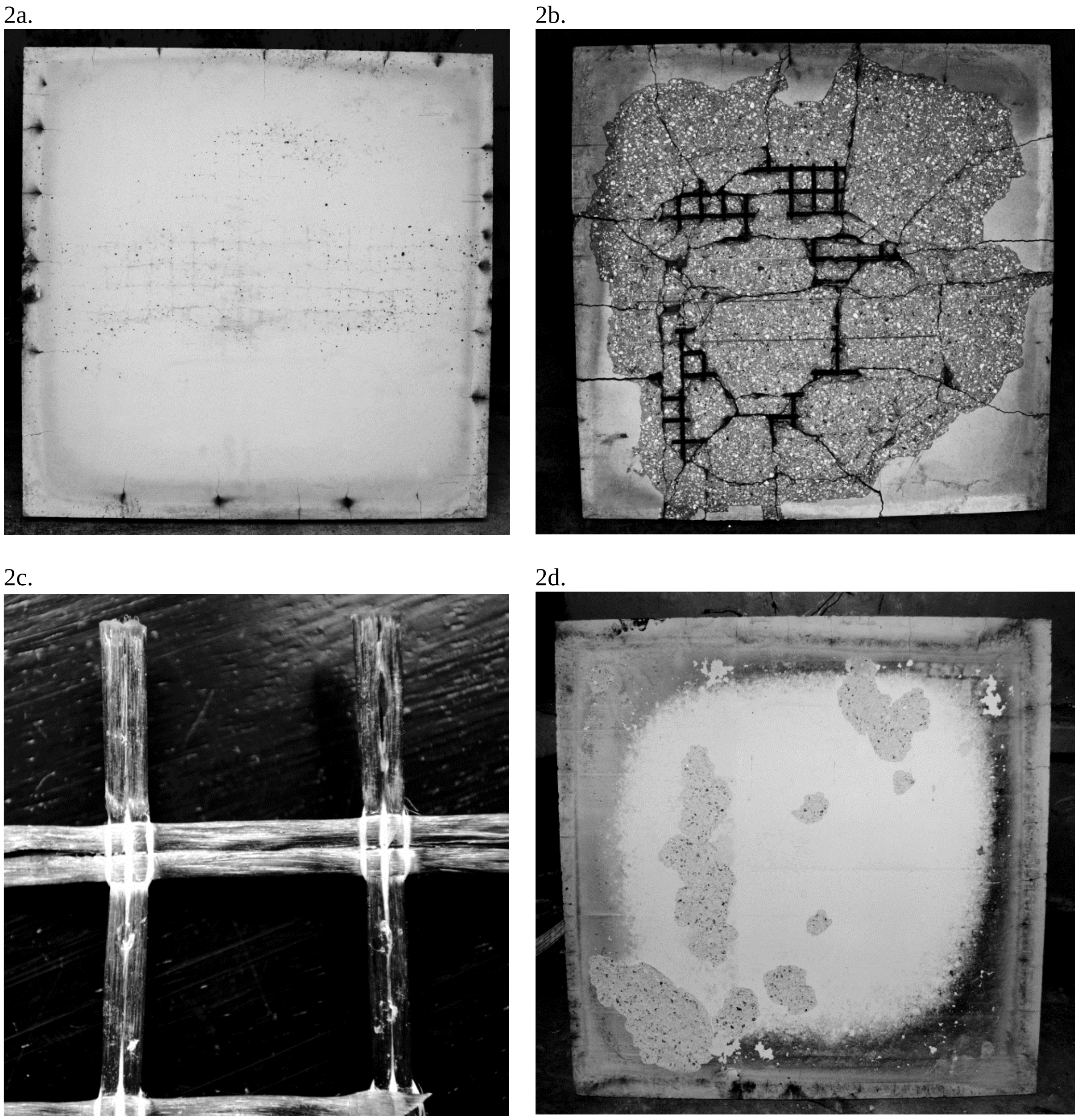

Figure 2. Fire test results and BFRP mesh. Set 2.202M (2a). Set 2.301M (2b). Basalt mesh before fire test (2c). Element from previous testing showing surface spalling (2d).

All the samples from Set 2 without mesh spalled and got thoroughly destroyed between 10 and 12 minutes so the test was stopped after that period of time. Of the samples with BFRP mesh, only two got destroyed by explosive spalling at 10 and 11 minutes. This can be linked to higher moisture content and concrete composition. Set

2.202M passed the 40min test without any damage (Figure 2a). Set 2.301M spalled and got severely damaged but the BFRP mesh kept it in one piece (Figure 2b). Those observations confirm the initial hypothesis of the mesh acting as a pressure release for water vapour and helping the fire exposed concrete. Among the debris of spalled elements with mesh, numerous concrete pieces from the unexposed top surface were found with the shape of the mesh moulded in the matrix. The energy released by the concrete at the time of spalling is enough to move it upwards, and the fracture at the mesh plane indicates an absence of bond between the two materials and a weakened section of the concrete at that location. A two-step spalling was observed on all the elements except Set 2.202M, in the form of a preliminary surface spalling (3 to 4mm deep) followed by the explosion of the specimen (Figure 2b). A previous test of similar tiles with the concrete mix of Set 1 showed the same surface behaviour but no further spalling, as shown on Figure 2d.

The shape of the mesh, shown in Figure 2c, adds to the theory of pressure release as no concrete would flow between the two basalt rods tied together thus leaving more space. It can reasonably be assumed that some bond exists at ambient temperature, providing a vapour transport barrier at temperatures below the melting point of the epoxy matrix.

MODELLING WORK

Initial material model

The model developed here aims at proposing a first approach for characterising the evolution of the interface between concrete and BFRP mesh over temperature and its influence on the pore pressure of concrete. Comsol Multiphysics is applied allowing taking into account the coupling effect of temperature and pressure described by two non-linear differential equations. Those equations have been described by Bažant and Thonguthai (1978, 1979) and used by Ahmed and Hurst (1997) and Tenchev *et al.* (2001), primarily for large concrete structures such as nuclear power plants and recently applied to thin HPC profiles in a one-dimensional model (Hulin *et al*. 2013). Temperature follows Fourier's law and Darcy's law governs pressure. Coupled with the proper heat and mass balance equations, they give the field equations described in Eqs 1 and 2 respectively for temperature and pressure.

$$\left[\rho_S C_S - (C_a + \lambda_D)\frac{\partial w_d}{\partial T} - C_a\frac{\partial w}{\partial T}\right]\frac{\partial T}{\partial t} + \nabla.k(\nabla T) = C_a\frac{\partial w}{\partial p}\frac{\partial p}{\partial t} \quad (1)$$

$$\frac{\partial w}{\partial p}\frac{\partial p}{\partial t} - \nabla.\frac{a}{g}\nabla p = \left(\frac{\partial w_d}{\partial T} - \frac{\partial w}{\partial T}\right)\frac{\partial T}{\partial t} \quad (2)$$

where T is the temperature; p is the pore pressure; w is the free water content; w_d is the amount of chemically bound water released by heat increase, ρ_S and C_S are the density and isobaric heat capacity of the solid structure; C_a is the heat of vaporisation of water; λ_D is the heat of dehydration of chemically bound water; k is the thermal conductivity; a is the permeability and g is the gravity acceleration. The temperature dependent material parameters are described in Bažant and Thonguthai (1979) and Dwaikat and Kodur (2009). The boundary conditions are set to describe convection and radiation heating of the exposed surface and heat exchange with ambient temperature on the cold surface. For pressure the value is set at 20Pa in the furnace according to ISO834 and atmospheric pressure outside. Hulin *et al*. (2013) provides a more detailed description of the material model. The model presented in this paper updates the one-dimensional model to a two-dimensional model representing a section of concrete tile with a space accounting for the BFRP mesh. A temperature-dependent boundary condition describes the effect of the mesh.

Influence of the BFRP mesh – Temperature-dependent boundary condition

General scope

The description of the influence of the mesh on concrete spalling implies a new boundary condition at the interface with concrete that evolves with temperature to characterise melting of the epoxy coating and the space creation for pressure release. For this purpose, a 3-step boundary condition is proposed according to the experimental observations and the literature. Two critical temperatures settle those steps, namely the temperature of glass transition of epoxy (T_g) of 80°C (Cole and Julian 1954) and the temperature at which the epoxy fully changed phase (T_d) of 250°C. Step 1 ranges from ambient temperature to T_g and assumes an intact vapour transport barrier; Step 2 ranges from T_g to T_d and assumes a linear temperature-dependent degradation law from intact vapour transport barrier to the total vaporisation of epoxy; Step 3 ranges from T_d to the end temperature of the test and assumes that the epoxy is fully vaporised. The linear degradation assumption is not verified by experiment and will need further investigations to be fully described. The boundary condition is then applied as a pressure condition p_v on the epoxy/concrete interface, around the geometry of the BFRP mesh. in practice, this boundary condition can be seen as the profile of the mesh in a cut through the test specimens from Set 2.

Linear degradation law

The degradation of the vapour transport barrier is caused by the phase change of epoxy. When epoxy changes phase it creates a space that water vapour fills in. This volume is calculated as a percentage of the total available volume which corresponds to the volume of epoxy used in the BFRP mesh and is updated at each time step. It obeys the following Eq. 3

$$V = \frac{T - T_g}{T_d - T_g} V_T \tag{3}$$

where V is the available volume; V_T is the total volume of epoxy and T is the current temperature at the boundary. The release of pressure in this volume depends on the pressure gradient in the concrete at the interface with the mesh. The saturated pressure represents the initial pressure in the new void and triggers the mass flux (Eq.4) towards the new void. This mass flux gives access to a mass of water vapour transferred into the void using the time step t_s (Eq.5). The quantity of matter can then be calculated. The new void pressure for the new time step is updated using the ideal gas law, the quantity of water vapour transferred in the void and the void volume at the new time step (Eq.6).

$$\Phi = \frac{m}{dSdt_s} = \frac{a}{g} \nabla p \tag{4}$$

$$m = \int_{t_s} \iint_S \Phi dSdt_s \tag{5}$$

$$p_V = \frac{mRT}{MV} \tag{6}$$

where Φ is the mass flux; m is the mass of vapour; ∇p represents the pressure gradient in concrete at the boundary; a is the permeability; g is the gravity acceleration introduced for dimensional purposes; S is the surface concerned with the mass flux; t_s is the time step; M is the molar mass of water vapour; R is the universal gas constant; T is the temperature of the system at the boundary; V is the volume of voids calculated with Eq. 3 and p_V is the void pressure which is being updated for the new time step and which is used as a boundary condition for surface representing the concrete/epoxy interface.

Implementation and further optimisation

This calculation method is to be implemented as a pressure boundary condition on the interface between the concrete and the mesh. No field equations are used for the material behaviour of the mesh so no transport needs description within the mesh. The water vapour released in the void is considered as an ideal gas.

Further optimisation of the problem requires inclusion of the amount of gas created by epoxy vaporisation. A parametric study on the initial pressure given in the model to start the iteration on the void pressure p_v at Step 2 is also required to define the influence of the start pressure on the final result.

CONCLUSION

The influence of a BFRP mesh on the fire behaviour of HPC thin plates was experimentally investigated. The observations showed that the contact interface between concrete and BFRP mesh develops voids when exposed to elevated temperatures. It was also observed that test specimens including a BFRP mesh resisted the high temperature exposure better than test specimens without BFRP mesh. It is deemed that a BFRP mesh benefits the fire endurance of HPC since it offers a way out for internal concrete pore pressure which fills out the voids left by the melting epoxy coating.

It has been observed that on a mechanical point of view the BFRP mesh lowers the stress resistance as this degrading process creates a void with no mechanical strength. As a consequence concrete often breaks along the plane where the mesh is located when spalling occurs. The overall bending resistance of HPC including BFRP mesh has been found much lower than that of concrete reinforced with steel. Comparison with a steel mesh showed that steel is preferable over BFRP for structural reinforcement in fire since in this test program no specimen including steel has failed mechanically.

The new voids are hypothesised to weaken the concrete, lowering its mechanical strength, and the lack of bond would destroy the mechanical reinforcement action of the BFRP mesh. It is expected that the mesh geometry controls the volume of voids created as the concrete hardens around it, and that the epoxy coating melting temperature dictates the bond efficiency with concrete.

A first modelling approach has been proposed, using a linear degrading law under the form of volume creation where pressure can be released. Development of the model is on-going and includes numerical analysis, parametric studies for the influence of the initial pressure and epoxy content, as well as the implementation of the combustion products of the epoxy coating.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from Connovate who provided the tests samples and the Dansk Brand og sikringsteknisk Institue (DBI) for funding and performing the test.

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