Investigation on influence of the loading rate on concrete cone failure

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Abstract

The loading rate significantly influences structural response. The structural response depends on the loading rate through three different effects: through the creep of the bulk material between the cracks, through the rate dependency of the growing microcracks and through the influence of structural inertia forces. The first effect is important only at extremely slow loading rates whereas the second and third effects dominate at higher loading rates. In this paper, a rate sensitive model, which is based on the energy activation theory of bond rupture and its implementation into the microplane model for concrete are given. To investigate the importance of the rate of the growing microcracks and the influence of structural inertia, static and dynamic analyses were carried out. The results show that with an increase of the loading rate, the pull-out resistance increases. The comparison between model prediction and test data for uniaxial compression failure of concrete shows that the model realistically predicts the influence of the loading rate on the compressive strength and initial Young's modulus.

Keywords: concrete, concrete cone failure, finite element analysis, rate sensitivity, microplane model, crack band approach.

1 Introduction

It is well known that loading rate significantly influences structural response. The structural response depends on the loading rate through three different effects: through the creep of the bulk material between the cracks, through the rate dependency of the growing microcracks and through the influence of structural inertia forces, which can significantly change the state of the stresses

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and strains at the material. Depending on the type of material and the loading rate, the first, second or third effect may dominate. For quasi-brittle materials, such as concrete, which exhibit cracking and damage phenomena, the first effect is important for relatively low loading rates (creep-fracture interaction). However, the last two effects dominate for higher loading rates (impact loading). This is especially true for the case of recently observed phenomena [1] for which a sudden increase of the loading rate in softening leads to reversal of softening into hardening. In the literature, a number of theoretical and experimental studies can be found that deal with the problem of the rate effect for concrete like materials [2–5]. In most of these studies, various stress-displacement relations, similar to the spring-dashpot models of viscoelasticity, were used. In the present paper a model for the rate dependency of the crack propagation is adopted that is applicable over many orders of magnitude of the loading rate. The model is based on the rate process theory [6] of bond ruptures. It is coupled with the M2-O microplane model for concrete [7], which has been shown to realistically simulate failure of concrete structures for complex three-dimensional stress-strain states [8]. Practical experience, a large number of experiments and numerous numerical studies for anchors of different sizes confirm that fastenings are capable of transferring a tension force into a concrete member without using reinforcement [9]. Provided the steel strength of the anchor is high enough, a headed stud subjected to a tensile load normally fails by cone shaped concrete breakout. Experimental and theoretical investigations clearly show that for the pull-out problem, cracking of concrete is an important aspect of the resistance mechanism. In contrast to a number of structural systems, which rely only on the material strength, the concrete cone resistance relies mainly on the energy consumption capacity of concrete, which is directly related to the concrete cracking. Since cracking is a time-dependent phenomenon, it is important to know how the loading rate influences the concrete pull-out capacity (impact, seismic action, etc.). The experimental results indicate that the loading rate significantly influence the concrete cone pull-out capacity [10]. However, due to the limited number of experiments, which are available only for relatively narrow range of loading rate, there is an obvious need for further theoretical and experimental investigation. It is well known that the concrete cone resistance exhibits significant size effect on the ultimate load [10]. For quasi-static loading, the size effect can be well predicted by the size effect formula that is based on linear elastic fracture mechanics (LEFM) [8]. Presently there is no experimental or theoretical investigation in which the size effect on the concrete cone capacity was systematically investigated for different loading rates. For long term loading (very low loading rates), in which creep of concrete plays important role, the size effect becomes stronger compared to the normal loading rates [3]. Therefore, one of the aims of this numerical study was to investigate how relatively fast loading rates, where creep of the concrete is of a minor importance, influence size effect on the pull-out capacity. To distinguish between the influence of the rate dependent concrete cracking and structural inertia on the size effect, the results of static and dynamic analyses were evaluated and compared.

2 Rate dependency in the M2-O microplane model

The rate dependency in the here presented version of the thermodynamically consistent M2-O microplane model for concrete [6] consists of two parts: the rate dependency related to the formation (propagation) of the microcracks, which accounts for the effect of inertia forces at the level of the micro-crack tip, and the rate dependency due to the creep of concrete between the microcracks. The first part of the rate dependency is responsible for the short duration loads (impact), up to duration of one hour, and the second part is responsible for the long duration loading (creep fracture interaction). Unlike the model proposed in [3] in which the initial elasticity modulus is controlled by a simple viscoelastic model, in the current model the rate dependency related to the formation of microcracks is responsible for the rate dependent softening and for the rate dependent hardening (rate dependent elasticity modulus of concrete). The reason for this is due to the assumption that the microcracks start to grow immediately after the application of load. Consequently, the initial (secant) elasticity modulus is controlled by the rate of growth of microcracks. Note, that in the present formulation the influence of structural inertia on the rate effect is not a part of the constitutive law, however, this effect is automatically accounted for in dynamic analysis in which the constitutive law interacts with forces due to structural inertia. The second part of the rate dependency, in which creep of concrete is important, is in the constitutive law represented by the serial coupling of the generalized Maxwell model for concrete and the microplane model [11]. The discussion related this part of the model is out of the scope of the present paper.

3 Influence of loading rate on concrete cone failure

The experimental results [9, 12] for headed stud anchors loaded in tension show that the resistance and the peak displacement are higher than for the static loading. Furthermore, there is an indication that the failure mode also depends on the loading rate [1, 10]. Unfortunately, the experimental results are available only for relatively low loading rates and for anchors with relatively small embedment depths. To get more insight into the behaviour of headed stud anchors of different sizes loaded by different loading rates, a 3D static and dynamic FE analyses were carried out using the rate sensitive microplane model for concrete. To investigate the influence of the loading rate on the concrete cone failure, pull-out of headed stud anchor from a concrete block was simulated (Figure 1). The edge distance was chosen such that unrestricted cone formation was possible. The heads of the studs were designed such that the pressure under the head at peak load was relatively low (approximately 3 times the uniaxial compressive strength of concrete), i.e. the heads for all embedment depths were relatively large and they were not scaled in proportion to the embedment depth. Three embedment depths were considered: h_{ef} = 150, 890 and 1500 mm. In static and dynamic analyses, the load was applied by controlling the displacement δ of the stud. This type of loading is almost identical to control of the crack opening because the anchor stud is relatively stiff and deformation of concrete under the

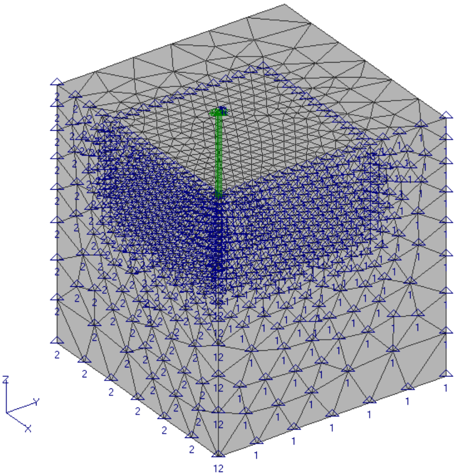

Figure 1: Typical finite element mesh of the concrete element.

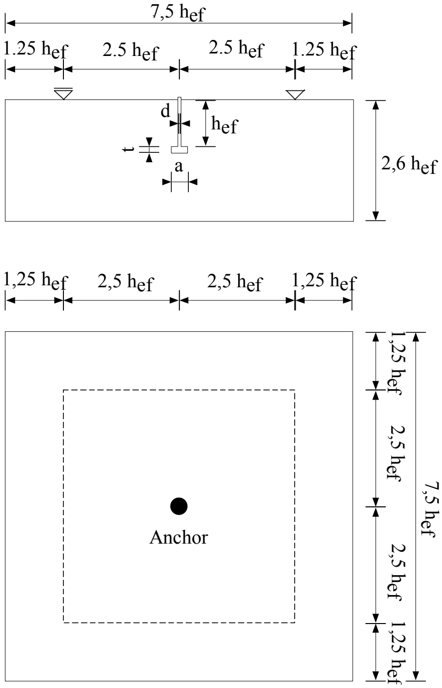

Figure 2: Investigated geometry.

head of the stud is relatively small (large head size). For each embedment depth the loading rates were varied from $d\delta/dt = 0$, (quasi static analysis – no rate effect) to $2\text{x}10^5$ mm/s. The typical finite element mesh and the geometry of the head of the stud are shown in Figures 1 and 2. The rate independent properties of concrete are taken as: Young's modulus E_C = 28000 MPa, Poisson's ratio ν_C = 0.18, tensile strength f_t = 3 MPa, uniaxial compressive strength f_c = 38 MPa and concrete fracture energy G_F = 0.1 N/mm. The behaviour of steel was assumed to be linear elastic with Young's modulus E_S = 200000 MPa and$_S$Poisson's ratio ν = 0.33. In the analysis, four node solid finite elements were used. To eliminate mesh size sensitivity the crack band method [2] was employed.

3.1 Static analysis

The typical load-displacement curves obtained in the static analysis for h_{ef} = 150 and 1500 mm (loading rate $d\delta/dt$ = 5 mm/s) shown in figures 3 and 4. It can be seen that for the smallest embedment depth, the load-displacement curve is more ductile and, in contrast to large embedment depth, it shows two peaks. The first corresponds to the initiation of the concrete cone and the second one is due the formation of the full concrete cone. The typical load-displacement curves for all loading rates (h_{ef} = 150 mm) are plotted in Figure 3. The calculated peak loads are summarised in Table 1. As can be seen, with the increase of the loading rate the peak load increases. Figure 5 shows the relative pull-out resistance for all

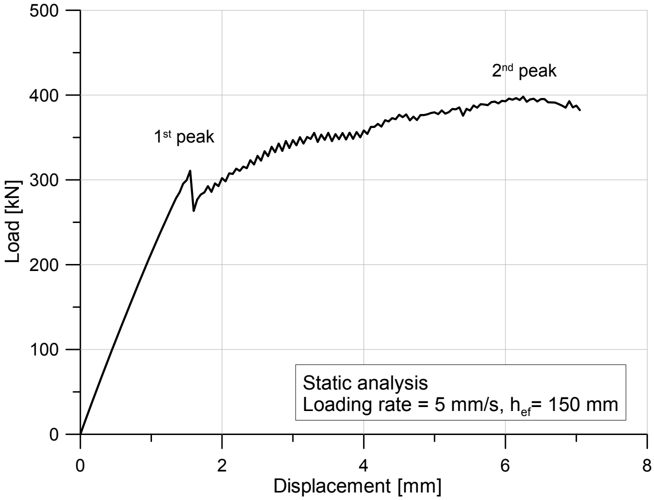

Figure 3: Calculated load-displacement curves for: h_{ef} = 150mm.

Table 1: Static analysis: summary of the calculated peak loads [kN].

h_{ef} [mm]	no rate effect	5 mm/s	20 mm/s	2x10^3 mm/s	2x10^5 mm/s
150	261	398	438	483	538
889	6226	6076	6304	6862	7885
1500	12314	13697	13792	15845	17356

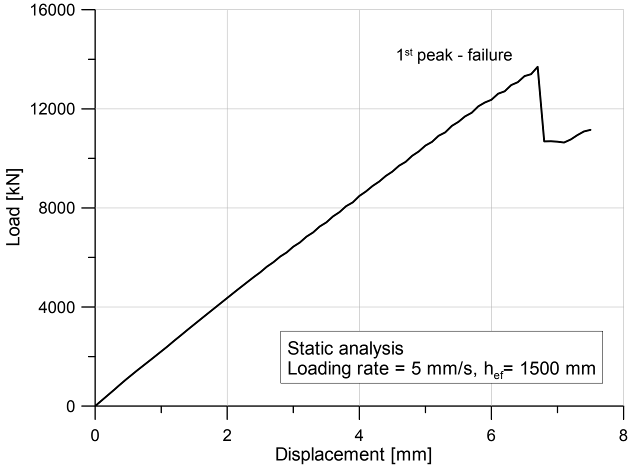

Figure 4: Calculated load-displacement curves for: $h_{ef} = 1500$ mm.

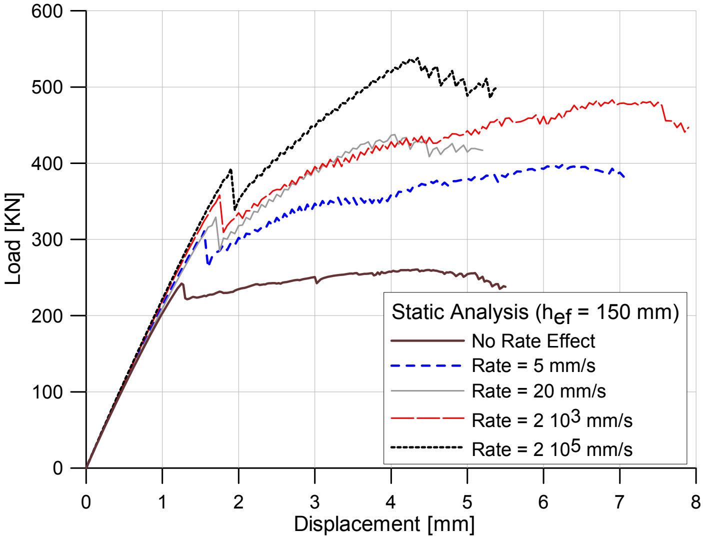

Figure 5: Calculated load-displacement curves for $h_{ef} = 150$ mm.

three embedment depths as a function of the loading rate. The resistance for static loading is taken as a reference. It can be seen that for all embedment depths, the increase of the maximum pull-out resistance is almost a linear function of the loading rate (lin.-log scale). The largest increase is obtained for the smallest embedment depth. For relatively large embedment depths ($h_{ef} = 890$ and 1500 mm) the influence of the loading rate on the peak load is almost identical, however, much smaller than for h_{ef} = 150 mm. The reason is probably due to the fact that for small embedment depth the size of the fracture process zone is large relative to the embedment depth, which leads to a stronger influence of the loading rate on the failure load. In most experiments the maximal loading rate was approximately 20 mm/s (earthquake) and only few were performed with high loading rate. In spite of the differences in the geometry of anchors, the numerical and experimental results show relatively good agreement. From results it can be seen that in the experiments and in the analysis there is a similar increase of the resistance when the loading rate increases. Numerical studies, in which the rate sensitivity was not considered, show that for anchors with relatively small head sizes the size effect is close to the prediction according to LEFM [13]. However, it has been recently shown [13] that for larger head sizes, such as were used in the present study, the size effect obtained in experiments and in quasi static FE analysis is weaker than the prediction based on LEFM. In Figure 6b, the relative nominal pull-out strength for all loading rates is plotted as a function of the embedment depth. In Figure 6 is also shown upper bound of the available test data [1] and [12]. For each loading rate the relative nominal strength is calculated as the ratio between the nominal strength and the nominal strength for h_{ef} = 150 mm ($\sigma_{N,150}$). The results of analysis without loading rate confirm previous results obtained in [13] Furthermore, it can be seen that by increase of the loading rate, the size effect becomes stronger, i.e. the reduction of the nominal strength for larger embedment depths is larger at higher loading rates. The results for very high loading rates coincide almost exactly with the prediction according to LEFM.

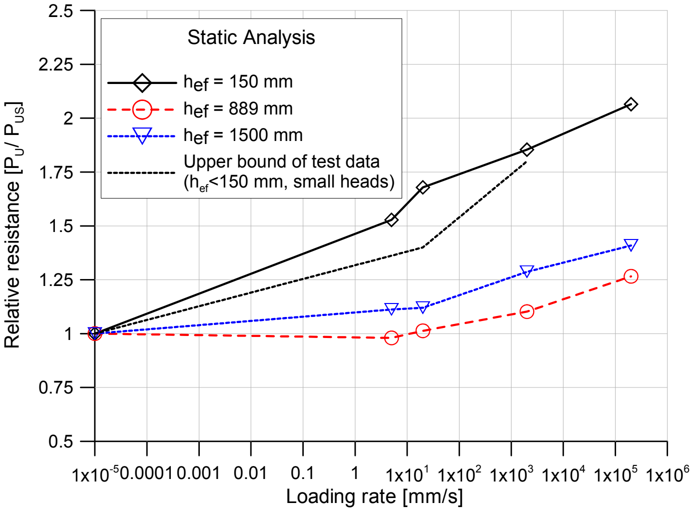

Figure 6: Influence of the loading rate on the anchor pull-out resistance: numerical results and upper bound of available test results.

3.2 Results of dynamic analysis

Due to limitation of this article, tables and figures for the results obtained by dynamic analysis are excluded. The results of dynamic analysis show that the failure mode depends on the loading rate. For relatively slow loading, the failure type is the same as in the static analysis, i.e. concrete cone failure However, for very high loading rates the failure mode changes and instead of concrete cone failure, the anchor fails in shear. The same tendency was also observed in the experiments [1]. It can be seen that for relatively low and moderate loading rates the resistance increases almost as a linear function of the loading rate However, after reaching certain loading rate the increase becomes progressive. The loading rate at which the resistance start to increase progressively is the critical loading rate. The critical loading rate is related to the embedment depth. The large the embedment depth, the smaller is the critical loading rate at which the increase of the pull-out resistance becomes progressive. The size effect on the nominal pull-out strength obtained in dynamic analysis is plotted in figure 7 for all loading rates. The same as in static analysis, the relative nominal strength is shown as a function of the embedment depth. It can be seen that for moderately high loading rates the size effect becomes stronger when the loading rate increases. It reaches maximum (LEFM) for loading rates between 20 and 200 mm/s. For further increase of the loading rate, however, there is an opposite tendency, i.e. the size effect on the nominal pull-out strength is weaker. It is interesting to observe that for the loading rate $d\delta/dt = 2x10^3$ mm/s the size effect disappears completely, i.e. the nominal pull-out strength is almost independent of the embedment depth. This loading rate approximately corresponds to the critical loading rate. For

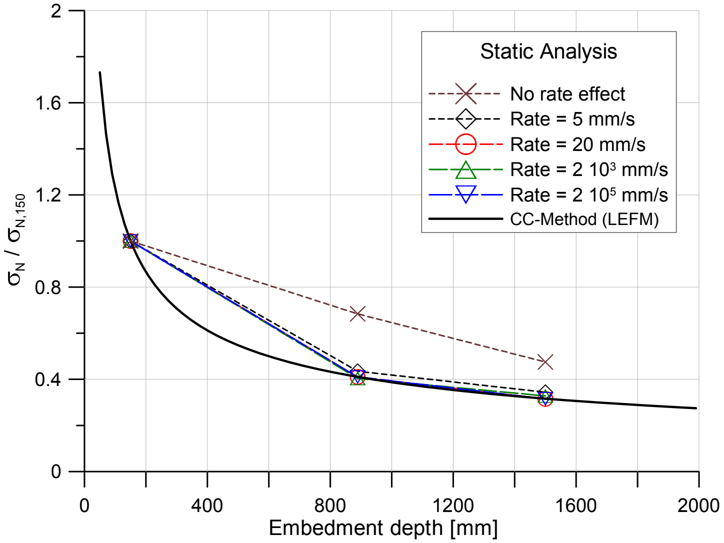

Figure 7: Size effect as a function of the loading rate (dynamic analysis).

loading rates larger than 2x10^3 mm/s the nominal strength increases with the increase of the embedment depth.

4 Conclusions

Based on the results obtained in this article there are several conclusions that can be drawn, namely that the loading rate significantly influences the pull-out resistance of anchors. For moderately high loading rates, static and dynamic analyses show the same response of the anchors. For these loading rates, the rate of the growing microcracks has a dominant influence on the rate dependent response. This effect is controlled by the inertia at the local micro-crack tip level. In the constitutive model the effect is accounted for based on the energy activation theory. The comparison between experimental and numerical results shows good agreement. For higher loading rates there is a large difference between static and dynamic analysis. After the loading rate reaches critical value, the increase of resistance becomes progressive. This is due to the structural inertia. At high loading rates the influence of structural inertia on the response becomes dominant and much larger than the influence of the rate of the crack growth (constitutive law). In static analysis the failure mode is typically concrete cone failure and it is independent of the loading rate. In dynamic analysis the failure mode for lower loading rates are the same as in the static analysis. However, when loading with higher loading rate the failure mode changes and is due to the shear failure (mixed-mode). The results of static analysis show that the size effect on the concrete cone capacity increases with increase of the loading rate, i.e. the reduction of the nominal strength is larger if the loading rate is higher. It is known that for very low loading rate the size effect is stronger if the loading rate is lower (creep-fracture interaction). Therefore, it can be concluded that there is a transitional loading rate for which the size effect is minimal. When the loading rate is larger or smaller than the transitional one, the size effect is stronger. Dynamic analysis confirms the results of the static analysis for relatively low loading rates. However, for higher loading rates the size effect on the nominal pull-out strength becomes weaker.

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