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FRP composites in enhancement of timber structures

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Abstract: *FRP composites in enhancement of timber structures.* Over last few decades timber engineering has significantly developed. It offers a large variety of alternatives to traditional materials and methods. For example, more and more often FRP (fiber reinforced polymer) composites, widely used in concrete structures, are getting extended to timber structures. However, the lack of established design rules regarding to FRPs usage in strengthening and repair of timber structures has significantly complicated its practical application. That is why in recent years techniques involving FPRs have been studied on many levels, such as issues of the bond between reinforced and reinforcement material, bondline delamination process, quality control procedures for on-site bonding, leading to the design rules development.

Keywords: FRP materials, design, analytical model

INTRODUCTION

FRP materials (fibre reinforced polymer) are characterized by specific properties that distinguish them from traditional building materials, such as low specific gravity together with very high mechanical parameters. High efficiency results from the two-phased structure of this material, consisted of high strength fibres (carbon, glass, aramid) and a resin matrix (usually epoxy). The resulting mechanical properties of the composite depend on the percentage and the mechanical properties of the two phases as well as the geometrical features of the reinforcement and the arrangement of the matrix [German 2001].

Among the FRP materials that can be used to reinforce the structure are CFRP - Carbon Fibre Reinforced Polymer, GFRP - Glass Fibre Reinforced Polymer and AFRP - Aramid Fibre Reinforced Polymer. In table 1 comparison of FRPs key mechanical properties are shown together with properties for steel. Because of the chemical resistance of carbon fibers to alkaline environment, high modulus of elasticity and tensile strength of the composite, carbon fiber composites are very often used at construction site. The use of FRPs instead of steel, creates new opportunities for designers and constructors due to considerably reduced weight gain and high corrosion resistance.

Table 1. Mechanical parameters of FRPs and steel

	CFRP	GFRP	AFRP	Steel
Tensile strength [MPa]	600-3690	480-1600	1720-2540	300-450
Young's modulus [GPa]	120-580	35-51	41-125	200

However, despite to the wide variety of possible industrial applications, the lack of established design rules is noticeable. In many situations it causes restriction in the use of FRP based techniques instead of traditional, most preferable techniques. Various committees are engaged in elaboration of the design rules for reinforced wood as well as in systematization of current knowledge on this topic [Triantafillou 1997, Radford et. al 2002; Broughton and Hutchinson 2003, Valipour and Crews 2011].

The aim of the article is the discussion of the design rules that could be implemented in specific regulations regarding design of timber elements reinforced with CFRP strip in various configuration.

METHODS AND ANALYTICAL ANALYSIS

The analytical models are a tool for description of a reinforced structural elements under applied load. Additionally, they allow to predict the reinforcement efficiency, even in cases particularly difficult to assess stability.

The reinforcement efficiency can be characterized by determination the stress values in the glueline and reinforcement material. In analysis the cross section of wood was 50 mm x 100 mm. The most common strength class of wood was considered – C24. On this basis the compression and tension strength in respective zones were determined (figure 1).

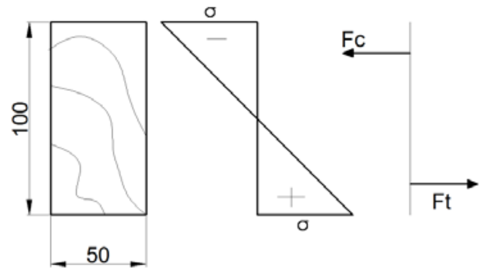

Figure 1. Wooden cross-section (C24), normal stress distribution

For the described strength grade of timber (C24), the characteristic value of bending strength is 24 N/mm^2. Therefore, the force acting on the section can be calculated using the formula (1).

$$F_c = F_t = 0{,}5 \cdot f_{m,k} \cdot b \cdot \frac{h}{2} = 0{,}5 \cdot 24 \cdot 50 \cdot \frac{100}{2} = 30\ [kN] \quad (1)$$

where,

F_c − compressione force possible to be transferred by the section [N],
F_t − tensile force possible to be transferred by the section [N],
$f_{m,k}$ − the characteristic value of bending strength [N/mm^2],
b − width of the cross-section [mm],
h − height of the cross-section [mm].

It was assumed that the analyzed cross-section is weakened with a presence of knot of 20mm in diameter (figure 2). In analytical model knots were represented by a simple boreholes. All calculations relate to the critical cross section, which is in the section corresponding to the vertical axis of the hole. In zones where the section is limited, it does not participate in stress transmission. These stresses should be transferred to the reinforcement. The worst situation is when reinforcement must take all tensile or compression stresses. This situation has been selected for further analysis.

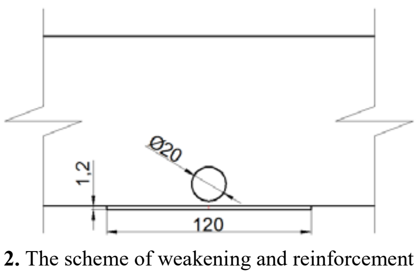

Figure 2. The scheme of weakening and reinforcement method

The first developed model relates to the reinforcement method consisting of CFRP strip (120mm of length, 50mm of width, 1,2mm of thickness) bonded to the bottom surface of bent element (figure 3).

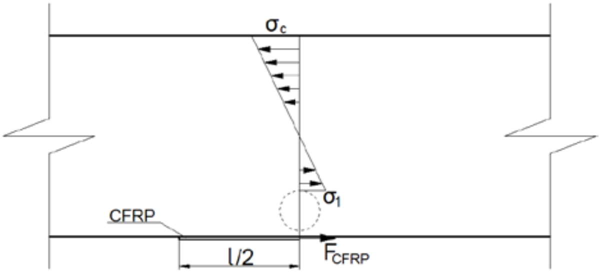

Figure 3. The scheme of weakening and reinforcement method

Stresses in CFRP strip as a result of tensile forces equal to 30kN may be calculated using the formula (3).

$$\sigma_{CFRP} = \frac{F_t}{b_{CFRP} \cdot h_{CFRP}} = \frac{30000}{50 \cdot 1{,}2} = 500\ [N/mm^2] \quad (3)$$

where:

σ_{CFRP} – stresses in CFRP strip $[N/mm^2]$,
b_{CFRP} – width of CFRP strip [mm],
h_{CFRP} – thickness of CFRP strip [mm].

The tensile strength of CFRP strip ($f_{k,CFRP}$) taken from the technical specification is 2800 N/mm^2. Therefore, the equation (4) can be formulated.

$$\sigma_{CFRP} \ll f_{k,CFRP} \quad (4)$$

It can be concluded that the strength of the CFRP tape is not exceeded, since its utilization efficiency is low.

The surface area of the glueline exposed to shear stress can be described by equation (5).

$$A_{ADH} = b_{ADH} \cdot l_{ADH} = b_{CFRP} \cdot l_{CFRP} = 50 \cdot 120 = 6000\ [mm^2] \quad (5)$$

where:
A_{ADH} - surface area of the glueline [mm^2],
b_{ADH} - bond line width [mm],
l_{ADH} - adhesive bond length [mm],
l_{CFRP} - CFRP strip length [mm].

Then the shear strength of the glueline necessary to proper functioning of the connection was calculated and compared with available standards guidelines (6). In the German version of the standard DIN-EN-1995: 2010 characteristic value of the bond shear strength is reported. When the length of the glueline is not less than 250mm, a characteristic value of shear strength is 4 N/mm^2. It is known that the strength of the glueline should not be less than the strength of bonded materials. In case of wood the characteristic shear strength is 4 N/mm^2 (PN-EN 338:2013). Mentioned strength values have to be considered as an indicative values, due to the fact that a standard dedicated to timber reinforced locally is not developed yet.

$$f_{k,1,k} = \frac{F_t}{A_{ADH}} = \frac{30000}{6000} = 5{,}0\ [N/mm^2] \quad (6)$$

where:

$f_{k,1,k}$ – characteristic shear strength of the glueline [N/mm²].

When the reinforcement material is in the shape of circular segment and it is glued inside the cross section, which is weakened with a hole of 20mm in diameter (figure 4), the shear strength required to transfer the load is considerably reduced. Figure 5 shows the geometry of the CFRP strip used.

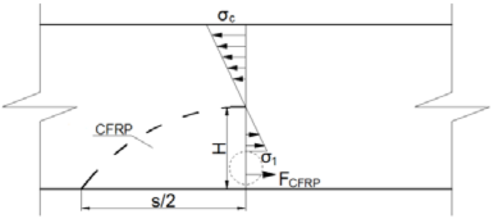

Figure 4. The scheme of the reinforcement

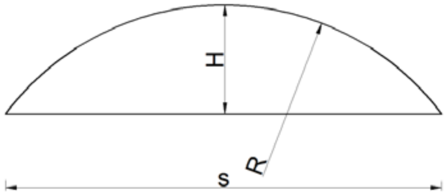

Figure 5. The geometry of reinforcement method

CFRP strip was shaped as a circular segment, its height H is 50 mm, the radius R and the thickness is 125 mm and 1.4 mm respectively. The length "s" of CFRP strip may be calculated using formula (7).

$$s = 2 \cdot \sqrt{2 \cdot R \cdot H - H^2} = 2 \cdot \sqrt{2 \cdot 125 \cdot 50 - 50^2} = 200\ [mm] \quad (7)$$

Stresses in CFRP stip can be calculated with the use of fomula (8).

$$\sigma_{CFRP} = \frac{F_t}{b_{CFRP} \cdot h_{CFRP}} = \frac{30000}{50 \cdot 1{,}4} = 428\ [N/mm^2] \ll 2800\ [N/mm^2] \quad (8)$$

The cross-sectional area of CFRP stip (A_{CFRP}) can be determined using formula (9).

$$A_{CFRP} \approx 2 \cdot \left(\frac{2}{3} \cdot s \cdot H + \frac{H^3}{2 \cdot s} \cdot 0{,}5\right) = 2 \cdot \left(\frac{2}{3} \cdot 200 \cdot 50 + \frac{50^3}{2 \cdot 200} \cdot 0{,}5\right) = 13636\ [mm^2] \quad (9)$$

The surface area of the glueline joining reinforcing material with reinforcement can be calculated using formula (10). Strength of a glueline, necessary to transfer loads is determined based on formula (11).

$$A_{ADH} = A - A_O = A - \pi \cdot r^2 = 13636 - \pi \cdot 10^2 = 13332\ [mm^2] \quad (10)$$

$$f_{k1,k} = \frac{F_t}{A_{ADH}} = \frac{30000}{13332} = 2{,}25\ [N/mm^2] \quad (11)$$

where:

A_O – the surface area of the opening [mm²],

r – radius of the opening [mm].

CONCLUSIONS

Because of the high strength of CFRP tape its utilization efficiency is very low. In order to improve the degree of utilization it is possible to apply the pre-compression, changing initial stress distribution.

The analytical model showed that reinforcement method in form of CFRP tape shaped into circular segment guarantees higher shear strength of the glueline in comparison to reinforcement bonded to the bottom side of bent beam. In this case shear strength of the glueline, necessary to provide a proper capacity of the joint, is lower than the value of a shear strength provided in DIN-EN-1995:2010 and PN-EN 338:2013 standard. This reflects the well-designed joint that will be able to transfer stresses being a result of an applied load.

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Streszczenie: *Kompozyty FRP we wzmacnianiu drewnianych konstrukcji*. W ciągu ostatnich kilku dziesięcioleci technika inżynieryjna rozwinęła się znacząco. Oferowany jest szeroki wybór alternatyw dla tradycyjnych materiałów i metod. Przykładowo, coraz częściej kompozyty FRP (Fibre Reinforced Polymer), powszechnie stosowane w konstrukcjach betonowych, stają się wykorzystywane w konstrukcjach drewnianych. Jednakże brak ustalonych zasad dotyczących projektowania konstrukcji wzmocnionych za pomocą kompozytów FRP powodują ograniczenie ich praktycznego zastosowania. Dlatego w ostatnich latach techniki obejmujące wykorzystanie FRP badano na wielu płaszczyznach, w tym kwestie połączenia pomiędzy materiałem wzmacnianym a wzmacniającym, procesu rozwarstwienia, procedur kontroli jakości technologii klejenia, co prowadzi do rozwoju zasad projektowania.

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