FE analysis and experimental validation of mechanical wedge–barrel anchors for CFRP rods

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\begin{abstract}
This paper presents a comparative study of the geometrical optimization of mechanical wedge–barrel anchors for prestressed carbon fiber-reinforced polymer (CFRP) rods. Various anchor configurations were simulated using three-dimensional finite-element (FE) models. The FE models were validated using the draw-ins of the wedges, which were measured in static tensile tests. The configurations consisted of a steel barrel and aluminum wedges, taking advantage of the previous anchors. The conical profile of the wedge and barrel in different configurations had either a curve or a constant differential angle. In addition, a series of geometric modifications were introduced to the wedge at the loading using a fillet or cut. The stress concentration at the loading end of the anchor and the modifications led to a reduction in the stress concentration. In addition, the anchor with a curved profile was selected as the optimal design because it had the smallest stress concentration owing to the smooth transition of the differential angle distribution along the wedge profile.
\end{abstract}

1. Introduction

Prestressing steel strands have been used in civil structures for a long time. As an alternative to prestressing steel, carbon fiber-reinforced polymer (CFRP) materials have been introduced and applied in prestressed structures because of their superior properties, including a higher strength-to-weight ratio, corrosion resistance, and fatigue resistance [1]. Substituting CFRP materials for steel in new structures or for strengthening existing structures has great potential in the prestressing industry considering the wide range of applications to different types of civil structures, e.g., concrete [2–6] and metallic [7–12] members and hangers for cable-stayed and suspension bridges [13,14]. However, one of the main challenges for the widespread use of CFRPs in prestressed structures is the development of safe anchors.

Mechanical wedge–barrel anchorage systems for prestressing steel strands have traditionally been used in various applications. However, the anisotropy, brittleness, and weak mechanical properties of prestressed CFRP materials in the transverse direction make the development of anchorage systems more difficult [15]. Different anchorage systems for prestressed CFRP plates [16–19] and rods [2,6,20–28] have been proposed by different researchers, and the static and fatigue performances of the anchors have been investigated experimentally.

Wedge-type anchorage systems have been introduced and developed for CFRP rods. In wedge-type anchors, the contact pressure on the CFRP rod and tensile force are simultaneously high at the loading end. This can lead to a stress concentration in this area and, thus, premature rupture. Consequently, the high tensile capacity of the CFRP rods cannot be achieved. Therefore, the main challenge for the development of wedge-type anchors for prestressed CFRP rods is minimizing the stress concentration on the CFRP rod at the loading end to prevent premature rupture.

Wedge-type anchors have been developed in two forms: (i) bonded anchors, which use adhesive around the rod, and (ii) mechanical anchors, which hold the rods purely through friction. Various types of mechanical systems have been introduced. A review of the existing bonded and unbonded anchorage systems was presented in [15].

This study focused on anchors based on gradient systems, as explained below.

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A gradient system was introduced for bonded wedge-type anchors to prevent the premature rupture of the rod [23,24]. In this anchor, a wedge was fabricated using epoxy. Particles were added to the epoxy to gradually increase the stiffness of the wedge at the loading end toward the free end of the anchor. Therefore, a gradient stiffness distribution along the wedge was achieved. In this manner, the contact pressure on the CFRP rod was minimized at the loading end, and a tensile capacity of 92% of the nominal strength of the CFRP rod was achieved. However, the on-site application of bonded anchors is complicated because they must be carefully prepared in the shop, which can make the installation procedure more difficult.

Mechanical wedge–barrel anchors have been proposed to address the above-mentioned limitations of bonded anchors. These anchors hold the CFRP rods through friction. The mechanism of these mechanical wedge–barrel anchors, including different stages of loading, is illustrated in Fig. 1. In the initial state, the CFRP rod and wedges are placed in the barrel. The next stage is presetting, in which the wedges are pushed into the barrel as a result of the compressive force of $P$ on the surface of the wedges. The presetting is performed before pulling the rod. Thus, the contact pressure around the CFRP rod increases, which prevents the slippage of the rod when the rod is pulled. As a result of the presetting, the wedges are inserted into the barrel at a distance of $\Delta w_{\text{preset}}$. The last stage is pulling, in which a tensile force of $T$ is applied to the CFRP rod.

The insertion of the wedge and rod into the barrel, shown by $\Delta w$ and $\Delta r$ in Fig. 1, respectively, is called the “draw-in.” The draw-ins measured with respect to the initial state. The ideal behavior of the anchor is that the draw-ins for the wedges and rod to be the same, i.e., $\Delta w = \Delta r$, which means that no slippage occurs between the wedges and rod. However, in practice, slippage between the wedges and rod may occur, i.e., $\Delta w \neq \Delta r$. In addition, in anchors with split wedges, different wedges might not have identical draw-ins.

Designing mechanical wedge–barrel anchors, which work purely through friction, is difficult because, on the one hand, the draw-in of the wedges must be large enough to prevent the slippage of the rod, while on the other hand, large draw-ins could result in a high contact pressure on the rod, which would lead to a stress concentration at the loading end and, consequently, a premature rupture in the rod.

Two methods have been introduced to prevent a stress concentration in mechanical wedge–barrel anchors. In the first method, a con-

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**Nomenclature**

| Symbol | Description |
|--------|-------------|
| $E_1$ | Longitudinal elasticity modulus |
| $E_{2,3}$ | Transverse elasticity modulus |
| $F_s$ | Tsai–Wu failure index |
| $F_{i}, F_{ij}$ | Coefficients of Tsai–Wu failure criterion |
| $f_{ud}$ | Ultimate tensile strength of the CFRP rod |
| $G$ | Shear modulus |
| $P$ | Presetting force |
| $T$ | Tensile force of the CFRP rod |
| $U$ | Displacement |
| $\alpha$ | Angle of the wedge cone with the vertical axis |
| $\beta$ | Angle of the barrel cone with the vertical axis |
| $\Delta r$ | Draw-in of the CFRP rod |
| $\Delta w$ | Draw-in of the wedge |
| $\Delta w_{\text{preset}}$ | Draw-in of the wedge after presetting |
| $\theta$ | Differential angle |
| $\nu_{12}$ | Major Poisson's ratio |

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**Fig. 1.** Loading stages for mechanical wedge–barrel anchors.
stent differential angle of $\theta$ is adopted between the wedge and barrel along the conical profile, as shown in Fig. 2(a). In this figure, $\alpha > \beta$. In the second method, shown in Fig. 2(b), the wedge and barrel have a conical curved profile. The curved profile creates a distributed differential angle along the cone, which increases toward the free end of the anchor. In both systems, the goal is to achieve a proper contact pressure distribution on the CFRP rod, i.e., the contact pressure is minimized at the loading end and increases toward the free end of the anchor. Both methods lead to a gradient distribution of the contact pressure on the CFRP rod.

For anchors with a constant differential angle, different values of $\theta$ have been introduced, ranging from 0.1° to 0.4°. To avoid damage to the rod in these anchors, either a soft sleeve (made of aluminum or copper) was used between the wedge and barrel [25,26] or the wedge itself was made of a soft material such as aluminum [27,28] or glass fibers (PPS-GF40) [6], without any sleeve. Anchors with curved profiles have been developed to further reduce the stress concentration at the loading end. Fig. 2(b) shows the dimensions used for the wedge–barrel anchor in a previous study [2] except for the length of the wedge, which was 80 mm rather than 70 mm. In this anchor, the conical profile of the wedge and barrel is a part of circle with a radius of $R = 1650$ mm.

Numerical simulations using the finite-element (FE) method have been performed for mechanical wedge–barrel anchors using two-dimensional (2D) [20,26,29,30] and three-dimensional (3D) [6,28,31,32] models. The contact pressure distributions on the CFRP rods were obtained using these FE models. One of the challenges in the numerical simulations of wedge–barrel anchors is the validation of the models with experimental results. In one study [28], the FE model was validated by comparing the FE results with the optically measured strains at the surface of the barrel using ARAMIS 3D [28] or by comparing the load–displacement or draw-ins of the components [6].

However, none of these studies performed a comparative investigation of anchors with different configurations, i.e., curved or constant differential angle profiles, to highlight the effect of the geometry on the stress concentration at the anchor loading end. In addition, none of these studies used a criterion to evaluate the stress concentration.

1.1. Innovations of this study

A comparative study was performed on various configurations of mechanical wedge–barrel anchors with curved and constant differential angles to identify the optimal configuration with the smallest stress concentration at the loading end. In addition, geometrical modifications to the anchors were introduced, and the effects of these modifications on the stress concentrations were investigated.

The anchor configurations considered in this study take the advantages of the anchors previously proposed anchors in [2,27]. In the anchor proposed in [2], the wedge and barrel had a curved profile, as shown in Fig. 2(b). However, in this anchor, a soft sleeve was required between the wedge and barrel to prevent damage to the CFRP rod. The anchor proposed in another report [15] had a constant differential angle and eliminated the need for a sleeve because the wedges were made of aluminum. However, to prevent slippage of the rod inside the anchor, the anchor was longer than that in Fig. 2(b). In the configurations considered for the anchors in this study, aluminum wedges were used, without any sleeve around the rod, using the dimensions shown in Fig. 2(b). The use of aluminum also reduced the required presetting force because it has a relatively low elastic modulus. In addition, it improved the contact pressure distribution on the CFRP rod through plasticization inside the barrel [33].

For the numerical analyses, 3D FE simulations were performed using the ABAQUS software. In the FE models, the plastic deformations of the aluminum wedges and the orthotropic properties of the unidirectional CFRP rods were considered. The FE models were validated using the experimental results from the draw-ins of the wedges after presetting and during the pulling of the rod.

To identify the anchor configuration with the smallest stress concentration, a criterion is required. Various failure criteria have been proposed for composite materials. The maximum tensile stress criterion predicts failure once each of the three principal stresses exceeds the material strength. However, this criterion overestimates the composite strength under multiaxial stresses [34]. The Tsai–Hill failure criterion is used for anisotropic materials and is an extension of the von Mises criterion, which is used for predicting the yielding of isotropic materials under multiaxial stresses. The limitation of the former criterion is that it is only applicable to composite materials with equal tensile and compressive strengths [35]. The Tsai–Wu failure criterion considers the influence of different tensile and compressive strengths [36]. This criterion is widely used in the design and failure analysis of composite materials because of its simplicity and high prediction accuracy under a multiaxial stress state [34]. In this study, the CFRP rods had different tensile and compressive strengths and were subjected to multiaxial loading inside the anchors. Therefore, the Tsai–Wu failure criterion was employed to determine the optimal anchor configuration.

1.2. Outline of study

The current paper is outlined as follows. First, the developed FE model is explained, including the details of the parts, material prop-

![Fig. 2. Two possible designs for wedge–barrel anchors.](image-url)
erties, boundary conditions, and contact behavior. Second, the validation of the FE model using the experimental results from the draw-ins of the wedges is discussed. Third, different configurations of anchors for the CFRP rods are introduced. Fourth, the contact pressure distributions on the CFRP rod for different anchor configurations are analyzed and interpreted using the FE models. Finally, the anchor with the optimal design is selected using the Tsai–Wu failure criterion.

2. FE simulations

2.1. Parts of FE model

The FE model developed for the wedge–barrel anchors using the ABAQUS software (version R2019x) is illustrated in Fig. 3(a). The parts in the model are the wedge, barrel, and CFRP rod. Because of its geometric symmetry, only one third of the anchor was modeled—that is, a 120° revolution was applied, as shown in Fig. 3(a).

Information about the element type and mesh for each part is presented in Table 1. The wedge and barrel were modeled as isotropic materials, and the CFRP rod was modeled as orthotropic. An investigation of the element type showed that the use of linear elements resulted in an inaccurate stress distribution in the parts, especially in the areas where bending deformations were dominant, e.g., at the loading end of the anchor, where local bending occurred. Therefore, the parts were discretized into quadratic reduced-integration elements, which have a larger number of integration points compared with linear elements and are appropriate for bending-dominated areas. A structured mesh was used for all the parts. A uniform mesh was obtained for the barrel using the sweeping technique. The mesh size for all the parts was 1.8 mm.

2.2. Material properties

The material properties for the different parts of the FE model are listed in Table 2. The material properties were either obtained from tests or provided by the manufacturer. Otherwise, values proposed in the literature were used.

The CFRP rods used in the simulations, and later in the experiments, had a nominal diameter of 8 mm and were manufactured by the S&P Clever Reinforcement Company AG, Switzerland. To avoid large plasticization, a high-strength steel, HSX 130, was used for the barrel, and the barrel was modeled as a linear elastic material. For the wedge, aluminum EN AW 6026 was used, with the true stress–strain curve shown in Fig. 4, which was obtained in static coupon tests based on DIN EN ISO 6892-1:2017 [37] using a 250-kN testing machine at Empa, Switzerland. In the FE model, the plasticity of the aluminum wedge was considered using a bilinear true stress–strain curve that was calibrated to the test results, as shown in the figure.

2.3. Boundary conditions and analysis steps

The boundary conditions of the FE model are shown in Fig. 3(b). Surfaces A and B, with the normal directions of \( n_A \) and \( n_B \), respectively, are shown in the figure. The displacements in normal directions \( U_{nA} = 0 \) and \( U_{nB} = 0 \). To define these constraints in ABAQUS, cylindrical coordinate systems were defined for surfaces A and B. In these cylindrical coordinate systems, the theta direction was parallel to the normal vectors of the surfaces, and the displacement in the theta direction was zero. In addition, the vertical displacement of the bottom surface of the barrel, shown by surface C, was fixed at zero, i.e., \( U_y = 0 \).

The FE analysis was performed in three steps—installation, presetting, and loading—as presented in Table 3. In the installation step, setting up an initial contact was necessary to avoid the convergence
Table 1
Element types and meshes of parts in FE model.

| Part      | Parameter          | Element type               | Mesh type  | Mesh size (mm) |
|-----------|--------------------|-----------------------------|------------|----------------|
| Rod       | Isotropic          | 3D quadratic reduced-integration | Structured | 1.8            |
| Wedge     | Isotropic          | 3D quadratic reduced-integration | Structured | 1.8            |
| Barrel    | Isotropic          | 3D quadratic reduced-integration | Sweep      | 1.8            |

Table 2
Material properties.

| Part      | Rod | Barrel | Wedge |
|-----------|-----|--------|-------|
| Material  | CFRP | Steel HSX | Aluminum EN AW-6026 |
| Ultimate tensile strength $f_{u}$ (MPa) | 2370$^a$ | 1250–1400$^b$ | 442$^c$ |
| Longitudinal elasticity modulus $E_1$ (GPa) | 160$^{1,3}$ | 200$^3$ | 71.7$^a$ |
| Transverse elasticity modulus $E_3$ (GPa) | 7.4$^a$ | 200$^3$ | 71.7$^a$ |
| Shear modulus $G_{13}, G_{12}$ (GPa) | $^7$ | – | – |
| Major Poisson ratio $v_{12}, v_{31}$ | 0.26$^i$ | 0.3$^i$ | 0.35 |
| Minor Poisson ratio $v_{23}, v_{32}$ | 0.02$^i$ | 0.3$^i$ | 0.35 |

$^a$ Based on the tensile coupon tests.
$^b$ Provided by the manufacturer (S&P Clever Reinforcement Company AG, Switzerland).
$^c$ Proposed in [32].

Fig. 4. Bilinear true stress–strain curve for aluminum EN AW-6026 used for wedges.

Fig. 3. In the static tests, wedge–barrel anchor was developed at Empa, Switzerland [39], as shown in Fig. 5. The anchorage consisted of a steel barrel in contact with three split aluminum wedges holding the CFRP rod. The anchorage has a curved conical profile, with the dimensions shown in Fig. 2(b).

3. Validation of FE model

A mechanical wedge–barrel anchor was developed at Empa, Switzerland [39], as shown in Fig. 5. The anchorage consisted of a steel barrel in contact with three split aluminum wedges holding the CFRP rod. The anchorage has a curved conical profile, with the dimensions shown in Fig. 2(b).

The experimental setup used for the uniaxial static tests is shown in Fig. 5. In the static tests, wedge–barrel anchors were subjected to different presetting forces of $P = 30, 50,$ and $70$ kN, and were loaded up to failure. The draw-ins of the wedges, $\Delta w$, after presetting and under the application of different tensile forces to the CFRP rod were measured. The results of these measurements were used to validate the FE model.

To validate the FE model developed based on the dimensions shown in Fig. 2(b), first, the model was calibrated. For this purpose, under a presetting force of $P = 50$ kN, the friction coefficient at the wedge–barrel interface, $\mu_{w_b}$, in the FE model was changed to fit the measurements of $\Delta w$ in the static tests. Second, the calibrated model was verified by comparing the values of $\Delta w$ obtained in the FE models and experiments under different presetting forces of $P = 30$ and $70$ kN.

3.1. Measurement of draw-ins in experiment

The draw-ins of the wedges, $\Delta w$, were measured using a Mitutoyo digital dial gauge with a reading precision of 0.001 mm and a ring located on the top surface of the barrel, as shown in Fig. 6. The initial state in the figure corresponds to the state when the wedges were placed in the barrel and the wedge surface was 22.2 mm from the barrel surface.

The loading protocol of the static tests (according to [40]) is shown in Fig. 7, in which the load increased gradually. At tensile load levels of 20.6, 41.2, 61.7, and 72 kN, the draw-ins of the wedges and CFRP rod were measured after 5 min. These load levels corresponded to 0.2, 0.4, and 0.6 of the CFRP rod nominal tensile strength ($T_{\text{nom}} = 102.9$ kN).
kN). In addition, at a load level of 72 kN, the stabilization of the draw-ins was checked after 30 min. To verify the FE model, only the draw-ins after 5 min were used because the increase in the draw-ins after 30 min at a load of 72 kN was attributed to creep deformations, which were not considered in the simulations.

3.2. Calibration of FE model

In the FE model, the mesh size and friction coefficients at the wedge–barrel interface, $\mu_{wb}$, were adjusted to fit the experimental results obtained from a presetting force of $P = 50$ kN. In the first step, an initial value of 0.3 was considered for $\mu_{wb}$ and the mesh size was changed to obtain the optimal mesh size for each part. As given in Table 1, a mesh size of 1.8 mm for all parts was selected in the FE model because mesh sizes finer than 1.8 mm did not change the stress values in the model.

Once the appropriate mesh size was determined, the mesh size was kept constant in the model, and $\mu_{wb}$ was changed until the $\Delta w$ values approached the experimental results. Finally, a value of $\mu_{wb} = 0.19$
was chosen for the friction coefficients at the wedge–barrel interface. In a previous study [28], the optimal friction coefficient at the wedge–barrel interface was found to be 0.15, which was relatively close to the value considered in this study. The draw-ins of the wedge, $\Delta w$, with respect to the tensile force in the CFRP rod, $T$, are shown in Fig. 8. In this figure, the $\Delta w$ value at $T = 0$ corresponds to the draw-in after the presetting force, i.e., $\Delta w_{\text{preset}}$.

In the experiments, the specimens were subjected to a tensile load up to failure. However, the draw-ins were not measured for tensile loads greater than 72 kN. Therefore, only the draw-ins up to a tensile load of 72 kN are compared in Fig. 8.

3.3. Verification of FE model

The FE model was verified using the $\Delta w$ values measured in the static tensile tests under presetting forces of $P = 30$ and 70 kN, as shown in Fig. 9. The figure shows that the draw-ins obtained in the FE model and experiments were similar. Therefore, the FE model was validated.

4. Various configurations for anchors

After validating the FE model, a comparative study was performed on various configurations for the wedge–barrel anchors, with either curved or constant differential angle conical profiles. The dimensions used for the wedge and barrel were similar to those used by anchor A in a previous study [2], as shown in Fig. 2(b). The different anchor configurations are presented in Table 4. In this table, $A$, $c_d$, and $f_r$ represent the anchor, constant differential angle, and friction radius, respectively, e.g., $A-c_d-0.23\degree$ is an anchor with a constant differential angle of $0.23\degree$.

As shown in the table, the configurations were divided into four types. The first type, $A$-curved, is an anchor with a curved conical profile for the wedge and barrel, as shown in Fig. 2(b). For anchor type 2, $A-c_d$ three different differential angles were considered: $0.1\degree$, $0.16\degree$, and $0.23\degree$ (see Fig. 2(a)). The differential angles considered were in the range of those introduced in previous studies [6,26,30].

In addition, two modified configurations were considered as anchor types 3 and 4. In these anchors, the wedges and barrels had a constant differential angle of $\theta = 0.1\degree$. The intention of these modifications was to remove a volume of material from the wedge at the loading end to reduce the stress concentration in this area, which is explained in section 5.

The type 3 anchors are shown in Fig. 10. Different radii of 0.5, 2.0, and 4.0 mm were applied to the fillet at the loading end to investigate the effect of the fillet radius on the contact pressure distribution on the CFRP rod. These anchors are $A$-fr-0.5, $A$-fr-2, and $A$-fr-4 in Table 4.

In the other type of modified anchor, i.e., type 4, the geometry of the wedge at the loading end was changed by cutting a volume of material, as shown in Fig. 11. For anchors $A$-cut-3’ and $A$-cut-40’, as listed in Table 4, the lengths of the inclined cut lines were 20 and 6 mm and the angles of the inclined cut lines were 3’ and 40’, respectively.

5. Results of FE analyses

5.1. Contact pressures on CFRP rods for anchor types 1 and 2

The contact pressure on the CFRP rod for the anchor with a curved profile (type 1) was compared with that of the anchors with different constant differential angles (type 2). For these anchors, the contact pressure on the CFRP rod on the path shown in Fig. 3(a) was obtained using the FE models. Fig. 12 shows the results under a presetting force of $P = 50$ kN. As shown in Fig. 12(a), at a tensile load of $T = 72$ kN, the contact pressure gradually increased from the loading end and reached a maximum at the free end.

As a result of the greater tensile force of $T = 120$ kN on the CFRP rod, as shown in Fig. 12(b), the contact pressure on the rod increased because of the larger draw-ins of the wedges. However, at the loading end, a peak appeared in the contact pressure for anchors $A$-cd-0.1’ and $A$-cd-0.16’, while for anchors $A$-cd-0.23’ and $A$-curved, no stress peak was observed.

The effect of the mesh size on the peak value of the contact pressure on the CFRP rod for anchor $A$-cd-0.1’ is presented in Appendix A. The peak values were sensitive to the mesh size, i.e., the smaller the mesh size, the greater the peak.

5.2. Contact pressures on CFRP rods for modified anchors

The simulations discussed in section 4.1 showed that anchor $A$-cd-0.1’ had the highest peak for the contact pressure at the loading end. To minimize the peak value, geometric modifications were introduced to the anchor. The change in the geometry was performed in two ways: (i) adding a fillet at the loading end of the wedge and (ii) cutting a volume of material from the wedge at the loading end area. In both these modifications, a volume of wedge material was removed at the loading end area to reduce the contact pressure between the wedge and barrel and, consequently, the contact pressure on the CFRP rod.

The contact pressure distributions on the CFRP rod for anchor $A$-cd-0.1’ and the modified anchors are compared in Fig. 13 under a presetting force of $P = 50$ kN and a tensile force of $T = 120$ kN. The anchors with smaller fillet radii, i.e., $A$-fr-0.5 and $A$-fr-2, had peaks in the contact pressure, although the peak stress was smaller than that of anchor $A$-cd-0.1’. A larger fillet radius of 4 mm in anchor $A$-fr-4 eliminated the peak stress.

6. Selection of optimal anchor

6.1. Stress state on CFRP rod

Stresses in different directions were applied to the surface of the CFRP rod, as shown in Fig. 14. The stress components $\sigma_1$, $\sigma_2$, $\sigma_3$, and $\tau_{12}$ were the stresses applied to an element of the CFRP rod on Path A. In the coordinate system shown in the figure, direction 1 is the fiber direction, and directions 1 and 2 are perpendicular to the fibers. According to the FE model, the applied stresses on the element are defined as follows: $\sigma_1$ is the tensile stress caused by the application of the tensile load on the CFRP rod, $\sigma_2$ is the contact pressure, $\sigma_3$ is the compressive circumferential stress, and $\tau_{12}$ is the shear stress applied on the element resulting from friction between the rod and wedge. The other components of the shear stress were negligible. To obtain these stress components in ABAQUS, the stresses of the nodes on Path A were picked up using a cylindrical coordinate system.
Different types of anchors used in parametric study.

| Anchor type       | Anchor name | Description of the anchor |
|-------------------|-------------|---------------------------|
| (1) Curved profile| A-curved    | A curved profile for the wedge |
| (2) Constant differential angle| A-cd-0.1\° | A constant differential angle of 0.1\° |
|                   | A-cd-0.16\° | A constant differential angle of 0.16\° |
| (3) Anchors modified using fillet | A-fr-0.5 | A fillet with a 0.5-mm radius on the wedge at the loading end |
|                   | A-fr-2     | A fillet with a 2-mm radius on the wedge at the loading end |
|                   | A-fr-4     | A fillet with a 4-mm radius on the wedge at the loading end |
| (4) Anchors modified using cut | A-cut-3\° | A cut with a 3\° angle on the wedge at the loading end |
|                   | A-cut-40\° | A cut with a 40\° angle on the wedge at the loading end |

The Tsai–Wu failure criterion [36] was used to select the optimal composite material when failure index $F_s$ reaches unity (i.e., $F_s = 1$) [36,43]. In this study, failure index $F_s$ was used to select the optimal design configuration considering the fact that a greater $F_s$ value corresponded to a more critical stress condition.

6.3. $F_s$ values for different anchor configurations

The $F_s$ values for all the nodes on Path A were calculated for different anchor configurations, and the anchor with the smallest value of $F_s$ (at the loading end) was considered to be the optimal design. The results are presented in Fig. 15. For all the anchors, a peak occurred at the loading end. The greatest $F_s$ value was for anchor A-cd-0.1\°, with $F_s = 2.25$. With the modifications on this anchor, the $F_s$ values were reduced to 1.62 and 1.37 in anchors A-fr-4 and A-cut-40\°, respectively. The lowest $F_s$ value was obtained for the A-curved anchor with $F_s = 1.22$. Therefore, this anchor was selected as the optimal design.

For all the anchors, the failure index exceeded unity at the loading end (i.e., $F_s > 1$), as shown in Fig. 15, as under $T = 120$ kN, the failure was predicted in the CFRP rod. In this study, however, for the sake of comparison and choosing the optimal anchor, only the relative $F_s$ values were considered.
indices for various anchor configurations were of interest, rather than the absolute values of $F$s.

6.4. Slippage between wedge and CFRP rod

The slippage between the wedge and CFRP rod was not considered when selecting the optimal anchor because no large slippage was observed in any of the anchors, even at an ultimate load of $T = 120$ kN. Appendix B presents the slippage values of the rod inside the wedge for different anchors under various presetting and tensile forces, showing that the slippage was always smaller than 0.08 mm.

7. Discussion

In this section, the effects of the constant differential angles, geometric modifications, and curved conical profile on the contact pressure distribution on the CFRP rods (see Figs. 12 and 13) and, consequently, on the resulting stress concentration at the anchor loading end are discussed.

7.1. Effect of constant differential angle

To understand the reason for the peaks in the contact pressures on the CFRP rods, the contact pressure distributions on the inner and outer surfaces of the wedges for anchors A-cd-0.1° and A-cd-0.23° are depicted in Fig. 16. For anchor A-cd-0.1°, shown in Fig. 16(a), the contact pressure on the inner surface of the wedge at the loading had a peak. For anchor A-cd-0.23°, however, the contact pressure was zero, as shown in Fig. 16(b). This was attributed to the fact that for the anchor A-cd-0.23°, the wedge at the loading end tended to separate from the inner surface of the barrel due to its greater constant differential angle (see the illustration in Fig. 2(a)). Thus, at the loading end, the contact pressure on the outer surface of the wedge was smaller for an anchor with a greater differential angle (i.e., anchor A-cd-0.23°), as shown in Fig. 16, which,

![Fig. 11. Type 4 anchors, with cut on wedge at loading end.](image)

![Fig. 12. Contact pressure on CFRP rod for the type 1 and 2 anchors under a presetting force of $P = 50$ kN.](image)

![Fig. 13. Contact pressures on CFRP rods for modified anchors under $P = 50$ kN and $T = 120$ kN.](image)
consequently, resulted in a smaller contact pressure on the CFRP rod. Therefore, it is concluded that a greater differential angle would lead to the reduction or elimination of the peak in the contact pressure on the CFRP rod.

It is noted that although the increase in the constant differential angle results in a reduction of the peaks of contact pressure at the anchor loading end, it leads to the reduction of contact area between the wedge and barrel. This can be observed in Fig. 12 (a), in which the contact pressure is distributed in a shorter length for the anchor with the greatest constant differential angle, i.e., A-cd-0.23°. This effect is more pronounced under smaller tensile forces, under which the wedges are not well inserted into the barrel (compare the contact pressure distribution of anchor A-cd-0.23° under T = 72 and 120 kN in Fig. 12). This can lead to the slippage of the rod inside the wedges due to an insufficient frictional resistance under service (smaller) tensile loads, which is not the case for the anchors considered in this study.

### 7.2. Effect of geometric modifications

For the anchors with a cut, i.e., anchors A-cut-3° and A-cut-40°, no peaks in the contact pressure at the loading end area were observed, as shown in Fig. 13. Fig. 17 shows the contact pressures on the wedges of the modified anchors with cuts. The introduction of the cuts resulted in the elimination of the stress peaks on the inner surfaces of the...
wedges due to the removal of a volume of material at the loading end. The contact pressure gradually increased within the cut area. For the anchors, which were geometrically modified using fillet, the increase in the fillet radius resulted in a reduction in the contact pressure on the CFRP rod, as shown in Fig. 13. The reason is that by a greater fillet radius, a bigger volume of the material was removed from the loading end area of the wedge, which resulted in smaller contact pressure on the outer surface of the wedges and, consequently, on the CFRP rod. As shown in Fig. 13, for both types of modified anchors, i.e., using cut or fillet, a rapid increase occurred in the contact pressure in a small length at the loading end, leading to a higher stress concentration at this area.

7.3. Effect of curved profile

For the anchor with a curved profile, i.e., A-curved, the differential angle varied along the anchor, resulting in a distribution of differential angle. The effect of the curved profile on the distribution of the differential angle at the loading end is schematically illustrated in Fig. 18(a). In the initial state, the differential angle is zero because the curvatures of the profiles for the wedge and barrel are the same, as shown in Fig. 2(b). When the wedge moves into the barrel, the wedge tends to separate from the barrel at the loading end, which reduces the contact pressure on the CFRP rod. The differential angle between the wedge and barrel continuously increases toward the free end of the anchor.

Fig. 16. Contact pressure on modified wedges with cuts under presetting forces of $P = 50$ kN and $T = 120$ kN.

Fig. 18(b) depicts the contact pressure on the wedge under $P = 50$ kN and $T = 120$ kN, revealing a small contact pressure at the loading end and a gradual increase toward the free end (see also Fig. 12(b)).

The smallest $F_s$ value obtained for the A-curved anchor was attributed to the smooth transition of the differential angle owing to the existence of the curved profile, that is, the combination of the contact pressure with the tensile, hoop, and shear stresses (see Fig. 14) on the CFRP rod resulted in the smallest $F_s$ value for this anchor.

8. Summary and conclusions

In this study, 3D FE simulations were performed for various configurations of mechanical wedge–barrel anchors to achieve an optimal design with the smallest stress concentration at the loading end. The FE models were validated by comparing the draw-ins of the wedges with experimental results. The configurations considered were anchors with curved and constant differential angle profiles. In addition, geometrical modifications were applied to the anchors with a constant differential angle. The CFRP rod had a diameter of 8 mm, but the same approach could be implemented for different rod diameters. The main findings of this study are summarized as follows.

- The FE model was calibrated using the measured draw-ins of the wedges, $\Delta w$, from static tests. For this purpose, under a presetting force of $P = 50$ kN, the friction coefficient at the wedge–barrel

Fig. 17. Contact pressure on modified wedges with cuts under presetting forces of $P = 50$ kN and $T = 120$ kN.
The interface was changed to fit the measured values for $\Delta w$. Then, the draw-ins corresponding to $P = 30$ and $70$ kN were used to verify the FE model.

- For the anchors with a constant differential angle, the increase in the value of the differential angle from $0.1^\circ$ to $0.23^\circ$ reduced the peak in the contact pressure on the wedge and, consequently, on the rod at the loading end.

- To reduce the peak in the contact pressure on the wedge in the anchor with a constant differential angle of $0.1^\circ$, i.e., A-cd-$0.1^\circ$, geometric modifications were introduced by removing a volume of material from the wedges at the loading end using a cut or fillet.

- The geometric modifications resulted in a reduction in the peaks for the contact pressure on the rod at the loading end, especially for anchors with a fillet radius of $4$ mm, i.e., A-fr-$4$, and a cut angle of $40^\circ$, i.e., A-cut-$40^\circ$.

- The Tsai–Wu failure criterion was used to identify the anchor with the smallest stress concentration on the CFRP rod. Therefore, the anchor with the smallest $F_s$ values for the nodes on the CFRP rod surface at the loading end was selected as the optimal design. The greatest $F_s$ value was obtained for anchor A-cd-$0.1^\circ$, with $F_s = 2.25$. Modifications could reduce the $F_s$ values to 1.62 and 1.37 for anchors A-fr-$4$ and A-cut-$40^\circ$, respectively.

- The smallest $F_s$ value was achieved for the A-curved anchor with $F_s = 1.22$. Therefore, this anchor was chosen as the optimal design. This was attributed to the smooth transition and gradual increase in the differential angle from the loading end toward the free end.

9. Data availability

Some or all data and FE models that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Hossein Heydarinouri: Conceptualization, Methodology, Software, Supervision, Writing - original draft. Aleksandar Vidovic: Software, Writing - original draft. Alain Nussbaumer: Supervision. Elyas Ghafoori: Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Mesh sensitivity analysis

To investigate the effect of the mesh size on the peak value of the contact pressure on the CFRP rod, the mesh size of the wedge and rod for anchor A-cd-$0.1^\circ$ was changed locally at the loading end, as shown in Fig. A1. Mesh sizes of $0.1$, $0.07$, and $0.06$ mm were considered. As shown, the peak value of the contact pressure increased with smaller mesh sizes, indicating the sensitivity of the results to the mesh size.

Appendix B. Slippage between wedge and CFRP rod

The values of the slippage between the wedge and CFRP rod under different presetting forces are shown in Fig. B1. In the FE model, the slippage was determined by deducting the displacement of a node on the surface of the rod at the free end from that of a node on the wedge surface. As shown in the figure, the slippage generally...
decreased when the presetting force increased. This was attributed to the higher contact pressure around the rod when the presetting force was greater. In addition, the slippage values for the A-curved and A-ccd-0.23° anchors was greater than those for the other anchors. However, for all the anchors, the slippage was negligible, i.e., in the order of hundredths of millimeters.

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Fig. B1. Slippage between wedge and rod for different anchors under $T = 120$ kN.
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