Fire Testing of Concrete Beams With Fibre Reinforced Plastic Rebar

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Abstract

The behaviour of glass fibre reinforced polymer (GFRP) rebars reinforced concrete beams when exposed to fire are presented in this paper. The experimental programme involved fire tests based on British Standard 476 on two full-scale GFRP rebar reinforced concrete beams with dimensions in cross section 350mm x 400mm and 4400mm total length with a span length of 4250mm. The beams were designed and constructed according to Eurocode 2 and ACI-440. The purpose of this work was to evaluate the fire resistance of the GFRP reinforced concrete (RC) beams. GFRP rebars with thermoset resin were used for reinforcing beam 1 and GFRP rebars manufactured with thermoplastic resin were used for reinforcing beam 2. Shear reinforcement for beam 1 was GFRP stirrups and for beam 2 steel stirrups were used. Degradation in the flexural capacity due to fire was evaluated and compared. In this study loaded heating tests were implemented with the aim of collecting basic data for the validation of the model presented in the preceding papers.

INTRODUCTION

Most building structures must satisfy the requirements of building codes, which relate to the behaviour of those structures in a fire. Fire ratings for buildings refer to the time available in a fire before the structure collapses. The relevant property of the composite rebar is not its flammability or reaction to fire, but rather its ability to continue to sustain loads in an environment of rapidly rising temperatures. The properties of steel at different temperatures are well known as are the thermal properties of the material and this allows the modelling of structures with some degree of accuracy to predict a time scale for the ultimate loss of structural integrity. Data is required for glass fibre reinforced plastic (GFRP) rebar in order for similar calculations to be made. GFRP rebar have a wide range of potential applications but its advantages and limitations must be ascertained so it can be used appropriately. UK Building Regulations 2000[1] has identified the specific requirements for each category of structural element in a building in terms of resistance to collapse (load bearing capacity). The minimum period of fire resistance for the elements of most structures is 90 minutes.

In this study, glass fibre reinforced concrete beams using continuous fibre bars as main reinforcements were subjected to heating under load tests. The three beams in this project were designed based on Eurocode 2[2] and ACI 440[3] recommendations and constructed at Queen Mary London University premises. In addition another full-scale beam with the same dimensions and GFRP reinforcement ratio was constructed and tested as a control at room temperature. This test was carried out for the evaluation of flexural behaviour of the beam and to choose a sustained load for the fire test. The results of these tests are included. The objective of the study was to determine the fire resistance of GFRP reinforced concrete beams experimentally and to validate the predictive models for fire resistance, which had been introduced in previous papers[4,5] by the same authors.

BEAMS FOR THE TEST PROGRAMME

The reinforced concrete beam specimens were cast, using marine gravel as coarse aggregate. The dimensions of the beams were 350 x 400mm in cross section, 4400mm overall length and 4250mm supported span. The concrete composition for these beams is given in Table 1. In addition, three 100mm concrete cubes were cast using the same concrete. These gave an average compressive strength of 42 MPa after 28 days of casting.

Table 1. Concrete composition used for casting the testing beams

Item	kg/m^3
Ordinary Portland Cement (OPC)	380
20mm aggregate	700
10mm aggregate	360
Sand	735
Water	148
Water reducing admixture	(1% of OPC) 3.8 kg/m^3

Control beam and beam 1

GFRP rebar reinforcements for the control beam and beam 1 were supplied by Hughes Brothers, Inc. Figure 1a illustrates the various GFRP pieces. From left to right; L-shaped #7 (22mm) used for end rebar U-shaped #3 (9mm) used as stirrups rebars by attaching two pieces together and a cut piece of # 4 (12mm) used for the main reinforcement. Figure 1b shows the arrangement of the reinforcements in the section of the beam.

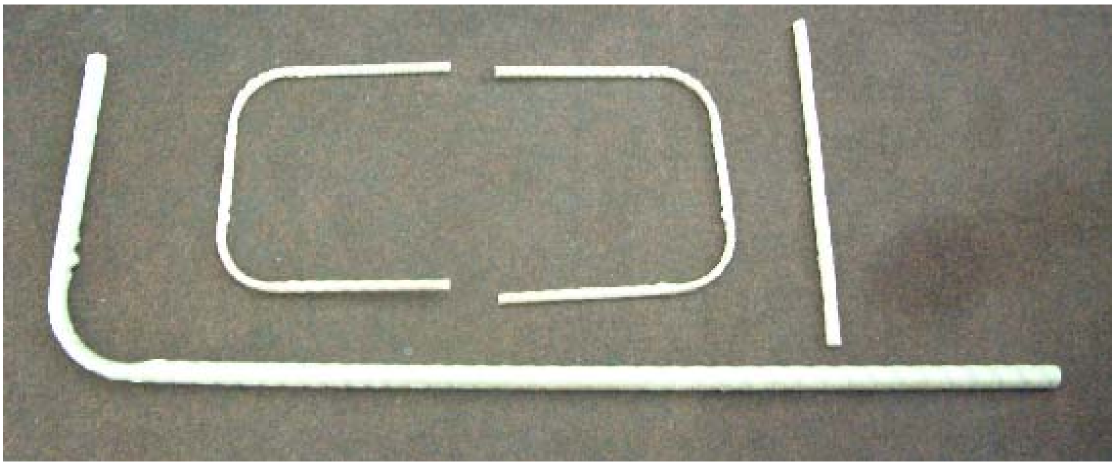


Fig 1a GFRP rebar shapes used as reinforcement for control beam and beam 1

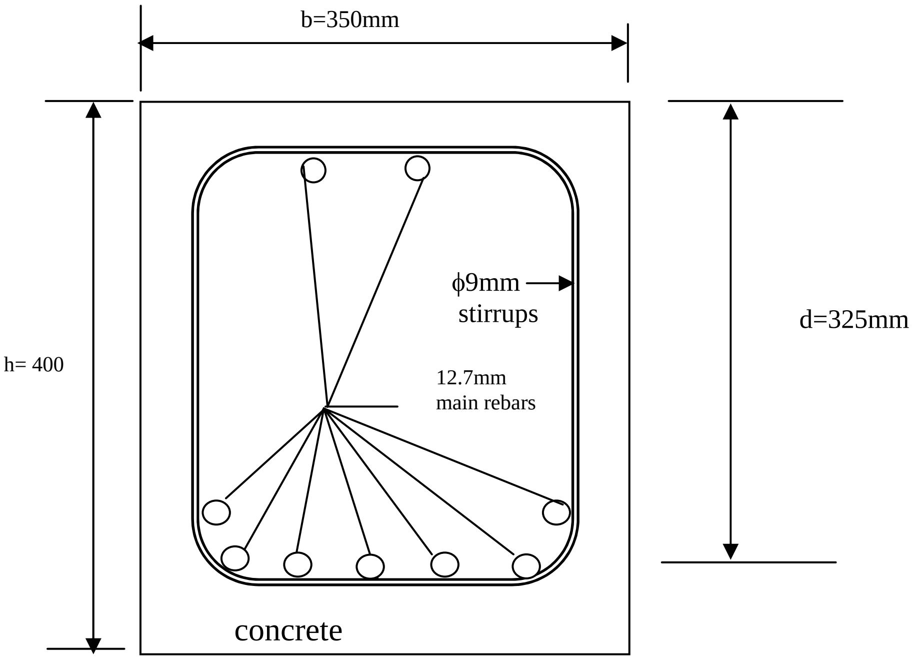


Fig 1b Beam cross section with reinforcement arrangement

Beam 2

Beam 2 was reinforced by GFRP rebar manufactured by the Dow Chemical Company. This rebar utilised a thermoplastic polyurethane resin matrix. Figure 2 illustrates the various pieces provided used for the construction of beam 2. From left to right; L-shaped #4 rebar used for end rebar, steel stirrup and a cut piece of # 4 (12mm) GFRP rebar used for the main reinforcement. Table 2, Table 3 and Table 4 give details of the reinforcement specifications used in this work. Same reinforcements arrangement as shown in Figure 1b used in beam 2.

Table 2 GFRP rebars specifications for control beam, beam 1 and beam 2

Specimens	Bar size (mm)	Cross sectional Area (mm^2)	Nominal Diameter (mm)	*Tensile strength (MPa)	*Modulus of Elasticity (GPa)
Control & Beam1	9	84.32	9.53	760	40.8
	12	144.85	12.70	690	40.8
	22	382.73	22.23	586	40.8
Beam2	12	130.69	12.8	≈1000	≈41

* Manufacture's data

The 10mm steel stirrups used for fabrication in beam 2 has tensile strength of 414MPa at yield and a Young's modulus of 200GPa.

Table 3 Control beam, beam 1 and beam 2

Tension reinforcement		Top reinforcement		Width of the beam (b)	Effect. depth of the beam (d)	Height of the beam (h)	Balance reinfor-cement ratio (ρ_{fb})	Ratio of GFRP reinforc-ement (ρ_f)	$\frac{\rho_f}{\rho_{fb}}$
Bar size	No. of bars	Bar size	No. of bars	(mm)	(mm)	(mm)	%	%	
12mm	7	12mm	2	350	325	400	0.45	0.89	1.98

Table 4 Specimens characteristics

Specimen	Main reinforcement			Tensile main reinforcement	A_t* (cm^2)	Tensile reinforcement ratio
	Type of fibre	External profile	Binder			
Control	Glass	Spiral	Vinyl ester	7 of ϕ12	10.14	0.89
Beam 1	Glass	Spiral	Vinyl ester	7 of ϕ12	10.14	0.89
Beam 2	Glass	Molded surface	Polyurethane thermoplastic	7 of ϕ12	10.14	0.89

* Total cross sectional area of tensile main reinforcement

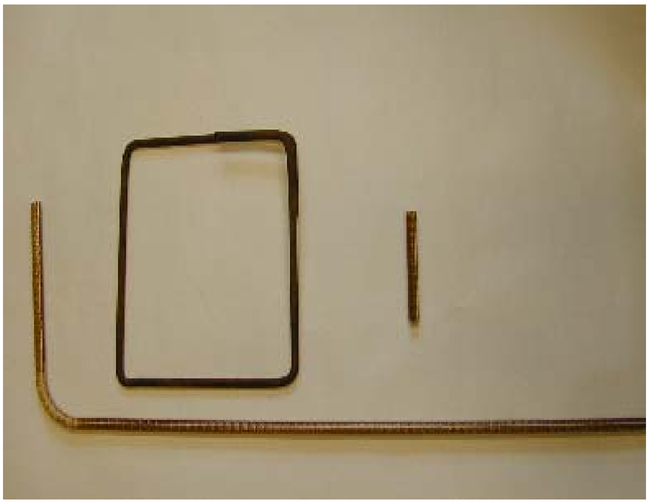


Fig 2 GFRP rebar shapes and steel stirrup used as reinforcement for beam 2

TESTING OF THE CONTROL BEAM AT ROOM TEMPERATURE

In order to evaluate the flexural behaviour of the proposed beam the flexural six point bending test was carried out at room temperature. The beam was subjected to increasing load in increments of 5-10kN, until final failure. The load was stopped at each increment for two minutes for observation. Load was applied with a hydraulic jack at four points on the beam. Vertical deflection was measured at mid centre using an LVDT transducer. The loading of the beam resulted in the load deflection curve shown in Figure 3. The initial linear relationship between load and deflection became non-linear after an applied load of approximately 60kN. This was accompanied by the onset of cracking in the concrete in tension face. The code of practice specifies a maximum deflection allowable of L/250 where in this case is 17.0mm and this is exceeded at a load of 90kN. A load of 40kN was selected for the fire test as being below the concrete cracking threshold.

The load was increased to a maximum of 310 kN which produced a deflection in the beam of 98mm. During unloading the whole beam moved back to the same position as prior to loading. This shows that recovery of the beam is not impeded by plastic deformation of the rebar as would be the case with steel reinforced beams. Modulus of elasticity in bending (E_B) of the control beam can be calculated from experimental results using Equation 1 given in ASTM D790M (1986)[6].

$$E_B = \frac{L^3 m}{4bh^3} \qquad (1)$$

Where E_B= modulus of elasticity in bending

L = support span, 4250mm
b = width of beam, 350mm
h = height of beam, 400mm
m = slope of the tangent to the initial straight-line portion of the load-deflection curve, N/mm of deflection.
From the load/deflection curve obtained from experimental results presented in Figure 3 the slope to the initial loading is obtained as 12500 N/mm and the slope for the second part of the curve is obtained as 2500 N/mm. By substituting the above in Equation 1 initial and secondary beam modulus is obtained as 10.7 GPa and 2.1 GPa respectively.

Fig 3 Load-deflection curve for control beam

FIRE TEST PROGRAMME

Instrumentation

Specimens for the fire test were equipped with thermocouples. The thermocouples were embedded in the concrete to obtain temperature distribution during fire test. The thermocouples used were "PTFE insulated k type twisted cables". The ends of the thermocouples were precisely located by placing them in 20x30mm miniature columns 400mm long, cast in the formwork prior to concreting the beam itself. Thermocouples were also attached to rebars and stirrups for beam 1 and beam 2. Figure 4 show the thermocouples (TC's) embedded in concrete in four location along the beam A, B and C at each four thermocouple were embedded No 1, 2 ,3 and 4 which were 80mm apart in the section of the beam.

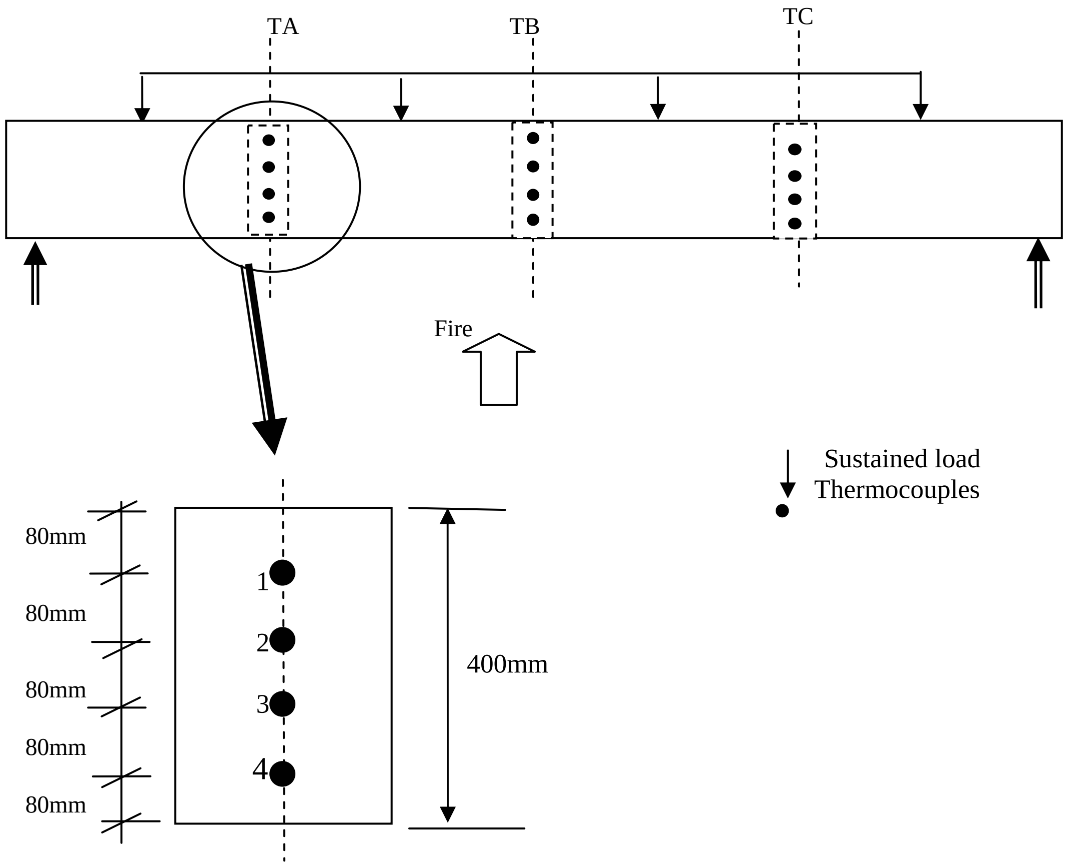
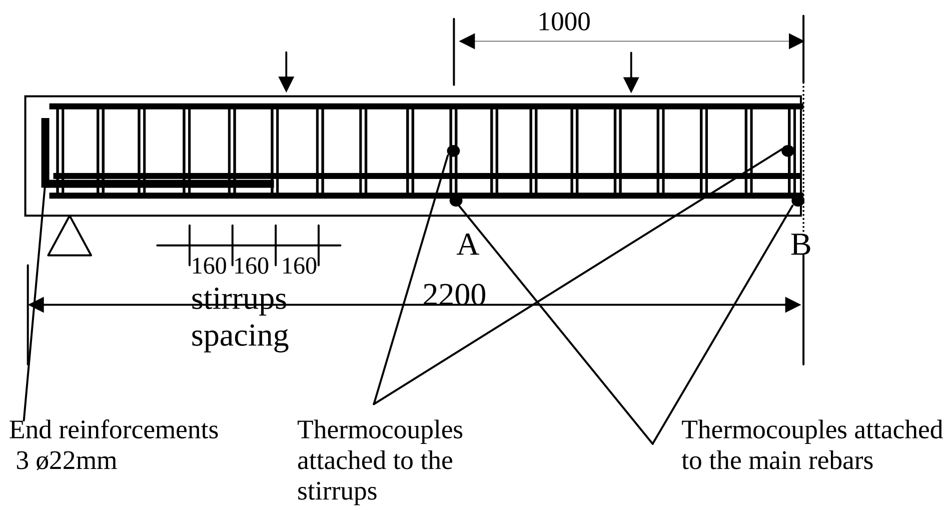


Fig 4 Thermocouples embedded in concrete. Group of thermocouples at A, B and C in concrete Nos. 1-4 at centre line 80mm c/c (3x4=12).

At the location A,B and C thermocouple were also attached to the 3 of the main reinforcements (x,y,z) as shown in Figure 5. Two thermocouples were also attached to the stirrups at location A and B. In total 23 thermocouples were used for each beam. Twelve embedded in the concrete (four at position A, four at position B and four at position C). Nine thermocouples to the rebars at location shown in Figure 5, three at each location. This is the region where the maximum flexural and shear stresses were expected to occur.



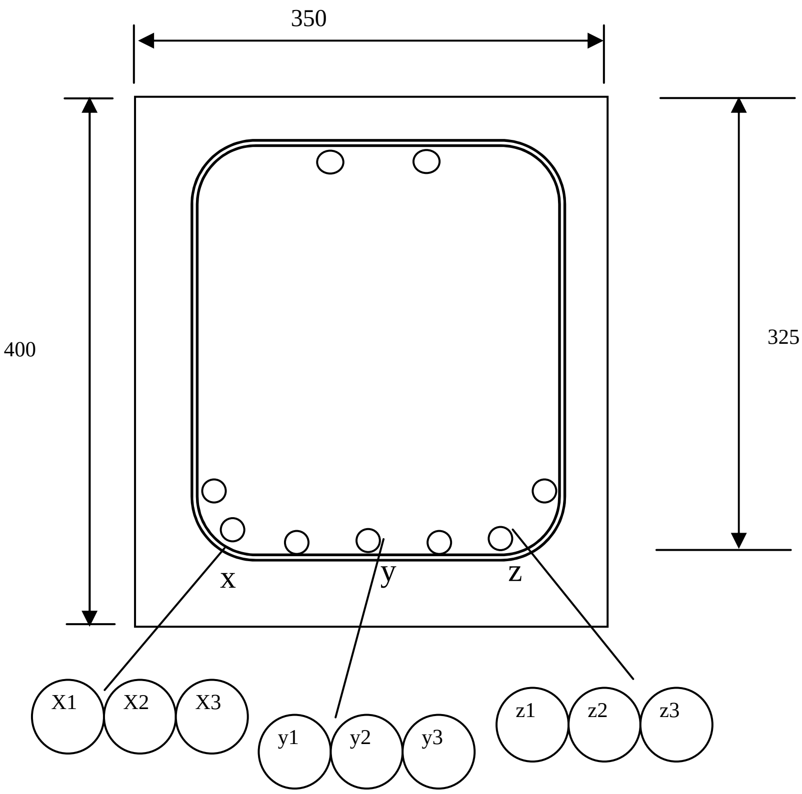


Fig 5 Specimen configuration and measurement points of temperature at the rebars

The experimental set up for the fire test is shown in Figure 6.

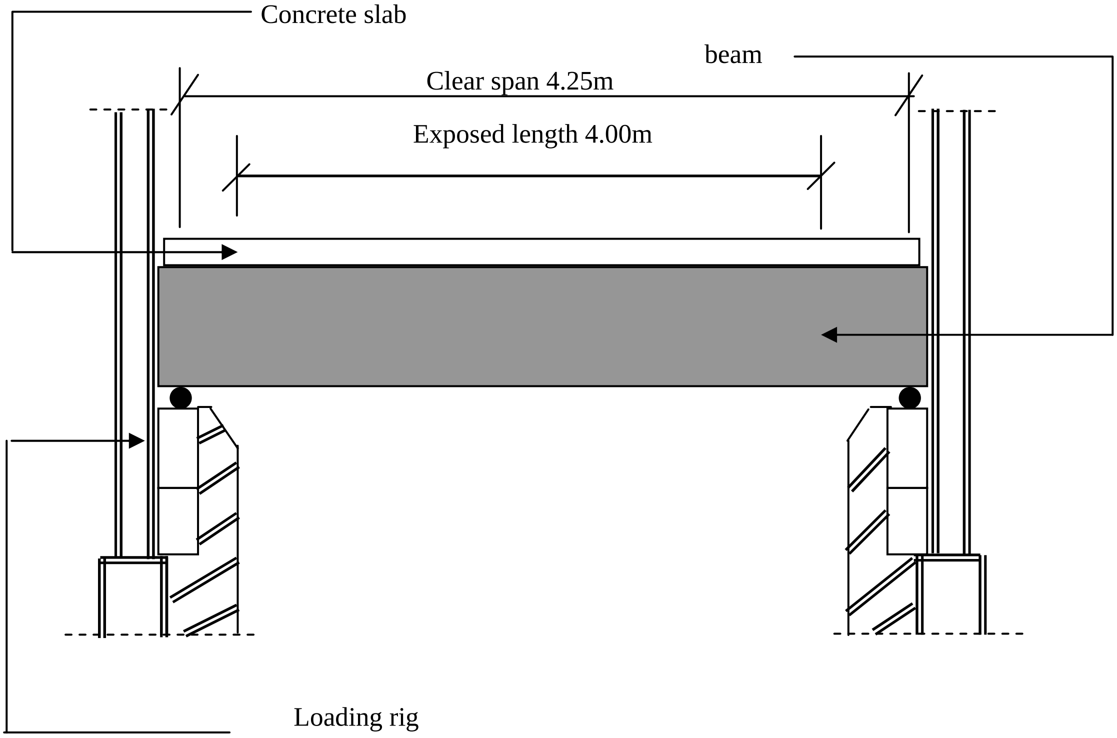


Fig 6 Fire test set up

Furnace details

The full scale fire testing was conducted at the Building Research Establishment, Watford UK. Furnace details used in this work are as follows; the internal dimensions of the furnace 4m wide x 4m long x 2m deep. Two sides walls contain the burners. One end wall has a door; the other end wall is modular and can be moved. The flue exit is in the floor at one end of the furnace. The top of the furnace is closed off with a test specimen, or a set of refractory-lined steel cover slabs. The furnace is lined with 1400 grade insulating brick (density approx. 880 kg/m^3) to comply with British Standard, ISO and EN requirements. Burners were gas-fired nozzle mix burners. A total of 20 burners, arranged with 10 along two opposite sides of the furnace, approximately 1200mm above the floor. The loading rig sat above the furnace, running centrally along the length, parallel with the walls containing the burners. The rig provides a span of 4.25m for the beams. The load to a beam is applied hydraulically from above with four points of loading. The maximum test load is approximately 440 kN. The beam specimens were heated on three sides. The furnace temperatures were recorded, monitored and controlled to follow the standard fire curve in accordance with BS 476: Part 20[7]. The temperatures were measured at ten points in the furnace near the beam surface.

Test procedure

About one week prior to each fire test, the test beam was taken to the furnace room for instrumentation. At the start of the fire test 40kN load was applied by a hydraulic jack at four points 1m apart uniformly placed on the beam span. This was kept constant during each test by a hydraulic jack load cell monitor which was sat outside the furnace. The deflection was measured at mid-span point, using "Linear Voltage Deflection Transducers". The beam was placed centrally at the roof level of the furnace. The walls of the furnace were constructed with bricks. The roof was made with precast prestressed slabs, which were painted with fire resistance paint with insulation at the top. The gap between the slab-insulation and the beam were carefully packed with insulation, rock wool and ceramic wool, to protect the instrumentation above the slabs and to allow the beam to deflect freely under load. The four points load were applied on the beam through four pre-made holes in the pre-stressed slab of the roof. The loading rig was the same loading rig that was used for the testing control beam. Ten TC's inside ceramic tubes were hung from ceiling of the furnace to measure the temperature near the surface of the beam during the fire test. It was decided that the test should be terminated when the specimen attained a large deflection, or when it was judged as incapable of sustaining the applied load or showed signs of instability, whichever occurred earlier.

FIRE TEST RESULTS

The sequences of events observed during the fire test on each beam are listed chronologically in Tables 6 and 7 and deflection-time curves are shown in Figure 7. A slow but steady increase in beam deflection was recorded from outset of the test, but this settled down and the beams were effectively stable after approximately 30 minutes at this time the only observed effects were small amount of concrete spalling from the corner of the beams. Cracking in the concrete became evident in both beams after about 75-80 minutes which was accompanied by flaming from the crack regions. The beams exhibit a suitable increase in deflection which was identified as failure after 94 minutes for beam 2 and 128 minutes for beam 1. The appearance of the beams after failure and cooling to room temperature is shown in Figure 8 and Figure 9. The mode of failure of beam is via flexural-shear cracks and spalling of the concrete. After the fire testing the beam were removed from the furnace. It was observed that beam 1 was splitting in two.

Table 6 Observation of fire test on beam 1

Time (min)	Observations
0	Test started
12	Small amount of spalling at bottom corners of beam
75	400mm long crack evident longitudinally along bottom of beam approximately 300mm in from left hand edge of beam. Flaming from near end on bottom and side of beam
100	Crack has grown to approximately 800mm long and another has formed 40mm up the side100mm long
127	Large chunks have fallen off and a large crack 35mm wide has formed around the whole perimeter at mid length. Cracks are showing all over the beam
132	Load removed
140	Large chunk fallen off
143	Test stopped

Table 7 Observation of fire test on beam 2

Time (min)	Observations
0	Test started
14	Small amount of liquid dripping from bottom of beam
25	Small amount of spalling from corners of beam
50	Spalling evident from top of beam
80	300mm long longitudinal cracks have appeared mid way up near side of beam at left-hand end. Flickering flame on far side of beam
88	Crack on bottom of beam (tension face) opened approximately 2mm wide
92	More flaming from other parts of beam and 100mm long longitudinal cracks appeared mid length on bottom and near side
94	Rate exceeded for deflection
101	Rate of deflection was exceeded
104	Test Stopped

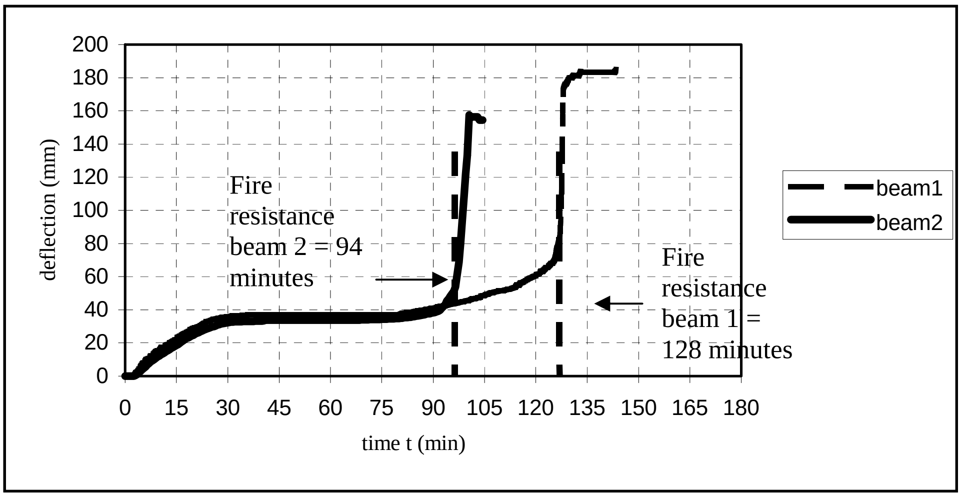


Fig 7 Heating time-deflection curves for beam 1 and beam 2

Fig 8 Rupture at the mid centre of the concrete in beam 1 after fire test

Fig 9 Failure of beam 2 after fire test inside the furnace shows some flexural cracks and rupture in the main reinforcement

Figure 10 depicts the temperatures measured at the mid centre of the beam in positions B, 80mm from bottom of the beam. The temperature increases with time. The ambient high temperature (T°C) at a point located at a distance of "x" mm from the face of the beam is assumed to be a function of fire exposure time. Figure 11 shows the maximum temperature measured at the rebar at each time interval. Figure 12 shows the average temperature at the stirrups. The data excludes some readings, which showed sudden, erratic and abrupt changes. This may be attributed to a possible shorting of a PTFE coated wire and the record showing temperature at a location other than the end of the thermocouple.

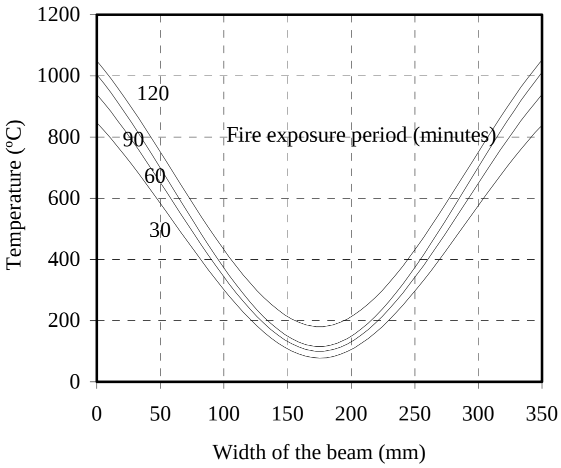


Fig 10 Temperature profile in the cross section of the beam 1 80mm from bottom of the beam for different fire exposure periods. The temperature of each side of the beam is an average reading from TC's in furnace on the each side of the beam.

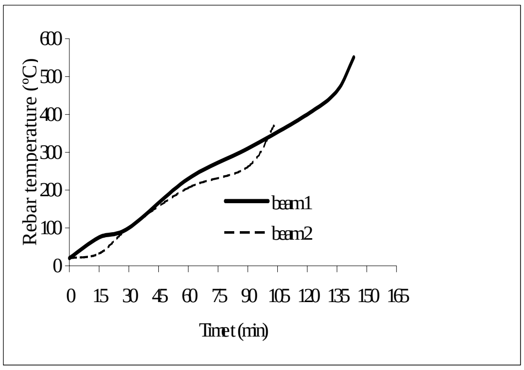


Fig 11 Heating time/ temperature in the rebars for beam1 and beam 2

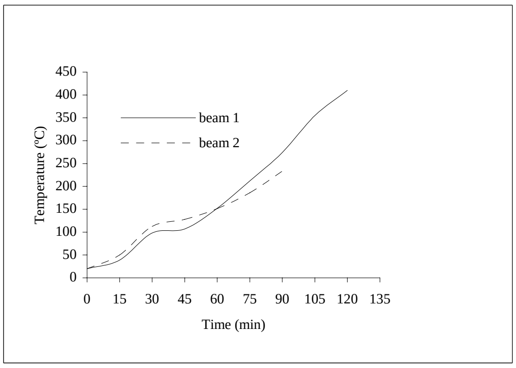


Fig 12 Average stirrups temperature in beam 1 and beam 2

DISCUSSION

All the results of the tested beams in comparison are given in Table 8. The rise in temperature in a concrete cross section, in response to high external temperatures, depends on a large number of factors. These factors include the moisture content of the concrete and the chemical composition of the aggregate and cement. Also, the development of temperature in a beam depends on the heating conditions and the heat transfer characteristics of the environment. However, these factors cannot be conveniently evaluated for the purposes of developing a general design rule. The heating time for beam 1 was 143 minutes with maximum central deflection of 185mm ≈L/23 and the heating time for beam 2 was 104minutes with maximum central deflection of 157.5mm ≈L/27. The difference may be attributed to the weaker bond strength between the rebar and concrete of beam 2 compared to beam 1. The deflection/time curves for both beam with fire resistance values is depicted in Figure 7. Sudden deflections in beam 1 and beam 2 were at 128 minutes and 94 minutes respectively. During visual observation subsequent to the completion of heating, the reinforcements were still seen emitting residual flames, this is thought to be due to the high temperature that the fibre bars had reached which aided ignition. The reinforcements which were extracted by chipping away the concrete, were found to have undergone thinning and carbonisation due to combustion.

It would appear from the fire tests using full-scale beams and analysis of the samples remained from the tests, that failure was due to fire penetration through the concrete beam cracks, which developed during testing. This resulted in burning of the matrix of the rebar, which caused interface cracking and de-bonding. This de-bonding resulted in shear cracks along the beam. In beam 1 in which GFRP stirrups was used, the beam split in two pieces after it was taken out of the furnace. Beam 2 was removed from the furnace in one piece, 30mm expansion was measured and beam was bent at the centre. In both beams spalling of the concrete occurred due to the pressure generated by the conversion of moisture in the surface layer of concrete to steam. After the fire test, samples of the rebars were collected from the tension face in middle of the beam in order to evaluate the effect of fire on the rebars. The samples were weighed and compared with unexposed samples. The weight of the rebar in beam 1 and beam 2 had reduced by 22.3% and 33.8% respectively.

Table 8 Results of loaded heating tests

Specimens	Load applied (kN)	Heating time (min.)	Failure mode	Failure time (min.)	Deflection at centre at end of heating (mm)	Average temp of bottom reinforcement at end of heating (°C)
Beam 1	40	143	Flexural failure and residual flames emitted from rebar	128	185	462
Beam 2	40	104	Flexural failure, large cracks at tension face of the beam and residual flames emitted from reinforcements	94	157.5	377

CONCLUSIONS

The fire resistance rating (load bearing capacity) for beam 1 was 128 minutes and for beam 2 was 94 minutes both beams were tested in accordance with BS 476 Part 21[8] 45% of allowable load was applied as service load the deflection was approximately L/23 for beam 1 and L/27 for beam 2. In the criteria for failure under load bearing capacity based on BS 476 : Part 20 (Section 10) [7] the deflection is L/20. The Building Regulations for fire safety recommend that the minimum periods of the fire resistance for the most groups of buildings should be of 90 minutes. These fire tests results indicate show that concrete beams reinforced with GFRP rebar will meet the fire design requirements for the minimum periods of fire resistance (fire endurance). A minimum clear concrete cover of 70mm is recommended for future design of GFRP-RC beams rebars under fire conditions.

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