Influence of loading rate on concrete cone failure

J. Ožbolt, K. K. Rah
Institute of Construction Materials, University of Stuttgart, Germany
D. Meštrović
Faculty of Civil Engineering Rijeka, Croatia

ABSTRACT: Three different effects control the influence of the loading rate on structural response: creep of bulk material, rate dependency of growing microcracks and structural inertia. The first effect is important only at extremely slow loading rates whereas the second and third effects dominate at higher loading rates. In the present 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 discussed. The rate sensitive microplane model is applied in a 3D finite element analysis of the pull-out of headed stud anchors from a concrete block. The results show that with an increase of the loading rate the pull-out resistance increases. For moderate loading rates, the rate of the micro crack growth controls the structural response. For much higher loading rates, however, the structural inertia dominates. The numerical results are in good agreement with experimental evidence.

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: (1) through the creep of the bulk material between the cracks, (2) through the rate dependency of the growing micro cracks and (3) through the influence of structural inertia forces, which can significantly change the state of the stresses and strains in 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 latter two effects dominate for higher loading rates (impact loading). This is especially true for the case of recently observed phenomena (Bažant et al., 2000) 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 (Reinhardt 1982; Curbach 1987; CEB 1988; Weerheijm 1992). 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 (Krausz and Krausz 1988) of bond ruptures. It is coupled with the M2-O microplane model for concrete (Ožbolt et al. 2001), which has been shown to realistically simulate failure of concrete structures for complex three-dimensional stress-strain states (Ožbolt 1995).

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 (Eligehausen et al. 1997). 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 (Klingner et al. 1998; ANCHR 2001). However, due to the limited number of experiments, which are available only for a 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 (Eligehausen et al. 1997). 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) (Ožbolt 1995). 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 an important role, the size effect becomes stronger compared to the normal loading rates (Bažant and Gettu 1992). 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 DEPENDENT MICROPLANE MODEL

The rate dependency in the here presented version of the thermodynamically consistent M2-O microplane model for concrete (Ožbolt et al. 2001) consists of two parts: (1) 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 (2) 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 by Bažant et al. (2000), 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 micro-cracks is responsible for the rate dependent softening and hardening (rate dependent elasticity modulus of concrete), respectively. 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 micro-cracks. 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 (Ožbolt and Reinhardt 2001). The discussion related this part of the model is out of the scope of the present paper. For more details, see Ožbolt and Reinhardt (2001).

The rate of strain $d\varepsilon/dt$ in a continuum with a number of parallel cohesive cracks, which may be imagined to represent macroscopic strain softening, can be expressed as:

$$\frac{d\varepsilon}{dt} = \frac{\dot{w}}{s_{cr}} + \frac{\dot{\sigma}}{E} \approx \frac{\dot{w}}{s_{cr}} \tag{1}$$

where ε = average macroscopic strain normal to the direction of parallel cracks, s_{cr} = spacing of the parallel cracks, E = Young's modulus of bulk material and $(d\sigma/dt)/E$ is the elastic strain ratio which can be, compared to the crack opening ratio dw/dt, neglected. After introducing a few reasonable simplifications into the concept that is based on the energy activation theory (Krausz and Krausz 1988), the influence of the rate effect on the rate independent stress-strain relation $\sigma^0(\varepsilon)$ can be written as:

$$\sigma(\varepsilon) = \sigma^0(\varepsilon)\left[1 + C_2 \ln\left(\frac{2\dot{\varepsilon}}{C_1}\right)\right] \tag{2}$$

where C_1 and C_2 are constants obtained by fitting test data (Bažant et al. 2000).

In the microplane model the macroscopic response is obtained by integrating normal and shear microplane stresses over all microplanes. The rate independent microplane stress components $\sigma^0_M(\varepsilon_M)$ (M = stands for microplane volumetric, deviatoric and shear components, respectively) are calculated from the known microplane strains ε_M using predefined microplane uniaxial stress-strain constitutive relations (Ožbolt et al. 2001). It seems reasonable to assume that the rate effect on each microplane component is of the same type as given by (2). Consequently, the rate dependency for each microplane component reads (Bažant et al. 2000):

$$\sigma_M(\varepsilon_M) = \sigma^0_M(\varepsilon_M)\left[1 + c_2 \ln\left(\frac{2\dot{\gamma}}{c_1}\right)\right]$$
$$\text{with} \quad \dot{\gamma} = \sqrt{\frac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}\ ;\ c_1 = \frac{c_0}{s_{cr}} \tag{3}$$

where c_0 and c_2 are material rate constants which have to be calibrated by fitting test data, $\dot{\varepsilon}_{ij}$ = components of the macroscopic strain rate tensor (indicial notation). From (3) it is obvious that the rate magnitude is not measured on the individual microplanes, which would be not objective, but on the macro-scale. Furthermore, in the microplane model, (3) applies on all microplane components except the volumetric compression, which is assumed to be rate insensitive. This is done because for volumetric compression there is no crack development since the material is compacted.

The above model parameters are calibrated based on the uniaxial compressive tests performed by Dilger et al. (1978). The tests have been carried out for three loading rates: 0.2 s^{-1}, $3.33x10^{-3}$ s^{-1} and $3.33x10^{-5}$ s^{-1}. Assuming average crack spacing of $s_{cr} = 100$ mm, the following values are obtained from the calibration procedure follows: $c_0 = 0.0004$ and $c_2 = 0.032$ (Ožbolt et al. 2006).

The rate sensitive microplane model accounts for the effect of inertia forces at the local, crack tip level, based on the energy activation theory. However, the influence of structural inertia on the rate sensitive material constitutive law is not a part of the constitutive model. This structural effect comes automatically from the structural dynamic analysis through the interaction between the inertia forces (stresses) and the constitutive law. Therefore, the calibration of the constitutive law was carried out for moderate loading rates for which macroscopic inertia forces do not have much influence on the rate dependent response of the material, i.e. only the rate of the crack growth controls the response.

The model automatically accounts for the stress-strain dependent rate sensitivity. This has been recently demonstrated by numerical studies in which the rate dependent response of cantilever and three-point bending plain concrete beams was studied (Ožbolt and Reinhardt 2005a; Ožbolt and Reinhardt 2005b). Moreover, it has been shown that with the increase of the concrete quality (high strength concrete) the influence of the loading rate decreases (Ožbolt and Reinhardt 2005a), what is also evident from the experiments (CEB 1988).

3 NUMERICAL ANALYSIS

The rate sensitive microplane model is employed in the here presented 3D FE study of the pull-out problem. Static analysis is performed using an implicit 3D FE code based on the incremental secant stiffness approach (Belytschko et al. 2001). In the 3D transient dynamic FE analysis the system of unknown displacements in each time step Δt is calculated by solving the following system of equations (Voigt notation):

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) - \mathbf{f}(t) = 0 \qquad (4)$$

where $\mathbf{M}$ = mass matrix, $\mathbf{C}$ = damping matrix, $\ddot{\mathbf{u}}$ = nodal accelerations, $\dot{\mathbf{u}}$ = nodal velocities and $\mathbf{f}(t)$ = resulting nodal forces. The resulting nodal forces are calculated as:

$$\mathbf{f}(t) = \mathbf{f}^{\text{ext}}(t) - \mathbf{f}^{\text{int}}(t) \qquad (5)$$

where $\mathbf{f}^{\text{ext}}$ and $\mathbf{f}^{\text{int}}$ are external and internal nodal forces, respectively. The above system of equations (4) is solved using an explicit direct integration scheme (Belytschko et al. 2001). The external nodal forces are known nodal loads. The internal nodal forces are unknown and they are calculated by the integration of the stresses over the finite elements. In the FE code used, the mass and damping matrices are assumed to be diagonal.

4 INFLUENCE OF THE LOADING RATE

4.1 *General*

The experimental results (Eibl and Keintzel 1989; Rodrigez 1995) for headed studs 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 (Klingner et al. 1998; ANCHR 2001). 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. The edge distance was chosen such that unrestricted cone formation was possible (see Fig. 1). 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. Such anchors have recently been used in the tests performed by KEPRI & KOPEC (2003) and they are often used in nuclear power plants. 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 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 $2x10^5$ mm/s. The typical finite element mesh and the geometry of the head of the stud are shown in Figure 1.

The rate independent properties of concrete are taken as: Young's modulus E_C = 28000 MPa, Poisson's ratio $\nu_C = 0.18$, 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 Poisson's ratio $\nu_S = 0.33$. In the analysis, four node solid finite elements were used (see Fig. 2). To eliminate mesh size sensitivity the crack band method (Bažant and Oh 1983) was employed.

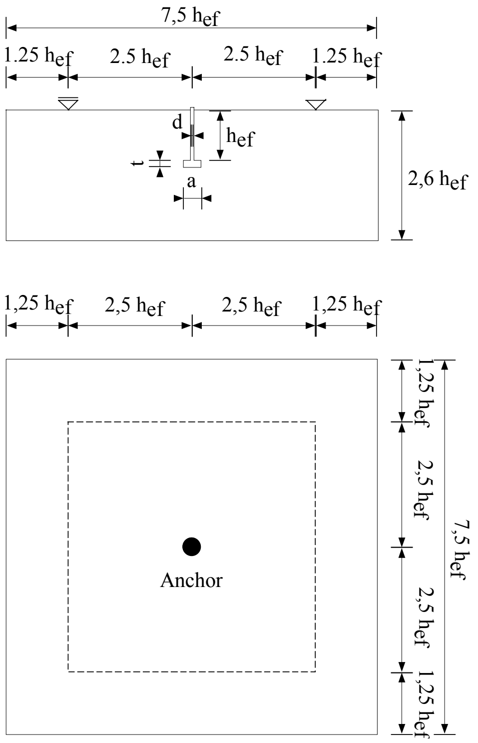

Figure 1. Investigated pull-out geometry.

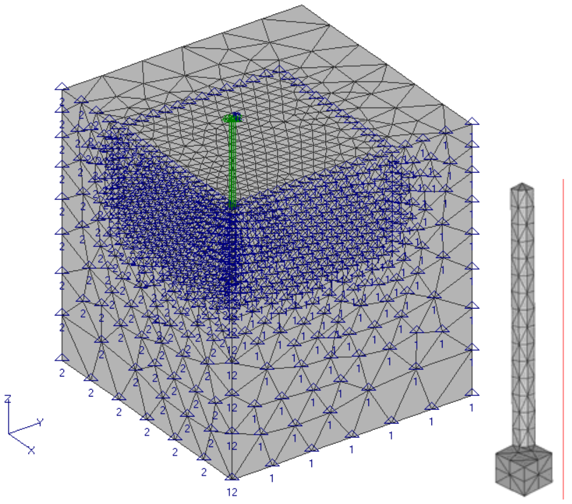

Figure 2. Typical finite element mesh of a concrete block and of the anchor ($h_{ef} = 150$ mm, 1/4 of the specimen).

4.2 *Static analysis*

The rate dependent load-displacement curves obtained in the static analysis for $h_{ef} = 150$ are shown in Figure 3. As can be seen, with the increase of the loading rate the peak load increases. Figure 4 shows the relative pull-out resistance for all 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 (linear-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. A typical concrete cone obtained in the static analysis is shown in Figure 5. The failure mode is independent of the loading rate and of the embedment depth.

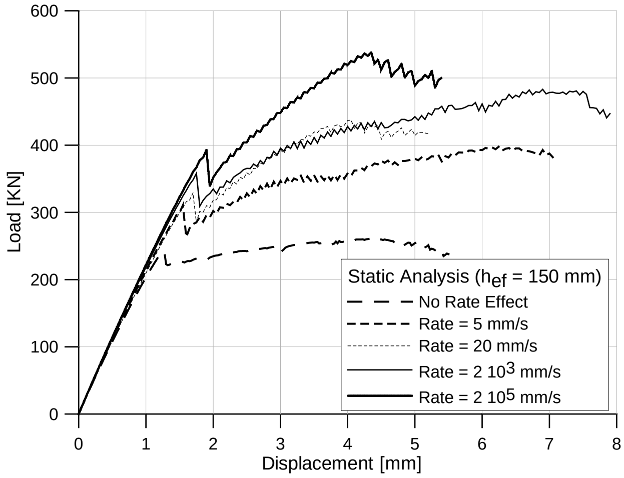

Figure 3. Calculated load-displacement curves for $h_{ef} = 150$ mm.

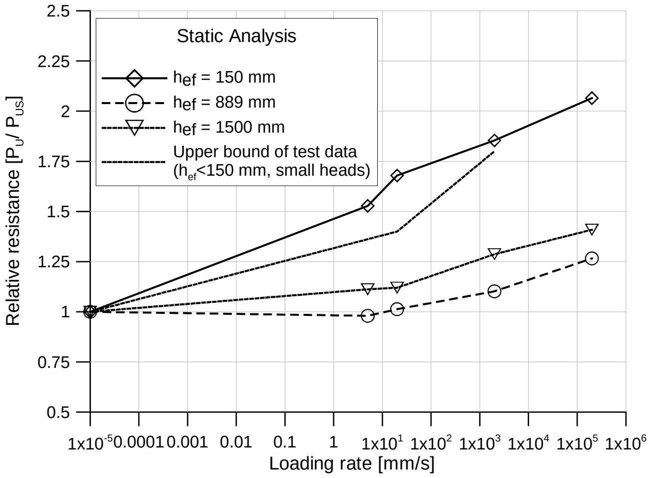

Figure 4. The influence of the loading rate on the anchor pull-out resistance – numerical results and upper bound of available test results (Klingner et al., 1998; ANCHR, 2001).

Figure 4 also shows upper bound of the available test data (Klingner et al. 1998; ANCHR 2001). The tests were performed on headed stud anchors with $h_{ef} < 150$ mm and the size of the anchor heads were relatively small. In most experiments the maximal loading rate was approximately 20 mm/s (earthquake) and only few were performed with high loading rate (ANCHR 2001). In spite of the differences in the geometry of anchors, the numerical and experimental results show relatively good agreement. From Figure 4 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.

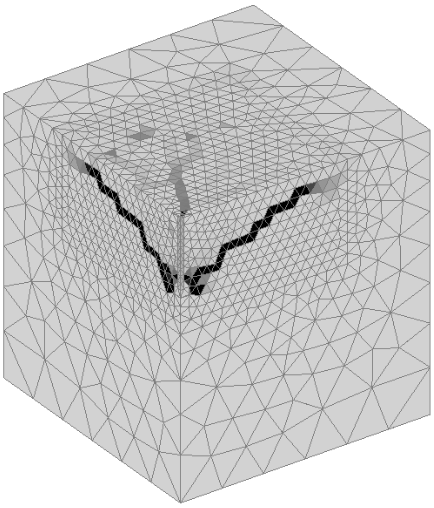

Figure 5. Typical failure mode obtained for $h_{ef} = 150$ mm.

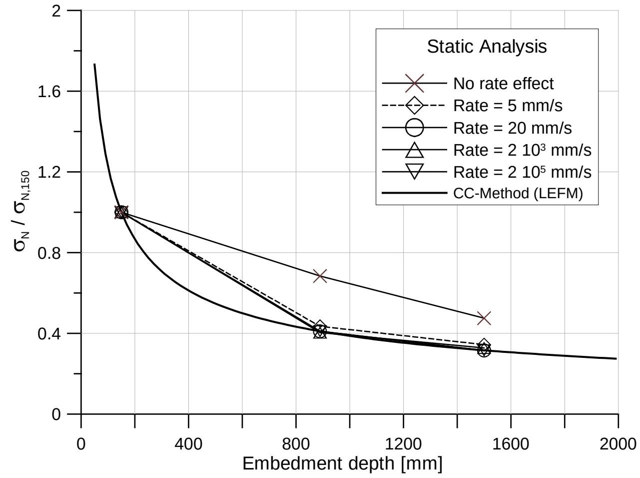

Figure 6. Size effect on the pull-out failure load as a function of the loading rate (static analysis).

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 (Ožbolt et al. 2004). However, it has been recently shown (Ožbolt et al. 2004) 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 6, the relative nominal pull-out strength for all loading rates is plotted as a function of the embedment depth. For each loading rate the relative nominal strength is calculated as the ratio between the nominal strength $\sigma_N = P_U/(h_{ef}^2 \pi)$ (P_U = ultimate load) and the nominal strength for $h_{ef} = 150$ mm ($\sigma_{N,150}$). The results of analysis without loading rate confirm previous results obtained by Ožbolt et al. (2004). 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.

At higher loading rates, the response is more brittle and consequently the size effect becomes stronger. This is also the case when a concrete structure is loaded slowly and the interaction between creep and fracture causes stronger size effect (Bažant and Gettu 1992; Ožbolt and Reinhardt 2005b). Therefore, it can be concluded that there is a transitional loading rate. For such a loading rate, the size effect is minimal. If the loading rate is larger or smaller than the transitional one, the size effect on the nominal strength increases. For slow loading rates, the creep-fracture interaction controls the rate dependency and for fast loading rates, the rate dependency is controlled by the rate dependent crack growth. However, this holds only for moderately large loading rates for which structural inertia can be neglected.

4.3 *Dynamic analysis*

To investigate the influence of structural inertia on the response of the headed stud anchors, the same study as presented in section 4.2 was repeated, however, dynamic analysis was performed. As mentioned in section 3, dynamic analysis was carried out using an explicit direct integration method. In the analysis, damping was set to 0.023 N s/mm. This appeared to be necessary because of numerical reasons, i.e. to get the explicit integration algorithm stable and to prevent local oscillations at the FE level. The mass density of the concrete and the anchor were set to $\rho = 2.3$ T/m^3 and $\rho = 7.4$ T/m^3, respectively.

The calculated load-displacement curves for $h_{ef} = 150$ mm and for three loading rates (slow, moderately fast and very fast) are plotted in Figure 7. In the figure reaction force versus prescribed anchor displacement are also shown. It can be seen that for very high loading rates the reaction forces are not even activated at the time when the load reaches its maximum value.

The results show that similar to the static analysis, the pull-out resistance increases with an increase of the loading rate. However, for relatively high loading rates, the increase is much higher than that in the static analysis. Moreover, for constant loading rate, the increase is higher for larger embedment depth. The reason for the increased strength is structural inertia forces, which are typically higher in larger structures than in small structures.

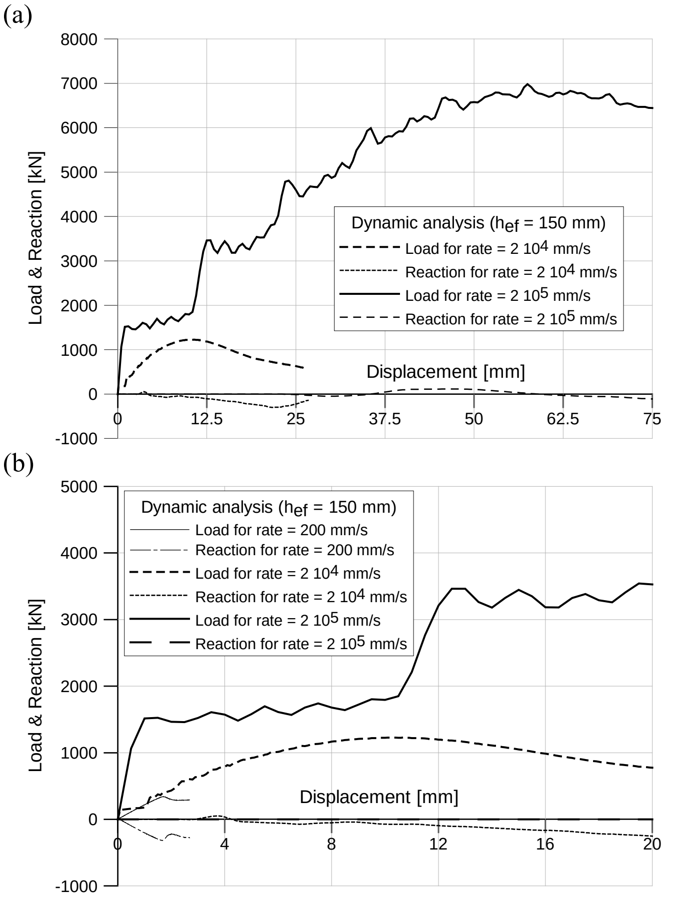

Figure 7. Dynamic analysis: calculated load (reaction) – displacement curves for $h_{ef} = 150$ mm: (a) high loading rates up to the displacement of 75 mm and (b) detail of the displacement up to 20 mm.

The predicted 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 (see Fig. 8a). However, for very high loading rates the failure mode changes and instead of concrete cone failure, the anchor fails in shear (mixed-mode, see Fig. 8b). The same tendency was also observed in the experiments (ANCHR 2001).

The relation between the relative maximum pull-out resistance and the loading rate is plotted in Figure 9 for all embedment depths. It can be seen that for relatively low and moderate loading rates the resistance increases almost as a linear function of the loading rate (lin.-log scale). 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 larger the embedment depth, the smaller is the critical loading rate at which the increase of the pull-out resistance becomes progressive. Figure 9 shows qualitatively the same relation between the resistance and the loading rate as already observed for compressive and tensile (mode-I) rate dependent failure of concrete (CEB 1988; Ožbolt and Reinhardt 2005a,b).

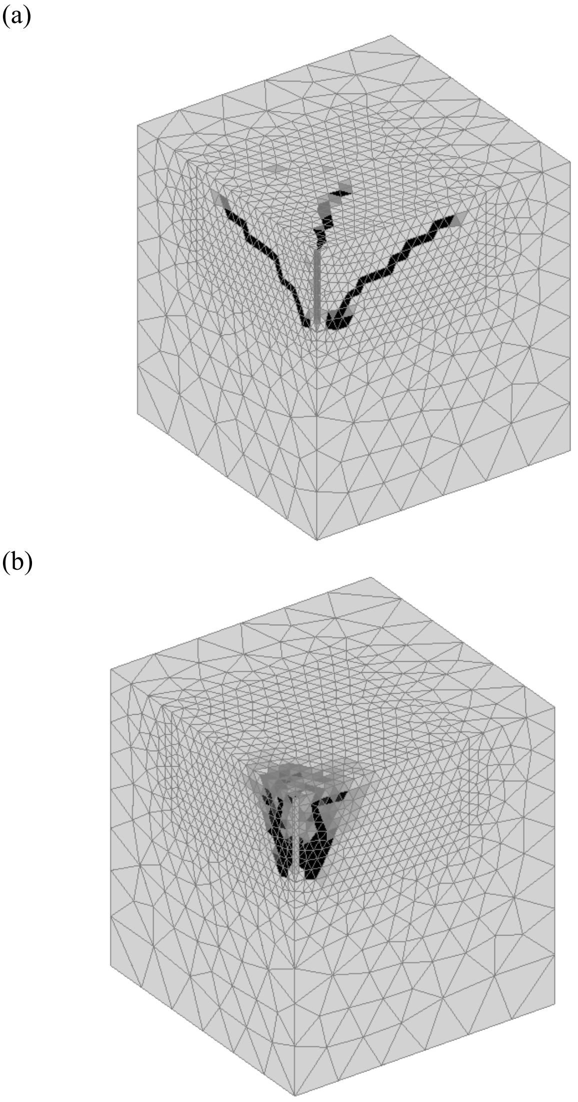

Figure 8. Dynamic analysis: calculated failure modes for $h_{ef} = 150$ mm: (a) loading rate $d\delta/dt = 200$ mm/s and (b) loading rate $d\delta/dt = 2\text{x}10^5$ mm/s.

The size effect on the nominal pull-out strength obtained in dynamic analysis is plotted in Figure 10 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 to 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 $d\delta/dt = 2\text{x}10^3$ 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 loading rates larger than $2\text{x}10^3$ mm/s the nominal strength increases with the increase of the embedment depth. This is caused by structural inertia forces, which for extremely high loading rates and large embedment depths significantly influence the pull-out resistance and failure mode.

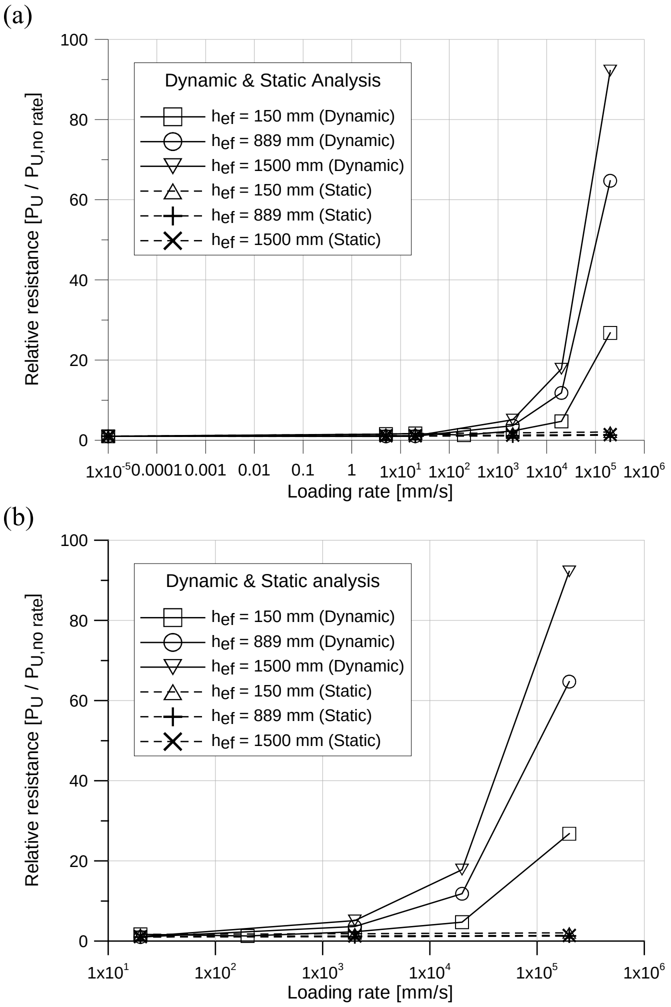

Figure 9. Dynamic analysis: influence of the loading rate on the relative pull-out resistance: (a) loading range from 10^{-5} mm/s and (b) loading range from 10 mm/s.

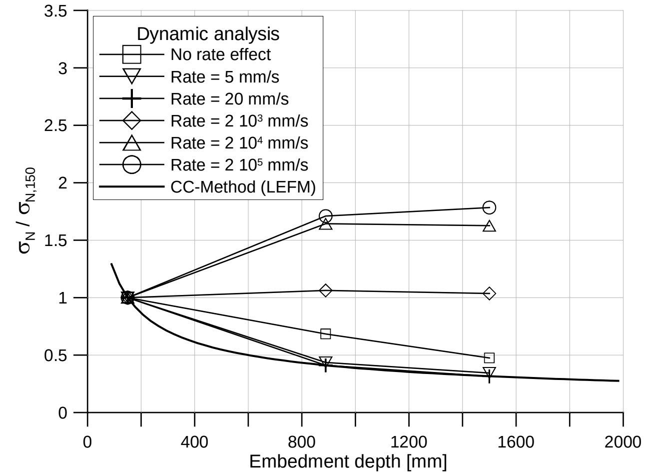

Figure 10. Size effect on the pull-out failure load as a function of the loading rate (dynamic analysis).

5 SUMMARY AND CONCLUSIONS

The rate sensitive model, which is based on the energy activation theory of bond rupture, is implemented into the M2-O microplane model for concrete. 3D FE static and dynamic analyses of headed stud anchors pulled out from a concrete block at various loading rates were carried out. Based on the results of the study the following conclusions can be drawn: (1) 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; (2) For higher loading rates there is a large difference between static and dynamic analysis. After the loading rate reaches a 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); (3) 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); (4) 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; (5) 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. For the loading rate $d\delta/dt = 2\text{x}10^3$ mm/s the size effect disappears, i.e. the nominal pull-out strength becomes almost independent of the embedment depth. For loading rates higher than $2\text{x}10^3$ mm/s there is an opposite tendency, i.e. the nominal strength increases with the increase of the embedment depth.

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