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Simplified methods to determine shear strength in reinforced concrete beams with fiber-reinforced polymers exposed to fire

Métodos simplificados para la determinación de la resistencia al corte en vigas de hormigón armado con polímeros reforzados con fibras expuestas al fuego

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Abstract

The importance of structural design under fire conditions, together with the uncertainty in the behavior and resistance of reinforced concrete structures with fiber-reinforced polymer bars (FRP) at high temperatures, reveal the need for more research along these lines. Although there are studies evaluating the flexural and shear strength of elements exposed to fire, there are no standards nor regulations specifying the procedures thereto. This work proposes methods to calculate shear strength in FRP-reinforced concrete beams, with rectangular cross-section, based on the degradation of the properties of the materials and/or the reduced concrete cross-section, as recommended by (Diab, 2014), Eurocode 2 (EN-1992-1-2, 2004) and (Saafi, 2002). In accordance with the thermal analysis executed with the Super Tempcalc software, these procedures were applied to 13 beams of different dimensions and reinforcements, subjected to standard fire of the ISO-834 standard on three sides, thereby obtaining the shear capacity degradation curves for each case. The results show that the EN-1992-1-2 (2004) allows to adequately predict the shear strength of RC beams with FRP under fire conditions..

Keywords: *Beam, reinforced concrete, shear, fire, fiber-reinforced polymer (FRP)*

Resumen

La importancia del diseño de estructuras expuestas al fuego, junto con la incertidumbre en el comportamiento y resistencia de las estructuras de hormigón armado con barras de polímeros reforzados con fibras (PRF) a elevadas temperaturas, evidencian la necesidad de más investigaciones en este sentido. Aun cuando existen estudios dirigidos a la evaluación de los esfuerzos resistentes de flexión y cortante en situaciones de incendio en estos elementos, no existen normas o regulaciones que especifiquen procedimientos para ello. En este trabajo se proponen métodos para el cálculo de la resistencia al corte en vigas de hormigón armado con PRF, de sección rectangular, a partir de la degradación de las propiedades de los materiales y/o la sección reducida de hormigón, según lo recomendado por (Diab, 2014), el Eurocódigo 2 (EN-1992-1-2, 2004) y (Saafi, 2002). Partiendo del análisis térmico realizado con el programa Super Tempcalc, estos procedimientos se aplicaron en 13 vigas, con distintas dimensiones y armados, sometidas al fuego estándar de la norma ISO-834 (2000) en tres caras, obteniéndose las curvas de degradación de la capacidad a cortante para cada caso. Los resultados demuestran que las diferencias entre los valores de resistencia al corte fueron muy pequeñas para todo el tiempo de exposición al fuego considerado.

Palabras clave: VIga, hormigón armado, cortante, fuego, polímeros reforzados con fibras (PRF)

1. Introduction

The global impact of fiber-reinforced polymers (FRP) on civil engineering is mainly due to their great advantages in the construction sector, such as high corrosion resistance, high strength to weight ratio compared with steel, in addition to their resistance to the action of chemical substances and fatigue strength. Nevertheless, aspects such as low ductility, low modulus of elasticity, lower shear strength and low resistance to high temperatures can limit their use as reinforcement materials in concrete structures (Wainshtok et al., 2017). In reinforced concrete elements with FRP, the temperature increase reduces the strength and stiffness of the bars, as well as the bond performance between the bar and concrete, mainly due to the degradation of the matrix (Hajilooet al., 2018); (Özkal et al., 2018).

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Most of the experimental or numerical studies carried out to date on reinforced concrete elements with FRP exposed to fire have focused their attention on the flexural behavior (Adam et al., 2015); (Bilotta et al., 2020); (Gao et al., 2016); (Kodur y Agrawal, 2016); (Petr et al., 2019); (Rafi et al., 2011); very few of them are focused on assessing shear strength.

However, real fire events have showed the importance of shear failure due to fire exposure, which have raised increasing awareness of the fact that it can be a critical condition to the point that it can be the ruling failure in RC elements during fires (Diab, 2014).

It is extremely difficult to model the complex interaction of shear strength mechanisms at high temperatures, since fire increases the cracks' height and, therefore, reduces the depth of the compression zone (Kashwani and Al-Tamimi, 2014). This phenomenon is further aggravated in reinforced concrete elements with FRP, because the lower stiffness of this type of reinforcement leads to higher cracking rates, which reduces the compression zone and, consequently, the contribution of concrete to shear strength is reduced as well (Bywalski et al., 2020).

(Albuquerque and Silva 2013) and (Diab, 2014) agree that existing design methodologies at ambient temperature allow assessing the shear capacity of an element exposed to fire, thereby considering the reduction of the shear stress in the stirrup and concrete and/or in the effective cross-sectional area, as a consequence of high temperatures. (Albuquerque and Silva 2013) present a calculation procedure to determine the degradation of shear strength in RC beams with steel, based on the reduction of the concrete cross-section (500°C isotherm method) and the consideration of an actually cracked region, as proposed by the Eurocode (EN-1992-1-2, 2004). Meanwhile, (Diab, 2014) formulates and validates a method based on strength degradations, based on mean temperatures of shear reinforcement and concrete.

Concerning RC beams with FRP, there are no standards or regulations specifying procedures for high temperature designs. Although design codes and guidelines for RC elements with FRP (ACI-440.1R, 2015; CAN/CSA-S806-12, 2017; ESCC, 2005) do mention these materials' susceptibility to fire, only CSA S806-12 (CAN/CSA-S806-12, 2017) provides guidance for the designer, which includes slab recommendations regarding the necessary concrete cover to obtain a specific fire resistance for an FRP-reinforcement, once their critical temperature is known.

In relation to RC beams with FRP, (Saafi, 2002) offers a design method supported by the same philosophy used in steel reinforcement. The author determines the strength degradation of FRP based on the stirrup's mean temperature. Regarding concrete, he considers a strength reduction and, at the same time, reduces the cross-section according to the 700°C isotherm method, which is neither justified nor referenced.

The need to identify reliable and simple procedures to estimate the shear capacity derives from the actual possibility of structures suffering shear failure during an event, especially reinforced concrete structures with FRP, which are characterized for having less shear strength than steel. Another reason is the lack of international technical literature dealing with validated simplified methods to evaluate the shear capacity of RC beams with FRP exposed to fire.

This work presents and compares calculation methods available in the literature to assess the shear strength degradation in RC beams exposed to fire, with the aim of identifying a simplified analytical procedure, which can be applied when FRP bars are used as concrete reinforcement.

2. Discussion and Development

The study considers 13 beams with different dimensions, covers and reinforcement amount (Table 1), which are factors that highly influence the resisting capacity of reinforced concrete beams when exposed to fire (Bywalski et al., 2020); (Diab, 2014). The studied beams considered 12 beams reinforced with FRP bars (P beams), with tensile strength of 800 MPa and modulus of elasticity of 50000 MPa, and one beam reinforced with steel (A), in order to establish a comparison and obtain criteria regarding the use of one method or the other. All cases assumed concrete with compressive strength of 25 MPa.

Table 1. *Analyzed reinforced concrete cross-sections with FRP*

Beam	Cross-section Dimensions		Cover [mm]	Longitudinal Reinforcement		Transverse Reinforcement	
	b (mm)	h (mm)		ρ_L(%)	Bars	ρ_T(%)	S (mm)
A1	250	400	30	0.66	STEEL 3Ø16	0.32	Ø8@125
P1	200	300	30	0.66	FRP 3Ø12	0.40	Ø8@125
P2	250	300	30	0.66	FRP 2Ø16	0.32	Ø8@125
P3		400	30		FRP 3Ø16	0.32	Ø8@125
P4						0.29	Ø8@135
P5						0.27	Ø8@150
P6		500	30		FRP 2Ø20 1Ø16	0.32	Ø8@125
P7	300	400	30	0.38	FRP 3Ø12	0.38	Ø10@150
P8				0.57	FRP 3Ø16		
P9				0.89	FRP 3Ø20		
P10	350	650	30	0.46	FRP 3Ø20	0.19	Ø10@240
P11			40				
P12			50				

In order to determine the shear strength of the beam at high temperatures, the methodology proposed in (ACI-440.1R, 2015) regarding the design of RC elements with FRP at ambient temperature was used, which was modified to include the temperature effects according to the proposed methods. Therein, the shear strength provided by concrete (V_c) is evaluated with (Equation 1), while the shear strength provided by FRP stirrups, which are perpendicular to the axis of the element, is determined through (Equation 2):

$$\boldsymbol{V_c = (0.40k_s)\sqrt{f'_c}\cdot b\cdot d} \qquad (1)$$

$$\boldsymbol{V_f = \frac{A_{fv}\cdot f_{fv}\cdot d}{s}(sen\alpha + cos\alpha)} \qquad (2)$$

Where:
k_s *: Neutral axis depth of the cracked cross-section*

$$\boldsymbol{k_s = \sqrt{\left(n_f\rho_f\right)^2 + 2n_f\rho_f} - n_f\rho_f} \qquad (3)$$

n_f*: Ratio of the modulus of elasticity of concrete to the FRP*
ρ_f*: Geometrical proportion of the FRP reinforcement in tension*
f'_c*: Compressive strength of concrete*
A_{fv}*: Total reinforcement area in the web within a spacing s*
f_{fv}*: Working stress of the FRP transverse reinforcement, obtained as the lowest value between* $0.004E_{fu}$ *and the resistance in the bend area of the stirrup* f_{fb}*:*

$$\boldsymbol{f_{fb} = \left(0.05\frac{r_b}{\emptyset_c} + 0.3\right)f_{fu} \leq f_{fu}} \qquad (4)$$

Where:
r_b *is the internal bend radius of the bar,* $\emptyset_c$ *is the nominal diameter of the FRP bar, and* f_{fu} *is the ultimate tensile strength of the FRP bar.*

2.1 Thermal Analysis

The thermal analysis uses numerical modeling, a tool that is still widely used for solving structural engineering problems under fire conditions, as an alternative to the expensive physical tests. Temperatures were obtained from the thermal modulus Super Tempcalc, of the Swedish software Temperature Calculation and Design (Fire Safety Design, 2007), which allows doing two-dimensional analysis of structures exposed to fire, whose efficiency has been demonstrated in several previous studies (Albuquerque and Silva 2013); (Larrua and Silva 2013); (Larrua et al., 2015). The heating of the cross-sections was modeled through the standard fire curve (ISO-834, 2000) and, as boundary conditions, the lateral and bottom sides of the beams were assumed to be exposed to the fire. Given the fact that the cross-section has a rectangular geometry, the grid was defined by rectangular elements of four nodes of 0.5 cm. The adopted initial temperature (ambient) was 20°C, considering fire exposure times up to 135 minutes, which were defined in each case by the failure of the analyzed cross-sections. (Figure 1) shows the temperature fields and isotherms resulting from this analysis for the cross-section of 200 x 300 mm, with a fire exposure time of 45 minutes.

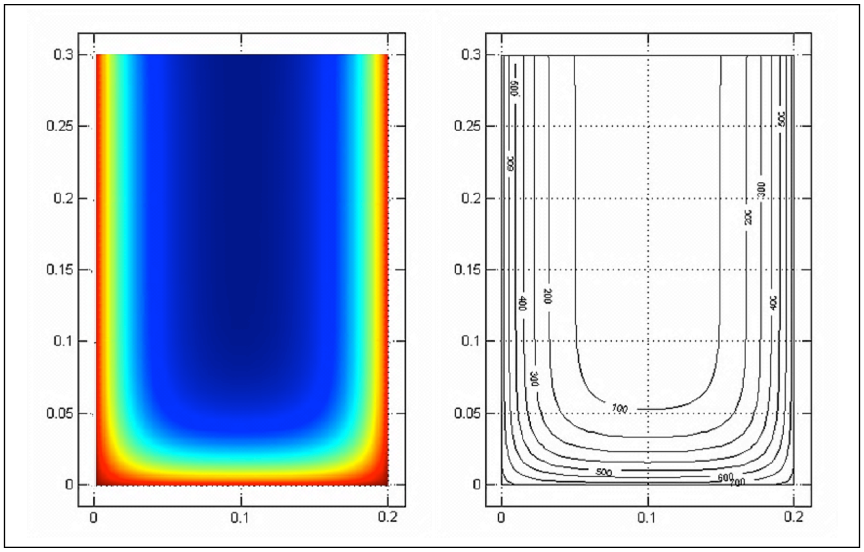


Figure 1. *Temperature fields and isotherms of the beam cross-section of 200 x 300 mm*

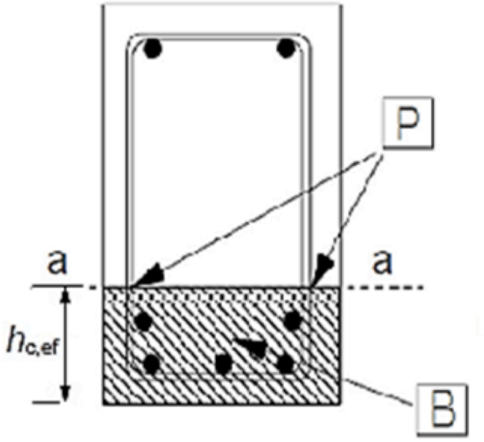
The physical and thermal properties of concrete (thermal conductivity, specific heat and density) were obtained from (EN-1992-1-2, 2004), while the properties proposed by (ACI-440.1R, 2015) and (Nasreen, 2016) were considered for the FRP bars.

2.2 Mechanical Analysis

The following three methods identified in the literature were used in concrete elements reinforced with steel as well as with FRP, whose considerations for shear strength calculations differ from one another: The method proposed by Eurocode 2 (EN-1992-1-2, 2004), recognized as the most complete and updated regulatory document regarding structural design under fire conditions; the method proposed by (Diab, 2014), as a result of his investigations addressing the shear capacity evaluation of steel-reinforced concrete beams exposed to fire; and the method proposed by (Saafi, 2002) regarding the specific case of FRP-reinforced beams.

2.2.1 Method of the Eurocode 2 (EN-1992-1-2, 2004)

The Eurocode 2 presents a simplified method, which considers the concrete strength reduction due to the effects of temperature as a consequence of a reduction of the resistant area. This reduction is given under the assumption that in zones where concrete reaches a temperature over 500°C, concrete is excessively damaged due to the fire action and it is "ignored". Therefore, the reduced cross-section, with dimensions b_t (reduced width) and d_t (reduced effective height), will be the one surrounded by the isotherm of 500°C. Furthermore, according to the hypothesis adopted in the method, the characteristic compressive strength of concrete in this region is the same *considered at ambient temperature ($f'_{c\theta} = f'_c$). Regarding the transverse reinforcement, it should be kept in mind that, unlike the longitudinal reinforcement, it has a temperature gradient when beams are exposed to fire on three sides. Consequently, in order to define the stirrup temperature, it is assumed that the maximum stresses of the shear reinforcement are produced in cracked areas, thereby determining an effective tension area in the concrete cross-section, or the area favoring the appearance of cracks. Thus, the reference temperature is in point P, located at the intersection of the upper limit of this area with the stirrups (Figure 2).*



B: Effective tension area of the cross-section

Figure 2. Reference point to calculate the stirrups' temperature (EN-1992-1-1, 2002)

According to (EN-1992-1-1, 2002), the height of the effective area ($h_{c,ef}$) is calculated as the lowest value among those resulting from the (Equation 5), (Equation 6) and(Equation 7):

$$h_{c,ef} < 2.5(h - d) \tag{5}$$

$$h_{c,ef} < \frac{h-x}{3} \tag{6}$$

$$h_{c,ef} < \frac{h}{2} \tag{7}$$

Where:
d: effective height of the total cross-sectional area
h: height of the total cross-sectional area
x: neutral axis depth of the total cross-sectional area

2.2.2 Mean Temperature Method

The method considers the mean temperature of the concrete and the reinforcement. For calculating the concrete temperature, (Diab, 2014) proposes and validates a method based on the mean temperature of the total cross-sectional area.

In relation to the reinforcement, the temperature is determined by calculating the mean temperature of all finite elements contained in the area of one of the stirrup legs. The use of this method is justified, since the distance between the finite elements is the same and the shear stresses are assumed constant along the stirrup height (Diab, 2014).

The respective strength reduction factors of the concrete and the transverse reinforcement are calculated on the basis of these temperatures.

2.2.3 Method Proposed by Saafi for FRP-reinforced Beams (Saafi, 2002)

(Saafi, 2002) takes into account the effect of temperature on the shear capacity of concrete by considering a reduction of the resisting area and a reduction of the concrete compressive strength (f_{cT}). The width of the reduced section (*bt*) is obtained by ignoring the concrete whose temperature exceeds 700°C, while the degradation factor of the compressive strength is determined based on the cross-section mean temperature, calculated according to the mean temperature of each strip, where it is discretized (the area outside the 700°C is included as zero). The shear strength degradation of the reinforcement is calculated according to the mean temperature of the stirrup leg.

2.3 Shear Strength at High Temperatures

The three procedures described above were applied to the cross-sections detailed in (Table 1), thereby obtaining the shear strength values at high temperatures for each cross-section analyzed (Table 2).
The reduction factor of the compressive strength of concrete was taken from (EN-1992-1-2, 2004); while for the FRP, the reduction factors of the resistance and the modulus of elasticity were considered, as proposed by (Blontrock et al., 1999) and indicated in (Saafi, 2002).

Table 2. *Summary of shear strength results at high temperatures for analyzed reinforced concrete cross-sections with FRP*

Beam	***Fire Exposure Time (min)***	***Shear Strength at High Temperature ($V_{n,\theta}$) [kN]***					
		EC -2	***Mean Temperature***	***Δ EC- 2– Mean T. (%)***	***Saafi***	***ΔEC- 2– Saafi (%)***	***Δ Mean T. –Saafi (%)***
A1	*45*	*121.80*	*124.50*	*2.17*	*123.9*	*1.7*	*0.48*
P1	*45*	*24.19*	*25.97*	*6.85*	*25.56*	*5.36*	*1.58*
P2	*45*	*25.63*	*27.25*	*5.94*	*27.09*	*5.39*	*0.59*
P3	*45*	*40.12*	*42.98*	*6.65*	*42.41*	*5.40*	*1.33*
P4	*45*	*38.54*	*41.23*	*6.52*	*40.66*	*5.21*	*1.38*
P5	*45*	*36.58*	*39.10*	*6.45*	*38.53*	*5.06*	*1.48*
P6	*45*	*53.72*	*59.16*	*9.19*	*57.15*	*6.00*	*3.40*
P7	*60*	*16.72*	*21.50*	*22.23*	*21.24*	*21.28*	*1.21*
P8	*60*	*19.46*	*24.82*	*21.60*	*24.47*	*20.47*	*1.41*
P9	*60*	*24.53*	*27.92*	*12.14*	*27.48*	*10.74*	*1.58*
P10	*70*	*11.88*	*27.89*	*57.39*	*27.45*	*56.71*	*1.58*
P11	*70*	*50.82*	*57.92*	*12.27*	*56.95*	*10.77*	*1.68*
P12	*70*	*79.29*	*83.94*	*5.53*	*83.01*	*4.48*	*1.10*

The analysis of the results allows evidencing that values obtained from the mean temperature method recommended by (Diab, 2014), are, in all cases, irrespective of cross-section dimensions and reinforcement amounts, quite similar to those determined by the method proposed by(Saafi, 2002); no differences above 4% are appreciated, even though they apply different hypothesis for calculating the shear strength of concrete. The results obtained with the methodology proposed in Eurocode 2 were all below the values calculated by the other procedures, favoring safety, which can be explained by the fact that it was based on more elementary assumptions than the other two. This difference is more pronounced as fire exposure time increases.

Moreover, it was possible to observe that the differences between one methodology or the other in RC beams with FRP, as well astheir ascending behavior with increased fire exposure time, are similar to those obtained in conventional RC beams (Figure 3).

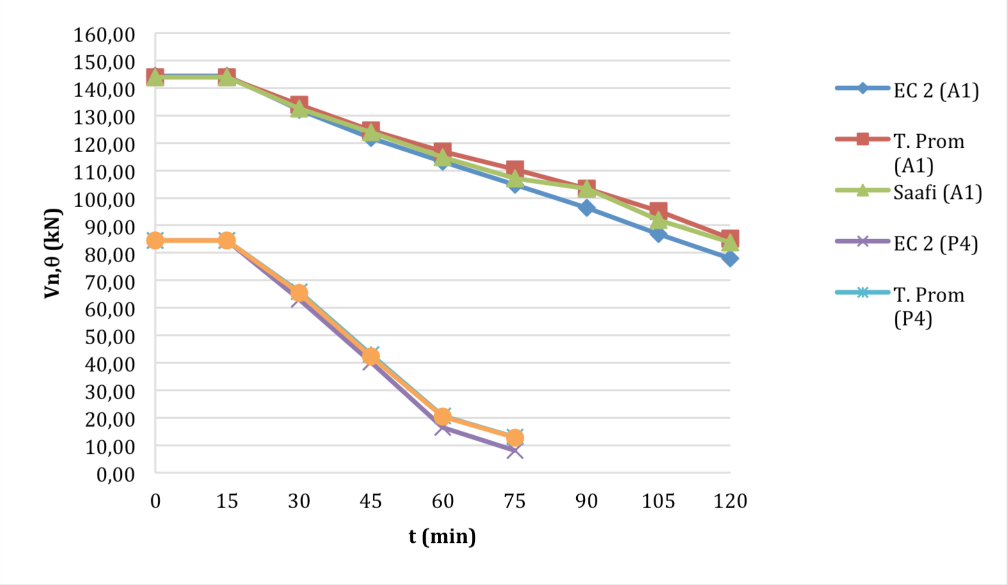


Figure 3. *Shear strength variation at high temperatures in beams A1 and P4 (250 x 400 mm)*

The study also demonstrated that when small covers are used, the EC-2 is much more conservative than in the other methods considered, whereby the strength capacity values are approximately half of those obtained by the mean temperature method or the method proposed by Saafi (Saafi, 2002). Likewise, a better approximation between the analyzed methods is observed when using greater bar diameters and smaller beam depths.

(Figure 4), (Figure 5) and (Figure 6) show the influence of these parameters on the shear strength degradation for the methods considered.

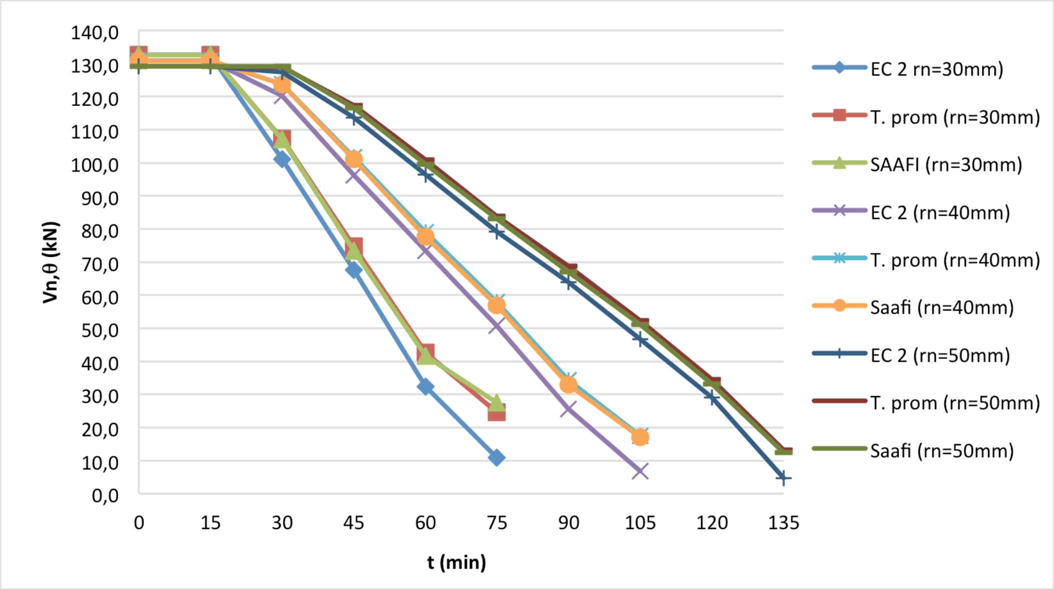


Figure 4. *Shear strength variation at high temperatures in beams P11, P12 and P13 (350 x 650 mm, r_n=30, 40, 50 mm)*

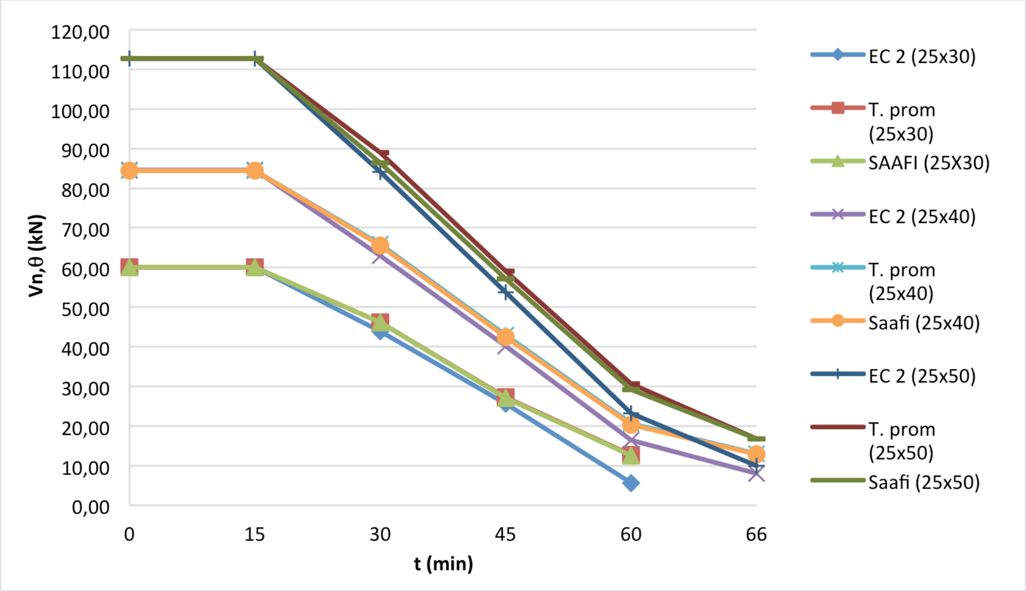


Figure 5. *Shear strength variation at high temperatures in beams P3, P4 and P7 (b=250 mm; h=300, 400, 500 mm)*

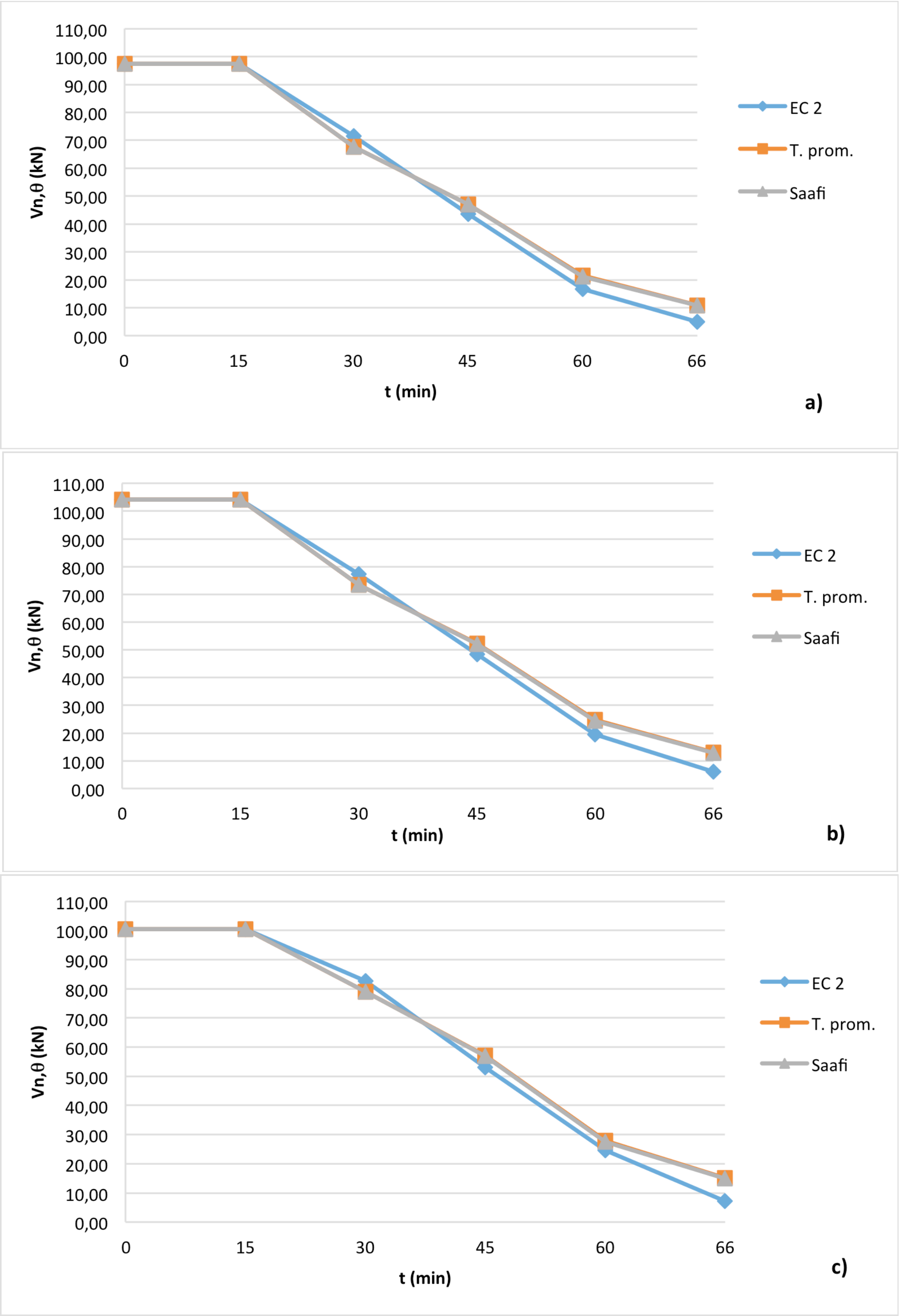


Figure 6. Shear strength variation at high temperatures in beams P8, P9 and P10 (300 x 400 mm; a) 3Ø12, b) 3Ø16 and c) 3Ø20)

3. Conclusions

This work analyzed three procedures to determine the shear strength of RC beams with FRP under fire conditions. The study was applied to 13 beams with different dimensions and longitudinal and transverse reinforcement amounts. Based on the results, the following can be concluded:

- *Recognized methods for calculating shear strength at high temperatures in steel-reinforced concrete beams are valid and can be applied when reinforcing with FRP bars.*
- *The (EN-1992-1-2, 2004) is the most conservative among the three procedures, which adequately predicts the shear strength of RC beams with FRP under fire conditions. Therefore, given the absence of tests that allow confirming these results, the authors recommend using this method to estimate the shear capacity of these elements.*

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