Parametric study on the effect of anchor's geometry on the stress distribution and crack initiation direction in a concrete body

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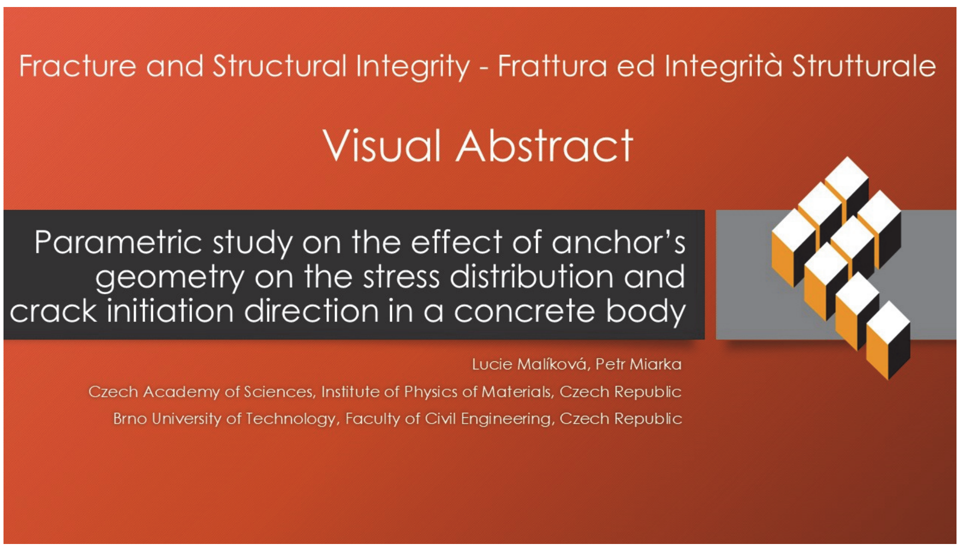

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INTRODUCTION

Steel anchors are an essential design component for fastening structural items to (reinforced) concrete or masonry. Anchors are used to attach steel elements to supporting concrete members. They are often overlooked and assumed to be a secondary design element. Nevertheless, they transfer external loading to the concrete structure and they are therefore very important and need to be designed correctly. There exist two basic kinds of anchors: post-installed and cast-in. Cast-in anchors are bolts that are installed in the concrete before it has set and dried. Post-installed anchor bolts are installed after the concrete is set in place and completely dried. Anchor-concrete fastening systems fail mostly through concrete-related failures. According to the type of loading (tension/shear) which is applied to the system, several kinds of failure can be distinguished: pull-out failure, steel failure, side-face blowout, concrete cone breakout and concrete splitting for anchors subjected to tensile loading or concrete pry-out failure, concrete edge failure and steel failure for anchors subjected to shear loading. The transferring from one to another failure mode is governed by several variables, such as embedment length, side cover, bearing area of the head, thickness of the concrete structural member etc.

Concrete cone failure, which is the topic of this paper, is characterized by a cone-shaped fracture in concrete in the vicinity of the anchor. This fracture is assessed as a brittle failure which is connected to a sharp drop of the load-displacement curve after peak load caused by quick unstable crack propagation in concrete. Various, both experimental and numerical, studies have been done [2,3,5,7,8,10,12,20,24] on anchors subjected to tensile loading, because it is important to investigate the influence of various parameters on anchor/concrete system behavior, its assessment and design. For instance, it was experimentally observed, that the use of additional reinforcement for increasing the strength or preventing the concrete cone failure is beneficial [9,13,21,27]. Additionally, Eligehausen et al. [4] found out that the circumferential cracking during the concrete cone failure happens at approximately 30 % of the ultimate load. Furthermore, it was observed that the concrete cone cracking depends on the anchor embedment depth: particularly, the length of the circumferential crack at the specific loading decreases with higher anchor embedment depth. Thus, capacity design methods often take into account various parameters (such as concrete strength, depth of embedment, thickness of concrete, edge distance, concrete reinforcement, anchor material grade, forces applied to the anchor, seismic loads etc.).

Recent numerical studies have provided various methods for modeling and simulating cracking process of concrete-like materials. Besides the finite element method (FEM) which is used within this study, extended finite element method (X-FEM) [18], discrete element method (DEM) [26], cohesive zone models [29], smeared and discrete crack models [19,22], and continuum damage mechanics [14] can be mentioned for instance. Of course, each of the methods mentioned exhibits its uncertainties and limitations, see e.g. [15,23]. Therefore, the finite element method has been chosen because of its benefits.

In this paper, the stress distribution around the anchor's corner is investigated. Especially, tangential stress is investigated based on the idea of the maximum tangential stress (MTS) criterion that says that a crack propagates in the direction where the tangential stress reaches its maximum. Also, the influence of the distance from the anchor's corner on the stress distribution is analyzed and discussed. The goal of this paper is to present results of a parametric study when the effect of specific parameters of the anchor-concrete system on potential crack initiation/propagation is assessed. Finite element method is utilized as a tool for calculation of the stress field around the anchor's corner. Comparison with the experimentally observed crack path is involved. Note that the results presented represent just a pilot study to obtain basic dependences, which can be utilized for suggestion of further research, which should be extended via more advanced material models, fracture energy and process zone assessment etc.

GEOMETRY AND NUMERICAL MODEL

The dimensions of one slice of the cylindrical concrete specimen with an embedded steel anchor subjected to tensile loading (pullout force) are schematically presented in Fig. 1. Note that the interface between the two materials (steel and concrete) is modelled using perfect adhesion.

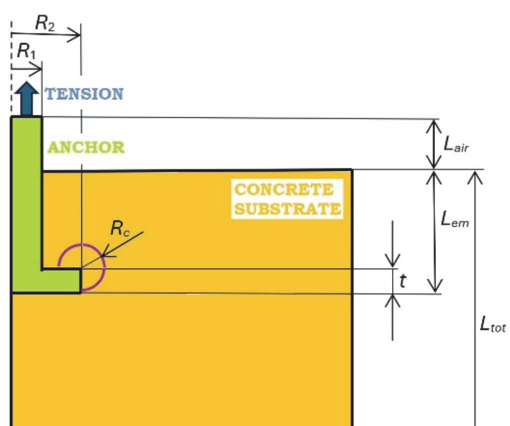


Figure 1: Dimensions of one slice of the cylindrical concrete specimen with an embedded steel anchor; axis of symmetry on the left.

As was mentioned in the previous section, some parameters were varied within the parametric study introduced in this paper in order to assess their influence on the stress field distribution in the vicinity of the anchor's corner. The radial distance, where the stress field was investigated, is represented via the circle with the radius R_C. The values of the individual geometrical parameters can be found in Tab. 1. As can be seen, the depth of the embedment of the anchor in the concrete, its outer radius and the radius of the circle for analysis of the tangential stress around the anchor's corner were varied within the study. Results obtained for selected configurations are presented in the following sections.

Parameter	Value	Unit
R_1	15.0	mm
R_2	20, 22.5, 25, 30, 35 and 40	mm
R_3	600.0	mm
R_C	1, 2, 3, 4 and 5	mm
L_{air}	25.0	mm
L_{em}	50.0 ÷ 500.0	mm
L_{tot}	600.0	mm
t	10.0	mm

Table 1: Dimensions of the numerical model of the concrete specimen with a steel anchor according to Fig. 1.

According to the suggested geometry, a finite element (FE) model was created by means of Ansys Parametric Design Language (APDL). PLANE183 element with quadratic displacement behavior was used for meshing of the specimen considering axisymmetric conditions, i.e. the 2D model represents one slice of the cylindrical concrete specimen with an embedded steel anchor. Elements refinement was defined near the anchor's corner where the crack most likely appears and where the stress field was investigated. An example of the FE mesh can be seen in Fig. 2, where also the boundary conditions are plotted; both axial symmetry on the left-side nodes (UX = 0) and zero vertical displacement on the bottom nodes (UY = 0). The upper part of the steel anchor was subjected to tensile loading, which was modelled through a non-zero vertical displacement value of UY = 0.05 mm. During parametric study, the maximum element size was several tens of millimeters at locations far away from the anchor and the minimum element size was about several tenths of millimeters at the anchor's corner. According to the sensitivity analysis performed, such an FE mesh ensures sufficient accuracy. As can be seen in Fig. 2, the stress field distribution was analyzed at specific radial distances from the anchor's corner. The values of this critical distance applied within this work can be found in Tab. 1 and are in agreement with the Theory of Critical Distances (TCD) published for instance in [25,28]. The TCD is an attitude assuming that material strength can be assessed via specific length scale parameters [1]. The critical length is thought of as a physical property that corresponds with the micro-/meso-/macro-structural characteristics of the material as well as with the specific features of the failure processes. Within static assessment, the TCD quantifies damage through an effective stress, σ_{eff}, which is obtained from the linear-elastic stress field. Thus, the critical distance can directly be estimated from the fracture toughness and tensile strength of the material:

$$R_C = \frac{1}{\pi}\left(\frac{K_{\mathrm{IC}}}{\sigma_{TS}}\right)^2 \tag{1}$$

Note that values of 0.5 MPa·m$^{1/2}$ and 4 MPa, respectively, were considered for the rough estimate of the critical distance typical for a common concrete, and therefore the R_C values were selected in the order of several millimeters. Both materials (steel and concrete) were modelled through the linear elastic material model considering the Young's modulus of 210 GPa and 23.5 GPa and Poissson's ratio 0.3 and 0.2 for steel anchor and concrete, respectively. The selected results are presented in the next section and follow the previous research published in [16,17].

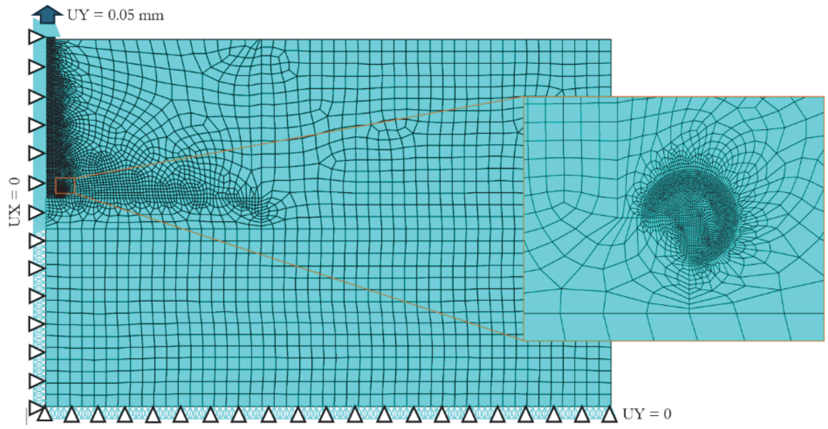


Figure 2: An example of the FE mesh and displacement boundary conditions used within the study.

RESULTS AND DISCUSSION

In this section, selected results of the above-described numerical parametric study on a concrete specimen with an embedded steel anchor subjected to tensile loading are presented. For the geometric configurations presented in Tab. 1, selected stresses (radial, tangential, shear, maximum principal and von Mises stress) were analysed. An example of the stress distribution around the anchor's corner at radial distance of 4 mm for one specific configuration are plotted in Fig. 3.

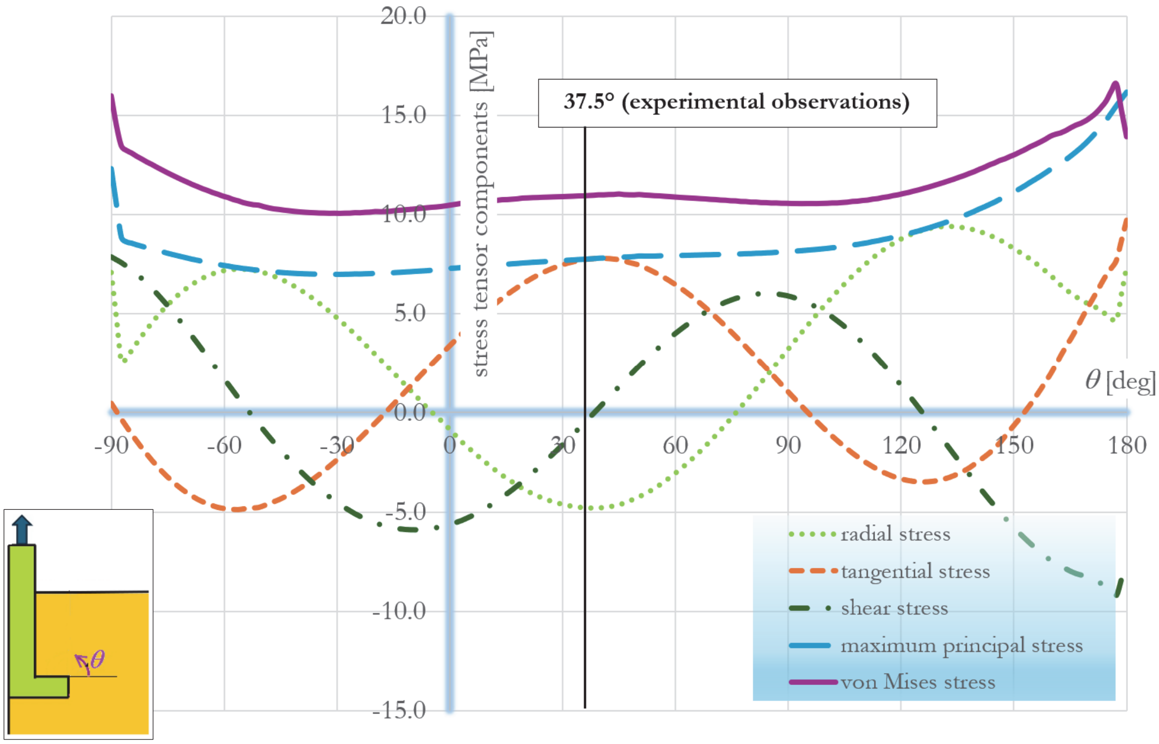


Figure 3: Distribution of selected stresses around the anchor's corner at the radial distance of 4 mm for a selected geometrical configuration (R_2 = 20 mm, L_{em} = 50 mm, other parameters follow Tab. 1).

Dependences in Fig. 3 exhibit various shapes for specific stresses. Nevertheless, there can be seen a good agreement between the angle of the maximum tangential stress and the experimentally observed angle of the concrete cone failure, which is 37.5° [5,11]. Thus, application of the idea of the MTS criterion seems to be reasonable from this point of view. Based on this agreement/observation, maximum tangential stress distribution at several selected (critical) radial distances was investigated for the specimen configurations introduced in Tab. 1 and the angle where $\sigma_{\theta\theta}$ reaches its maximum value was found for each of them. Although there is actually no crack in our numerical model, this approach follows the idea of the maximum tangential stress criterion derived by Erdogan and Sih [6] for crack propagation. When the values of the angle corresponding to the maximum tangential stress are analysed in dependence on the various depth of the anchor's embedment at various critical distances, the following curves can be obtained, see Fig. 4.

The dependence presented in Fig. 4 shows that the value of the θ_{max} angle, where the maximum of the tangential stress occurs, decreases with increasing depth of the anchor's embedment independently on the critical radial distance assumed for the analysis. In other words, the deeper the anchor's embedment, the flatter the concrete cone failure. This means that the circumferential crack propagates in more horizontal direction when the depth of the anchor's embedment increases. From this point of view, it can be concluded that a deeper anchor's embedment is safer in terms of concrete cone failure. The values of the θ_{max} angle vary from ca. 20° to 41° in dependence on the embedment length and critical distance. These values are again supported by the experimentally observed crack paths.

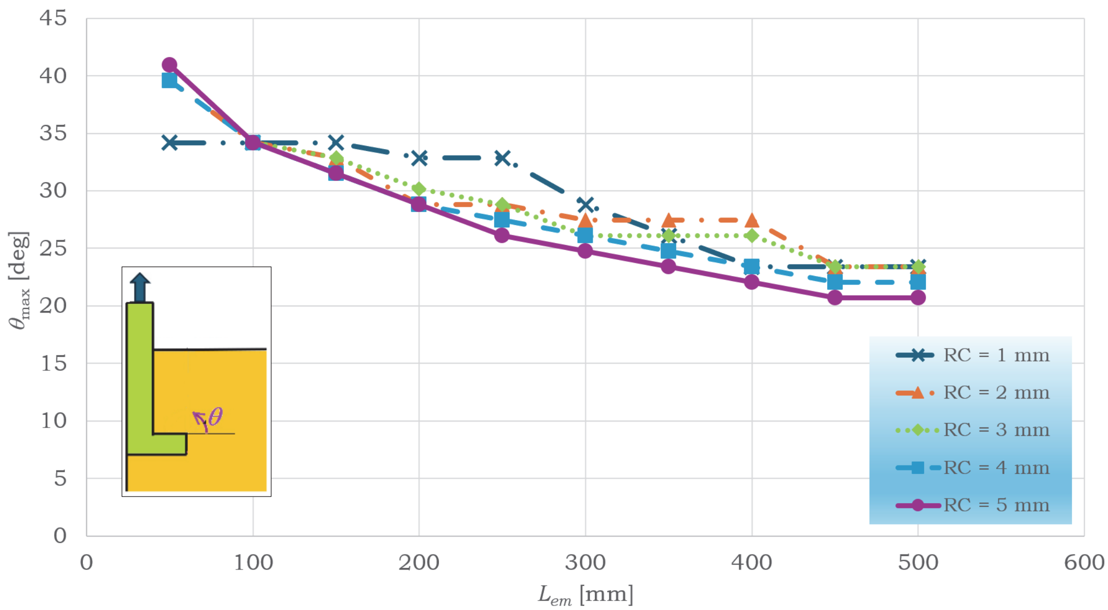
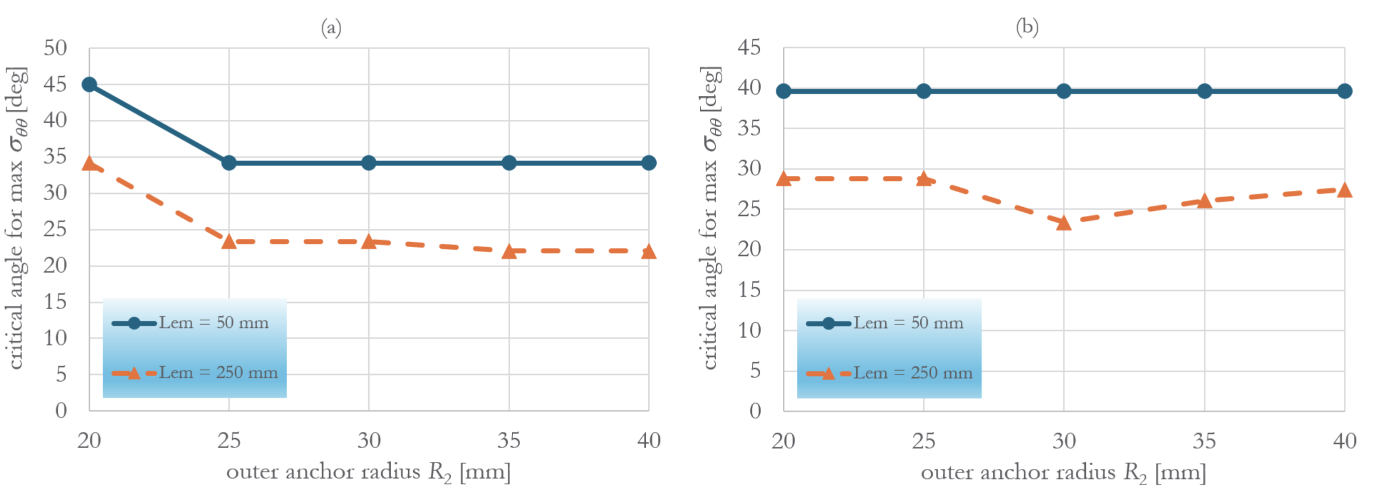


Figure 4: Dependence of the angle θ_{max} corresponding to the maximum tangential stress on the depth of the anchor's embedment for various critical distances.

Additional investigations were conducted considering various outer radii of the steel anchor, R_2 according to Fig. 1. In order to decrease the number of total configurations analysed, some of the other parameters were kept constant in this case. Middle values based on previous research [16,17] were assumed: embedment length L_{em} = 250 mm, critical radial distance R_C = 1 to 5 mm and thickness of the anchor's basement t = 10 mm. See the results of this partial analysis in Fig. 5.



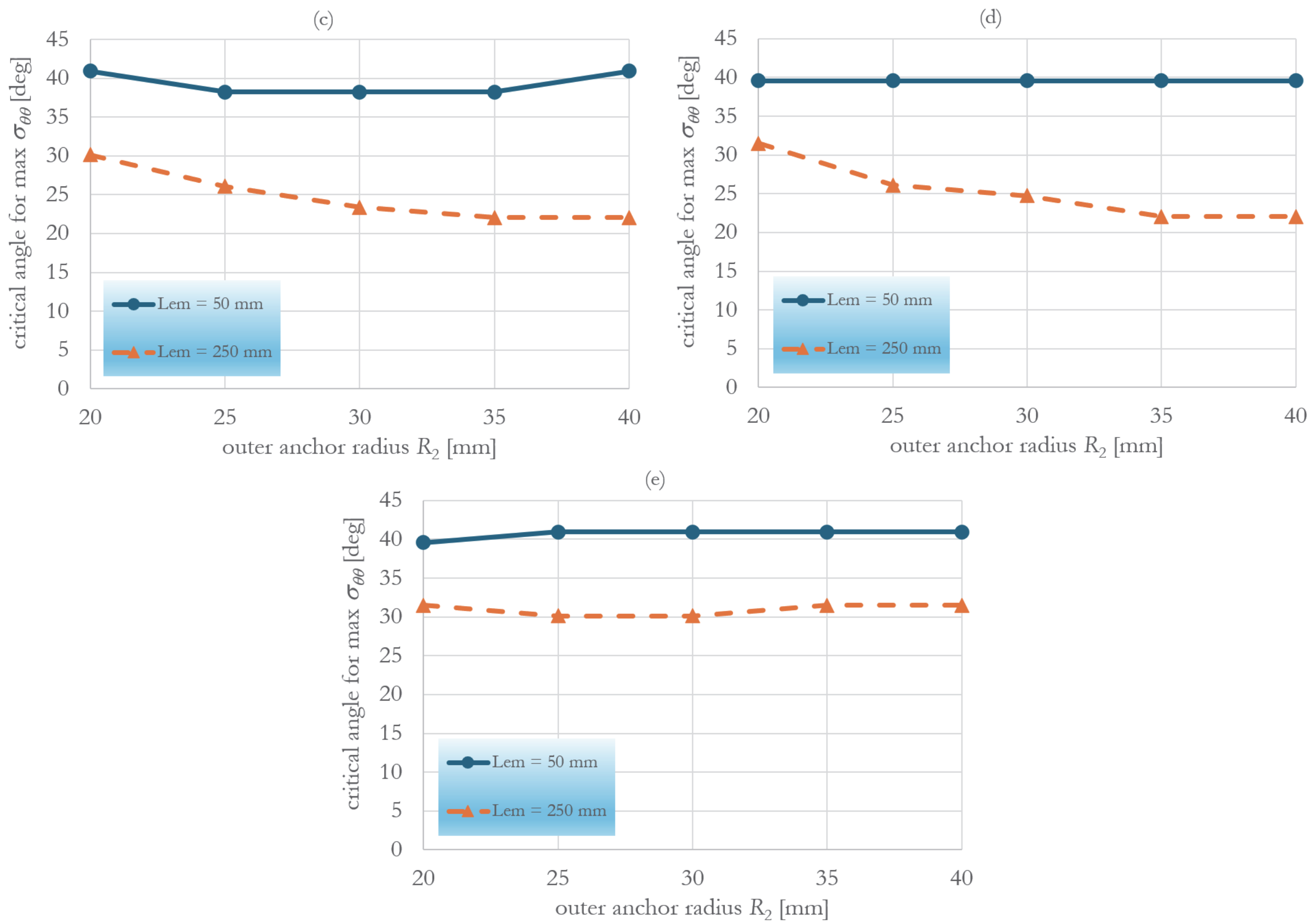


Figure 5: Dependences of the angle corresponding to the maximum tangential stress on the outer anchor's radius for two selected embedment lengths investigated at the critical radial distances: (a) $R_C = 1$ mm; (b) $R_C = 2$ mm; (c) $R_C = 3$ mm; (d) $R_C = 4$ mm; (e) $R_C = 5$ mm.

Results presented in Fig. 5 show that also the outer radius of the steel anchor can have an influence on the shape of the cone failure, especially when the length of the anchor's embedment is higher. Values of the θ_{max} angle are quite similar when various critical radial distances are applied. When the steel anchor is close under the concrete surface, the angle of the concrete cone failure seems to be independent on the outer radius of the steel anchor. Otherwise, for longer steel anchors, the critical angle corresponding to the maximum of the tangential stress slightly decreases with increasing outer radius of the anchor, especially when smaller critical distances are applied. This behaviour is again more advantageous in terms of a flatter concrete cone failure shape when the crack needs to overcome longer path towards the specimen surface.

If the results of both analyses are evaluated, it can be concluded that independently on the choice of the critical radial distance, the angle corresponding to the maximum tangential stress value decreases with increasing length of the steel anchor's embedment and with increasing outer radius of the anchor if the embedment is long enough. This founding can be beneficial for designing of anchor/concrete systems subjected to tensile loading. Of course, other fracture mechanical and economical aspects need to be considered during the design and assessment of such structures.

CONCLUSIONS

Within this paper, it was shown that the geometry of the steel anchor subjected to tensile loading can have a significant influence on the stress distribution in the concrete around the anchor and consequently on the shape of the typical concrete cone failure. Moreover, it was showed that the rather simplistic approach of LEFM to anchor failure is sufficient enough to provide with crack direction orientation and future cone failure. Finite element numerical model was created to apply the basic idea of the maximum tangential stress criterion that allows to predict crack propagation direction. Generally, these angles through the entire parametric study varied between ca. 20 and 40°, which is in accordance with experimental observations. Moreover, it was found out that the increasing embedment length of the anchor as well as the increasing anchor's outer radius are advantageous in terms of the circumferential crack propagation angle. In other words, the larger the mentioned parameters, the lower the angle corresponding to the maximum tangential stress. Thus, a flatter path of the cone crack improves the fracture resistance of the anchor/concrete system against failure. This should be taken into account together with other factors for design and/or assessment of such a kind of structures. Note that the same behaviour was observed independently on the choice of the critical radial distance where the tangential stress distribution was analysed.

Data availability

The data used in this study is available at (ZENODO repository): 10.5281/zenodo.15083222.

Acknowledgment

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