PAPER REF: 4050

CONCRETE STRUCTURES WITH EXTERNALLY BONDED REINFORCEMENT – STRUCTURAL FIRE DESIGN AND FIRE PROTECTION

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ABSTRACT

This work describes structural fire design process of RC structures with externally bonded reinforcement. First part, basing on the calculation method given in EN 1992-1-2, answers the question: is fire protection of externally bonded reinforcement needed in every situation? The second part shows how such fire protection should look like and how it should be designed. Moreover, a test procedure for determining the effectiveness of applied fire protection systems to concrete structural members reinforced with FRP (Fibre-reinforced Plastic), used in Fire Testing Laboratory of Building Research Institute (ITB) is presented.

Keywords: concrete, FRP, fire protection, design, test procedure.

INTRODUCTION

Externally bonded reinforcement is more and more commonly used. Often this is due to change in building exploitation, which often implies additional variable load or due to design or erection mistakes.

FRP composites come in various types: Glass Fibre-Reinforced Plastic (GFRP), Carbon Fibre-Reinforced Plastic (CFRP) and Aramid Fibre-Reinforced Plastic (AFRP). The fibres are embedded in the matrix which acts as the binder material for the composite and transmits the applied loads to the fibres. The composites are produced in various shapes: bars – typically 50 ÷ 100 mm wide, sheets and panels. Tensile strength of FRP composite reaches 1500 MPa, which is much more compared to typical mild steel – 235 MPa.

In accidental design situation this reinforcement may or may not be needed, as ψ reduction factors can significantly limit the loads. But if it is needed, a fire protection system must ensure full strength of the bondage between the reinforcement and the concrete element – consequently, have to ensure the load-bearing performance criterion (R) of the structural element in fire situation.

A common mistake committed by designers or site engineers is leaving the FRP, or other externally bonded reinforcement unprotected or not sufficiently protected. This is because the critical temperature is taken as the reinforcement critical temperature (e.g. 500°C for steel, 550°C for rebars in concrete), not the adhesive critical temperature (50°C ÷ 100°C), which is significantly lower value, thus more fire protection is needed. Fire protecting may not always be needed, but this has to be proven in detailed calculations.

Fig.1 Sample concrete slab and beam FRP reinforcement (Courtesy of Radyab Company)

STRUCTURAL FIRE DESGIN

In structural fire designing, temperature dependent, mechanical and thermal material properties are taken into account, as well as different combination of loads is determining the strain level in the structure. Actions on structures exposed to fire are defined in EN 1991-1-2 and depending on national regulations either a standard or natural fire can be assumed. As the EN 13501-2 defines the fire resistance classes based on the standard temperature-time curve, only this type of action will be considered later in this article.

According to EN 1990, depending on the imposed load category, the ψ_1 factor varies between 0.2 and 0.9 and the ψ_2 factor varies between 0 and 0.8, which significantly lowers the load level in fire situation. Due to very dangerous failure mechanism of RC structures reinforced with FRP of brittle fracture, external reinforcement can be left unprotected only if the RC structure itself is able to support the total load in accidental fire design situation. Otherwise, the FRP reinforcement have to be fully protected for the whole duration of design fire exposure period, providing 100% effectiveness the whole time.

The assessment, whether the external reinforcement needs to be protected or not, can be performed in accordance with EN 1992-1-2. The first step is establishing loads and reduction factor:

- Combinations of actions for accidental design situations can be obtained from the following formula:

$$\sum G_k + \psi_{1,1} Q_{k,1} + \sum \psi_{2,i} Q_{k,i} + \sum A_d(t) \tag{1}$$

- Combinations of actions for persistent design situations can be obtained from:

$$\sum \gamma_{G,j} G_{k,j} + \gamma_{Q,1} Q_{k,1} + \sum \gamma_{Q,1} \psi_{0,i} Q_{k,i} \tag{2}$$

- The reduction factor η_{fi} for the above combinations:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \tag{3}$$

where:

G_k – characteristic value of a permanent action,

$Q_{k,1}$ – characteristic value of the leading variable action *1*,

$Q_{k,i}$	–	characteristic value of the accompanying variable action *i*,
$A_d(t)$	–	design value of an accidental action caused by fire,
γ_G	–	partial factor for permanent action (usually taken as 1,35),
γ_Q	–	partial factor for variable action (usually taken as 1,50),
$\psi_{1,1}$, $\psi_{2,i}$	–	factor for combination value of a variable action

The η_{fi} value depends on the $Q_{k,1}$ / G_k ratio, the partial safety factors γ_G and γ_Q and the combination factor ψ_{fi}, taken as $\psi_{1,1}$ or $\psi_{2,1}$. The relation has been illustrated in Figure 1. Without detailed analysis a value η_{fi} = 0,7, given in EN 1992-1-2, can be taken as a safe assumption, yet it is recommended to calculate the exact value of the reduction factor η_{fi}, as it will most likely be lower (see Figure 2).

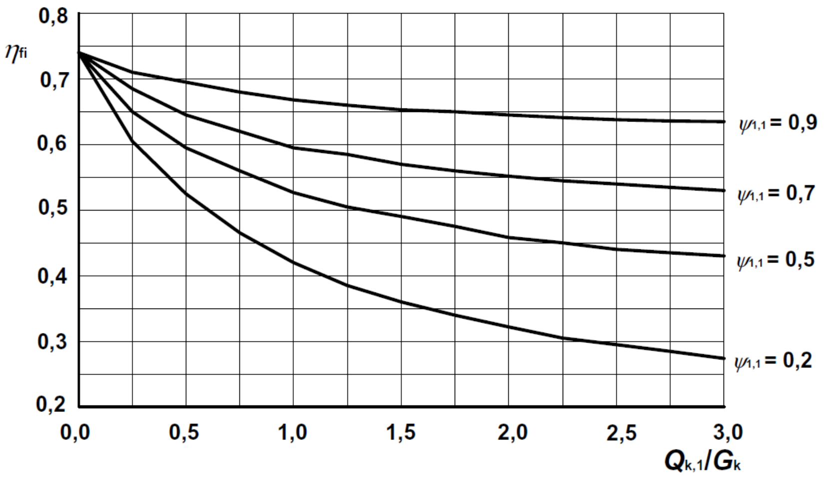


Fig.2 Variation of the reduction factor η_{fi} with the load ratio $Q_{k,1}$ / G_k (from EN 1992-1-2)

Once the combinations of actions for accidental and persistent design situations are established, the load bearing capacity of the RC structure without support from externally bonded reinforcement should be verified. This can be done either with tabulated data given in EN 1992-1-2, but it is recommended to use the 500°C isotherm method or the zone method, both also provided in EN 1992-1-2 Annex B, as they will provide more accurate results, often higher fire resistance class. Analysis will show whether the RC structure itself has enough load-bearing capacity in accidental design situations to ignore the extra reinforcement, designed primarily for the persistent combination of loads.

It may also happen, that the RC structure is capable to carry loads coming from the combination of actions for accidental design situations, but only in normal temperature conditions. In this case, fire protecting the FRP reinforcement can be discarded, if the RC structure is going to be protected to provide sufficient load-bearing capacity for the fire duration period. The algorithm is shown in Figure 3.

If protection is needed for FRP reinforcement, then the θ_{cr} critical temperature should be assumed as the adhesive critical temperature (e.g. 62°C). If it is needed only for RC structure, than it should be assumed as the reinforcement in concrete element critical temperature (e.g. 550°C).

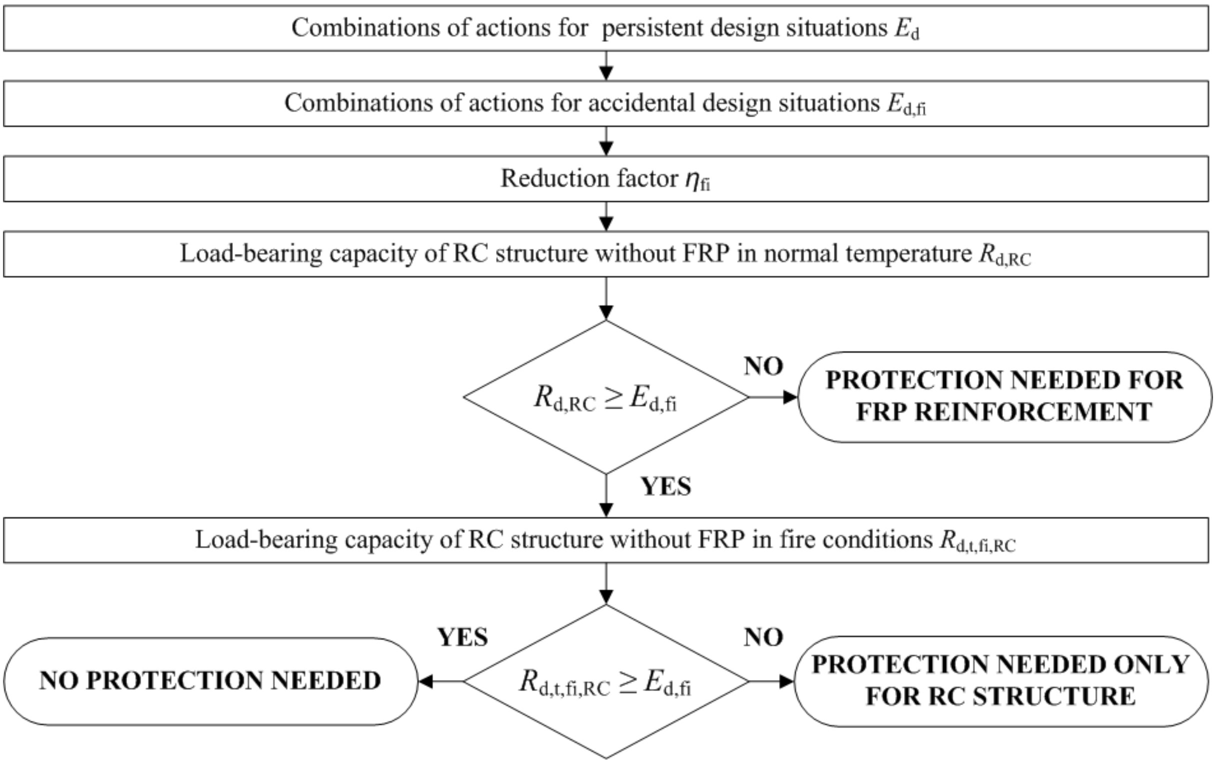


Fig.3 Algorithm for establishing whether fire protection is needed

FIRE PROTECTION SYSTEMS

Because of the adhesive low critical temperature (62 ÷ 100°C) and mostly long fire exposure times (60 minutes and more), only cladding or sprayed fire protection systems can be used on FRP reinforcement.

At the present time there is no test method written in the EN standards, which would provide a method for determining the contribution to fire resistance of concrete structural members reinforced with FRP. The standard test method described in ENV 13381-3, requires two fire tests per element type (floors, beams), one with minimum fire protection thickness, the other with maximum. This limits the applicability of the test results to a relatively small range of thicknesses (e.g. 10 ÷ 30 mm), which can be enough to cover the range of fire resistance classes from R 30 to R 360 for regular reinforced concrete structures, but is insufficient to provide enough data to properly assess the effectiveness of the tested fire protection in much thicker, multilayer configurations.

The method introduced in Building Research Institute (ITB) in the test method PB LP-054/1/11-2012 enhances the field of application of the fire protection systems. This is achieved in three steps:

1) analysis of the data obtained from the standard fire test programme (conducted in accordance with ENV 13381-3), to determine thermal conductivity, specific heat and density of the fire protection material, in function of temperature,

2) based on the results of the analysis from step 1, a fire test with various fire protection thicknesses, numerically calculated to provide sufficient insulation for 30, 60, 120 and 240 minutes of standard fire exposure, so that the temperature does not rise above the critical temperature for the FRP glue (e.g. 62°C), is carried out to provide more information on the material behaviour in fire conditions and its thermal properties,

3) analysis of direct results from the fire test and adjustment of the thermal properties of the fire protection system and further numerical analysis for enhanced assessment in accordance with the assessment procedure for PB LP-054/1/11-2012.

TEST PROCEDURE

The test method developed in the Fire Testing Laboratory of Building Research Institute (ITB), focuses on maximizing the amount of obtainable data from the fire test. The test specimen composes of small slab sub-elements and short beam sub-elements. Applied protection varies in thickness (up to 200 mm) and width on each element. Slab sub-elements are not fully covered, to enable the observation of the two-dimensional heat transfer in the concrete slab as well as from the sides of fire protection system. The sub-elements are isolated one from another with high density mineral wool, so as to not affect each other. The sizes, shapes and in-between sub-elements insulation type had been numerically verified to provide sufficient isolation of the sub-elements. As the temperature on the concrete surface rises much faster than in the reinforcing steel bars and the relevant temperature range is very low (< 200°C on the concrete surface) no imposed load on the test specimen is needed, as it would normally not influence the fire protection system behaviour.

The test specimen visualization is given in Figure 4.

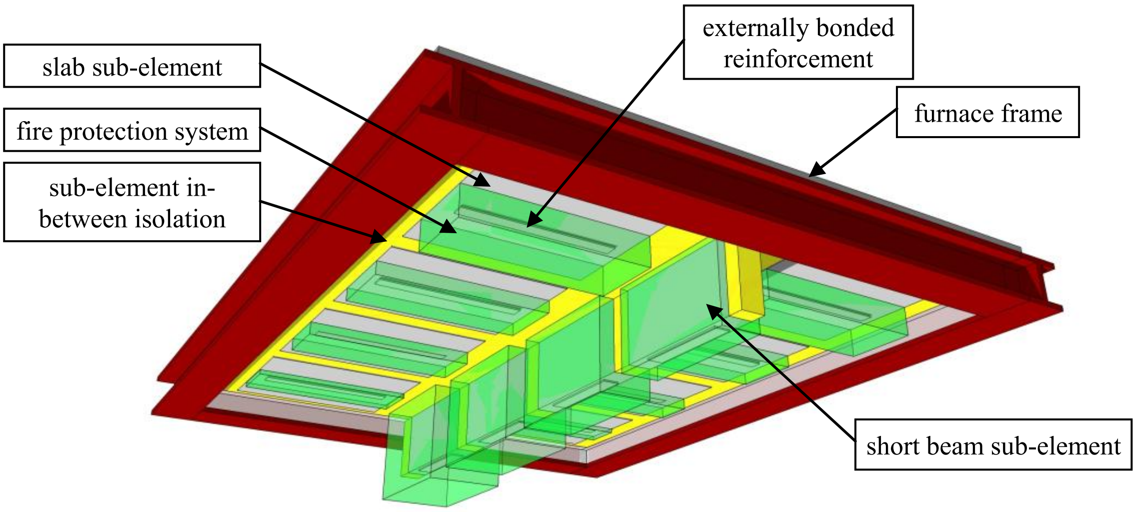


Fig.4 Test specimen visualization with cladding fire protection system

THERMAL ANALYSIS AND ASSESSMENT PROCEDURE

Basing on the fire test results thermal properties of the fire protection material are being determined. Chemical composition of the material, its properties in normal temperature conditions and behaviour in fire can indicate the shape of thermal conductivity and specific heat graphs in function of temperature. Especially any “temperature flattening” can show temperature levels where phase transitions occurs and a peak in specific heat function could be expected. By adjusting function values in subsequent iterations those functions can be established.

Because of non-linearity, various furnace conditions, variety in material properties itself and possible fixing errors, more than one set of properties is being formulated, depending on the fire protection system thickness.

The assessment procedure, also developed in Building Research Institute (ITB) provides two methods for determining the effectiveness of applied fire protection: graphical and numerical. In the first one a temperature-time graph is drawn with the limits of various maximum temperature levels (critical temperature for FRP adhesive, e.g. 62°C) as a function of time. The numerical method enables analysis of more complex design situations, such as: vicinity of openings, irregular geometry of the structure or reinforcement. A sample material properties and correspondence of the fire test results and numerical simulations are given in Figure 5 and 6. The set of presented data is valid for range of thicknesses from 10 to 30 mm.

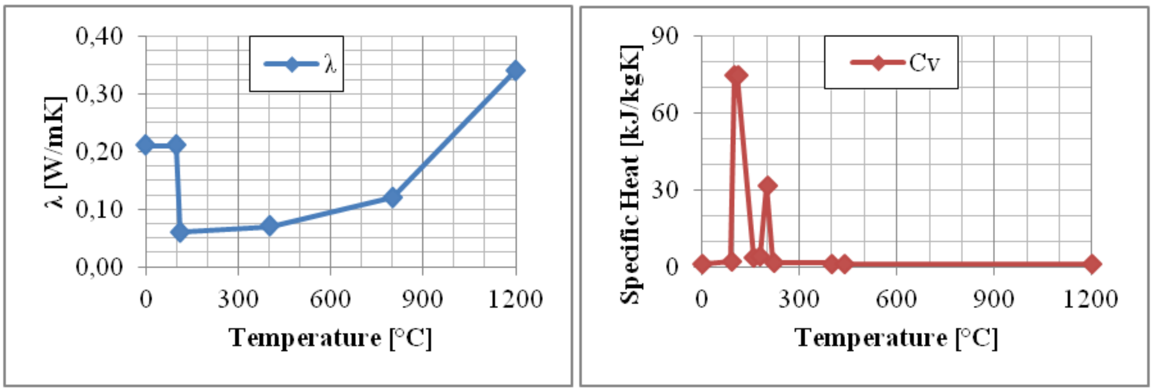


Fig.5 Sample results of material properties of one fire protection system

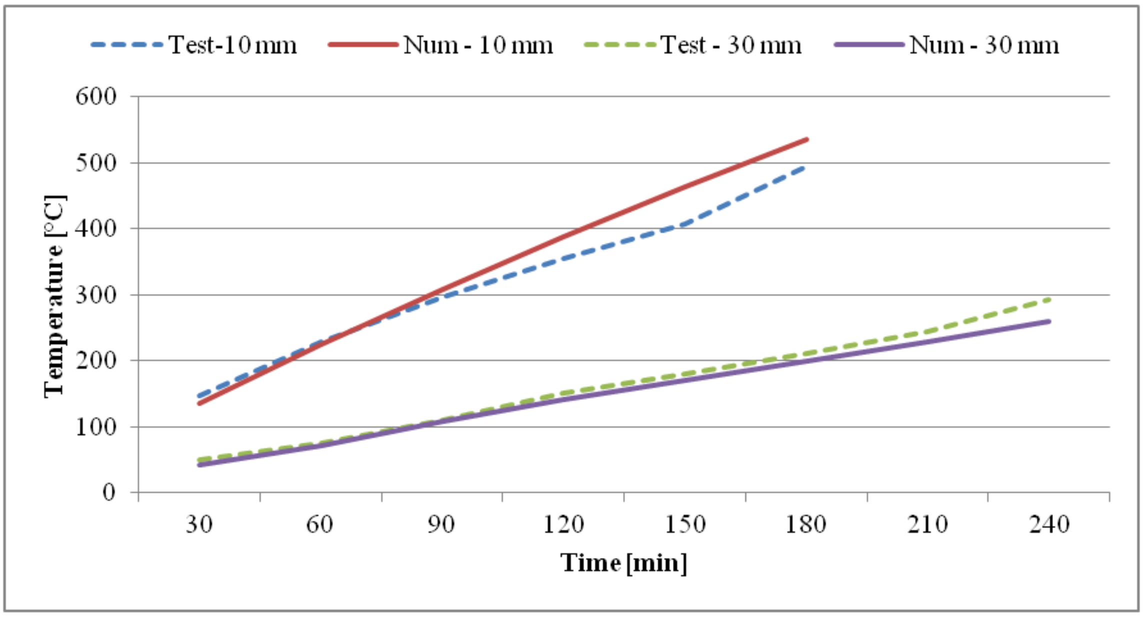
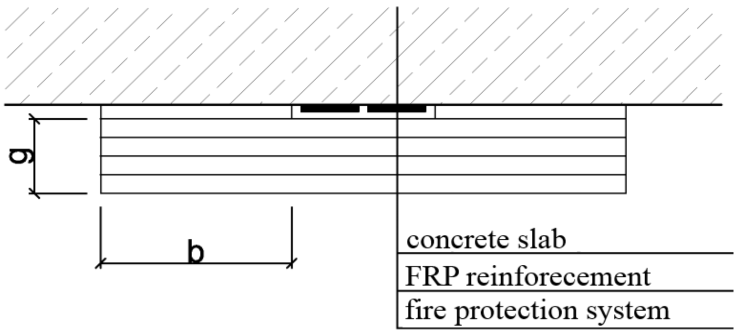


Fig.6 Comparision of the fire test results and numerical simulation

Tabulated data generated in the graphical method are based on the direct results from the fire test but apply only to flat slabs without any opening or irregularities in their geometry and to beams of minimum width 15 cm. Sample data are given in Table 1 and 2. The symbols are explained in Figure 7.



g – thickness of fire protection system

b – side width of fire protection system

Fig.7 Cross section of a fire protected concrete slab with FRP

Table 1 Sample test results for slabs

g / b [mm / mm]	**Temperature [°C] after fire exposure period**			
	30 min	*60 min*	*120 min*	*240 min*
25 / 25	82	218	403	646
25 / 50	48	136	284	508
50 / 50	45	82	199	409
50 / 100	30	45	87	247
100 / 100	24	36	69	120
100 / 150	22	26	41	81
150 / 150	21	24	38	77
100 / 200	22	25	33	59
150 / 200	21	22	28	51
150 / 250	21	22	26	38

Table 2 Sample test results for beams

g [mm]	**Temperature [°C] after fire exposure period**			
	30 min	*60 min*	*120 min*	*240 min*
25	44	113	256	547
50	31	44	77	270
100	23	28	37	61
150	21	23	29	41
200	20	21	25	34

CONCLUSION

This study has shown the principles of structural fire design of RC structures reinforced with FRP composites. Basing on the tabulated data or advanced calculation method given in EN 1992-1-2 and the basis of structural design given in EN 1990 it can be checked if the FRP reinforcement needs to be fire protected, or just the RC structure, or none of them.

Presented test method and assessment procedure provide tabulated data for designers enabling proper fire protecting the RC structure in fire conditions.

Further tests should be performed in order to verify the behavior of FRP composites in fire conditions and to obtain more information on mechanical material properties of FRPs at elevated temperature.

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Procedura Badawcza PB LP-054/1/11-2012 – Badania skuteczności ogniochronnej zabezpieczeń taśm stanowiących zewnętrzne doklejane zbrojenie elementów z betonu. (in Polish)

Procedura Oceny do PB LP-054/1/11-2012 – Procedura oceny skuteczności ogniochronnej zabezpieczeń taśm stanowiących zewnętrzne doklejane zbrojenie elementów z betonu. (in Polish)