EFFICIENCY OF PULTRUDED COMPOSITES IN CONSTRUCTIONS: ANCHORAGE, ADHESION, AND DURABILITY

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Abstract
An anchor device for the tensile load transmission on the composite rods by using a metal wedge glued into the splitted end of the rod is proposed. Calculations of a 3D stress-strain state of the anchor with a pultruded CFRP/epoxy rod were carried out by the finite element method accounting for elastic and elastic-plastic behavior of pottant material (epoxy resin) in shear. Numerical results were obtained for the anchors with various non-splitted anchorage length of the composite rod. The preliminary experiments carried out with the suggested type of the anchor confirmed its working capacity to transfer the tensile load on the high-strength UD CFRP/epoxy rod made by pultrusion. Failure of these rods was observed at the gauge section.

Keywords: anchor, CFRP, pultruded composites, rod, stress, wedge

1. Anchor system with pultruded composite rod. Theoretical study.
Utilization of fiber reinforced polymer (FRP) composites as prestressing or strengthening materials in civil engineering applications requires the development of reliable and practically effective anchor systems. Many efforts have been directed toward the development of such systems with composite tendons, especially unidirectional CFRP, GFRP or AFRP rods made by pultrusion. A number of different gripping mechanisms for FRP rods have been developed and investigated: clamps, plug and cone, resin sleeve, potted resin, metal overlay, and split plastic and metal wedges, but no particular design has been widely accepted [2, 3]. Thus, the anchorage of composite tendons remains one of most perplexing and challenging problem in the developing of commercial tendon systems.

The effectiveness of an anchor is measured by its “efficiency ratio”, which is determined as the strength ratio between the tensile strength of composite rod and the ultimate stress developed by the anchor [4]. It is well-known that the load-carrying capacity of the anchor system is controlled by the interfacial stresses on the composite rod, especially at the entrance
of the anchor, where the high tensile load is the cause of high stress concentrations. Minimization of the stress concentration at the loading end of the composite rod was the aim of different investigations, e. g. [2, 3, 5].

The present investigation deals with the anchor system with CFRP pultruded rod, where tensile load applied is transferred by means of metal wedge glued into a splitted end of composite rod. The aim of this study is to determine the rational way of load transferring, enabling to increase the anchor effectiveness. The anchor system considered includes a steel sleeve (with internal and external radii of 14.0 and 17.5 mm, \( E = 210 \text{ GPa} \), \( \nu = 0.35 \)), UD CFRP pultruded rod (with diameter of 5.5 mm and elastic properties \( E = 10 \text{ GPa}, \ E_{zz} = 169 \text{ GPa}, \ E_{xx} = E_{yy} = 5 \text{ GPa}, \ E_{xy} = E_{yz} = 3 \text{ GPa}, \ \nu_{xx} = \nu_{yy} = 0.4, \ \nu_{zz} = 0.017 \)), aluminum wedge (\( E = 72 \text{ GPa}, \nu = 0.33 \), length of 110 mm, angle of 7°) and potted epoxy resin (\( E = 3 \text{ GPa}, \nu = 0.35 \)). Inserted wedge with of the vertex angle \( \geq 7^\circ \) ensures a self-locking effect.

The 3D geometrical models of the anchor required for the stress-strain calculations using the finite element method (FEM) were constructed with the software SolidWorks 2007 (Fig 1a) and then imported into the software ANSYS 12.1 for the subsequent FEM modeling (Fig 1b). A quarter part of the anchors were only modeled because of the structure symmetry.

![Fig. 1. 3D geometrical (a) and FEM (b) models of the anchor considered.](image)

The FEM models were created by using 3D solid elements: SOLID186 (20-node) and SOLID187 (10-node). Numerical evaluations showed that the FEM model containing of about 11500 hexahedral and tetrahedral finite elements gave the results of satisfactory accuracy.

Firstly, an influence of the inserted wedge location on the anchor stress-strain state was studied. For this purpose, the FEM calculations based on the models with the different non-splitted anchorage length of composite rod (\( L_{\text{non-split}} = 200, 100, 50, 15 \text{ and } 5 \text{ mm}, \) see Fig. 1a) were carried out. Tensile force was applied in such way that longitudinal stress \( \sigma_z \) in the
The gauge section of CFRP rod (i.e. beyond the anchorage length) was equaled 3000 MPa.

The distributions of normal stresses $\sigma_z$ (a) and $\sigma_x = \sigma_y$ (b) in the CFRP/epoxy rod at the interface between composite rod and epoxy resin, calculated with account the elastic behavior of all anchor materials, were presented in Fig. 2 for two values of $L_{\text{non-split}} = 200$ and 5 mm. It is seen that the distribution shapes obtained for different values of $L_{\text{non-split}}$ are very similar and have the peak stresses at the corner point of the loaded end of the anchors, which is typical situation for the bonded joints.

![Fig. 2. Distribution of the interfacial normal stresses $\sigma_z$ (a) and $\sigma_x = \sigma_y$ (b) in CFRP/epoxy rod with the non-splitted anchorage length of 200 (a) and 50 mm (b).](image)

Numerical values of $\sigma_z^{\text{max}}$ in CFRP/epoxy rod calculated at this point for the anchors with the different non-splitted anchorage length $L_{\text{non-split}}$ are presented in Table 1. These data indicate that value $\sigma_z^{\text{max}}$ does not practically change with the non-splitted length reduction until it becomes a small enough (e.g. $L_{\text{non-split}} \leq 5$ mm) and the stress concentration at the corner point increases significantly.

**Table 1. Values $\sigma_z^{\text{max}}$ in CFRP rod at the corner point at the loaded end of anchor.**

<table>
<thead>
<tr>
<th>Type of FEM solution</th>
<th>$L_{\text{non-split}}$, mm</th>
<th>$\sigma_z^{\text{max}}$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Elastic</td>
<td>3529.2</td>
<td>3529.0</td>
</tr>
<tr>
<td>Elastic-plastic</td>
<td>3141.3</td>
<td>3141.0</td>
</tr>
</tbody>
</table>

It is well-known that a corner point singularity may exert strong local influence on the stress and strain fields in a solid body with such points [6]. Therefore, the FEM calculations of the anchors considered were also carried out with account of a plastic behavior of epoxy resin in shear deformation.

The available experimental data describing a nonlinear shear stress-strain behavior of epoxy resins [7–9] indicate that such nonlinear behavior with a reasonable accuracy may be described with a bilinear kinematic hardening material model. In addition to the elastic properties (modulus of elasticity and Poisson's ratio) of epoxy resin, this material model requires two extra characteristics: yield stress $\sigma_y$ and tangent modulus $E_T$. Analysis of these
experimental data (see Fig. 3) allowed us to assign the numerical values as $\sigma_y = 20 \div 50$ MPa, $E_T = 0.1$ GPa.

![Fig. 3. In-plane shear stress-strain curves for the epoxy adhesive: 1 [7], 2 [8], 3 [9].](image)

Maximum stress $\sigma_{z}^{\text{max}}$ at the corner point on the loaded end of the anchor with non-splitting anchorage length of 50 mm depending on the applied stress $\sigma_z$ calculated with the elastic and elastic-plastic FEM solutions are presented in Fig. 4.

![Fig. 4. Dependence of $\sigma_{z}^{\text{max}}$ on the applied stress $\sigma_z$. Elastic (----) and elastic-plastic (-----) FEM solutions; yield stress equals 20 (■) and 50 MPa (▲).](image)

FEM calculations showed that stress concentration at the corner point significantly reduces with account of the nonlinear shear behavior of epoxy resin. FEM solution in the elastic statement gave stress concentration of about 17.6%, but in the elastic-plastic one – only 1.9% (at $\sigma_y = 20$ MPa) and 4.6% (at $\sigma_y = 50$ MPa). It should be mentioned that maximum values of all plastic strains were small enough (< 2.5%), except the plastic strain $\varepsilon_{zx}$, which value near the point of singularity was greater than 50%.

The FEM calculations in the elastic-plastic statement confirmed also the result obtained with elastic modeling. Namely, the change of the inserted metal wedge location does not practically stress-strain state of the anchor considered, expect the case, when the non-splitting anchorage length was small enough ($L_{\text{non-split}} < 5$ mm) and led to the increase of dangerous stress concentration. Thus, we must conclude that the variation of the inserted wedge location can not be applied as a means of stress-strain state control in the composite anchor of
considered type and should be studied another possibilities.

2. Preliminary experimental study.

Preliminary experimental study was carried out for verification of the efficiency the suggested type of anchor with a pultruded composite rod. A series of the tensile tests of the anchors made with the pultruded CFRP/epoxy rods with diameter of 5.5 mm were carried out at the MTS system. The special device for a splitting of a pultruded rod end was designed. After splitting operation, an aluminum wedge of 110 mm length was glued into the splitted rod (Fig. 5a).

![a](image1) ![b](image2)

**Fig. 5.** Sectional view a part of the anchor (a) and its view after the MTS test (b).

The tensile tests carried out confirmed the efficiency of such type anchor for pultruded rods made of high-strength unidirectional composites. CFRP/Epoxy pultruded rods failed in the gauge section at ultimate tensile stresss higher than 2000 MPa and ultimate tensile strain of about 1.2%.

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3. REFERENCES


