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Design Issues in the Anchorage of Safety Barriers Installed on Bridge Curbs

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Abstract

Safety barriers are generally installed using post-installed systems (typically adhesive anchors), due to their flexibility and ease of installation. However, particularly for barriers installed at the edge of bridge decks, the geometry of the curb does not always make verification straightforward for the designer. Indeed, the checks prescribed by Eurocode 2 Part 4 are often overly conservative regarding concrete failure modes (such as cone failure and splitting), even though full-scale tests typically do not reveal any critical issues. The definition of the applied loads and their distribution, the stiffness of the system, and the dynamic effects due to impact are likely the main reasons behind this discrepancy between laboratory tests and analytical verifications. This paper critically analyses the influence of these parameters on the resistance of the connection, including a comparative overview of the approaches adopted by different design codes for the definition and application of impact loads.

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Keywords: Safety barriers, post-installed systems, concrete curbs, cone failure, splitting.

1. Introduction

Post-installed anchorage systems (typically adhesive anchors) are widely adopted for the installation of road restraint systems because they offer flexibility and ease of execution. For safety barriers placed at the edge of bridge

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decks, the curb geometry and limited edge distances can make design verification challenging, particularly when the anchorage is subjected to short-duration force pulses associated with vehicle impacts. Eurocode (EN 1992-4) based checks may become overly conservative for concrete failure modes such as concrete breakout (cone failure) and splitting, even though full-scale barrier tests often do not reveal critical issues.

The discrepancy between analytical verifications and experimental evidence is plausibly influenced by: (i) the definition of impact actions and their distribution to the anchorage, (ii) the overall stiffness of the barrier–curb–anchor system, and (iii) loading-rate effects associated with impact loading.

Loading-rate effects are commonly expressed through a Dynamic Increase Factor ($DIF = N_{u,dyn} / N_{u,stat}$) or dynamic load ratio and depend on anchor type and governing failure mechanism. Rodriguez et al. (2001) reported that expansion anchors may exhibit similar or lower dynamic tensile capacity, whereas undercut, grouted and sleeve anchors showed about 30% higher resistance with cone-type failure under dynamic loading. For chemically bonded anchors, moderate dynamic increases around 1.3 have been reported at high loading rates (Sato et al., 2004), while tests governed by concrete breakout show increases in the range of about 1.25–1.67 (Solomons and Berra 2005). A broader compilation at seismic-relevant loading rates highlights that bond-governed failures show modest increases, whereas concrete-breakout failures exhibit a steeper rate sensitivity, as reported in Fig. 1 and 2 (Eligehausen et al., 2011). At very high strain rates, larger increases have been reported in numerical studies, with DIF values exceeding 3 in specific configurations (Ahmed et al., 2019; Bao et al., 2023). Overall, rate effects are configuration-dependent and closely tied to the transition between cone and bond-dominated mechanisms, as emphasized by Ozbolt et al. (2006).

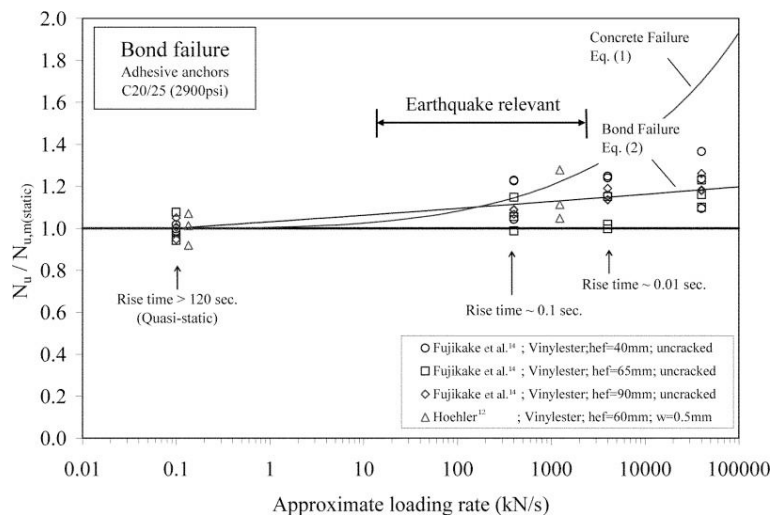


Fig. 1. Dynamic-to-static peak load ratio versus approximate loading rate for adhesive anchors failing by bond (adapted from Eligehausen et al., 2011).

Recent impact and impulse tests confirm this dependence on failure mode and boundary conditions: screw anchors tested under drop-weight loading exhibited dynamic load ratios typically around 1.1–1.6 with predominant concrete-cone breakout, Braimah et al. (2021); dynamic push-in tests on post-installed rebars governed by splitting reported much larger increases in peak load and absorbed energy at the highest loading rates (Nassr and Khair-Eldeen, 2017); and impulse loading of adhesive steel anchors showed that embedment depth and concrete strength influence both the rate sensitivity and the occurrence of failure-mode transitions (Braimah et al., 2009).

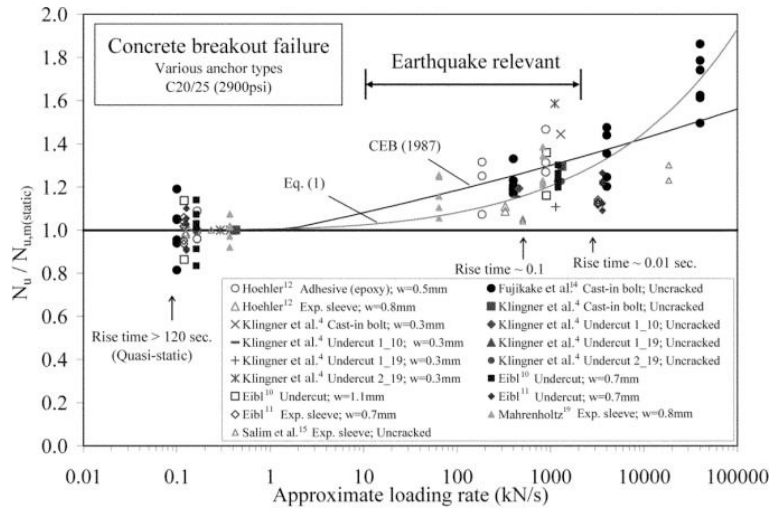


Fig. 2. Dynamic-to-static peak load ratio versus approximate loading rate for concrete-breakout failures in anchors (adapted from Eligehausen et al., 2011).

This paper presents rate dependent pull out test results for M20 adhesive anchors with a nominal embedment depth of $h_{ef} \approx 80$ mm, and examines their implications for curb edge anchorage design. A critical assessment of the governing parameters influencing connection resistance is provided, with the aim of improving understanding of both local and global effects induced by the anchorage system under dynamic loading conditions.

2. Background on loading-rate effects

The tensile resistance of anchorage systems in concrete can be sensitive to loading rate, with both the magnitude and the sign of the effect depending on anchor type and governing failure mechanism (e.g., concrete breakout versus bond-related failure). In the literature, loading-rate effects are reported using rise time, load rate (kN/s), or displacement rate (m/s), and are typically summarized through a dynamic increase factor (DIF) or dynamic load ratio.

For chemically bonded anchors and other post-installed systems failing by concrete breakout, experimental data at seismic-relevant rates generally show moderate increases (DIF $\approx 1.1 - 1.6$) (Sato et al., 2004; Solomons and Berra, 2005; Eligehausen et al., 2011), while higher strain rates can produce larger amplification in calibrated numerical models and simulations (Ahmed et al., 2019; Bao et al., 2023; Ozbolt et al., 2006). Conversely, bond-governed failures show smaller changes and may become critical as the concrete contribution increases with rate, which explains the failure-mode transitions reported in experimental compilations and parametric studies (Eligehausen et al., 2011; Mestrovic et al., 2015; Salim et al., 2005).

From a standards perspective, the ACI provisions (2023) explicitly allow for the adoption of DIF up to 1.25, depending on the loading regime, while still being associated with relatively low strain-rate levels.

Impact and impulse campaigns further underline the influence of boundary conditions: cone breakout under drop-weight impacts typically leads to modest dynamic load ratios, Braimah et al. (2021), whereas splitting-controlled configurations can exhibit much larger apparent increases in resistance and absorbed energy, Nassr and Khair-Eldeen (2017). This motivates reporting the experimental loading-rate sensitivity observed in the present M20 adhesive-anchor dataset.

3. Experimental research

To assess the effect of the strain rate on the mechanical response of bonded anchors under tensile load confined and unconfined tests were performed. All tests were performed on C20/25 concrete slabs (1.55m×1.25m×0.25m). The mix-design was selected according to EAD 0499 (2022) prescriptions, the maximum aggregate size was 20 mm.

The fasteners consisted of a 20 mm threaded rod, with an ultimate characteristic strength f_{uk} of 500 MPa and a yielding characteristic strength f_{yk} of 400 MPa. An epoxy adhesive was used as bonding agent, injected with a two components “gun” type applicator. The components were mixed through a special mixing nozzle as they were dispensed. The anchors were set and cured at ambient temperature (of about 20°C).

All holes were drilled with a 22 mm bit using a rotary hammer drill and cleaned using a stiff brush and a vacuum cleaner according to manufacturer instructions. The nominal embedment depth was equal to 4 diameters (80 mm). To assess the effect of the strain rate on the failure mode, both confined and unconfined tests were performed. Indeed, confined tests induced pull-out failure, while unconfined tests induced concrete cone failure.

Overall, 8 tests were performed, 4 confined and 4 unconfined. For each test configuration, standard tests (0.02 mm/s) and two high-rate tests (of about 22 mm/s) were performed.

The load was applied with a hydraulic jack (with a load capability of 300 kN) and the tests were displacement controlled. The jack was placed on a test frame as shown in Fig. 3. In unconfined tests, the legs of the frame are at a minimum distance of 32 cm (according to EAD0499, (2022)) while in confined tests a steel plate with a central hole is placed below the frame to confine the test. The load was monitored with a load cell and acquired with a MOOG system at 600 Hz.



Fig. 3. Test setups: on the left confined and on the right unconfined tests

4. Experimental results

Table 1 summarizes the tests results in terms of bond strength (τ) evaluated as uniform bond stress along the embedment depth (in the evaluation the actual embedment depth was considered). The mean value (τ_m) of twin specimens and the ratio between high-rate and low-rate bond strength is also reported.

The low-rate (LR) tests were performed at a displacement rate of 0.02 mm/s according to EAD prescriptions, while high-rate (HR) were performed at around 22 mm/s and 26.6 mm/s in confined and unconfined tests respectively.

Pull-out strength is higher than concrete cone failure, and in both test configurations the high-rate tests exhibited a higher strength.

It appears that the increase in resistance in the case of concrete breakout failure is higher than that observed for pull-out failure (23% vs 17%). However, although it is evident that increasing the loading rate leads to an apparent overstrength (on the order of 20% for the tested rates), no definitive conclusions can be drawn regarding the overstrength associated with one failure mode compared to another, given the limited number of tests.

Table 1- Test results

#	mm/s	Confined			mm/s	Unconfined		
		τ (MPa)	τ_m (MPa)	τ_{HR}/τ_{LR}		τ (MPa)	τ_m (MPa)	τ_{HR}/τ_{LR}
M20 HR-1	22.0	39.11	40.78	1.17	26.7	16.47	15.68	1.23
M20 HR-2	22.0	42.44			26.5	14.89		
M20 LR-1	0.02	36.05	34.98		0.02	13.02	12.80	
M20 LR-2	0.02	33.91			0.02	12.57		

Figures 2 and 3 show the load vs time and the load vs stroke (displacement of the jack) for confined and unconfined tests respectively. Pull-out failure (Fig. 4) seems to be less brittle than cone breakout (Fig. 5). However, it seems that at high-rate pull-out failure is more brittle than in the low rate tests.

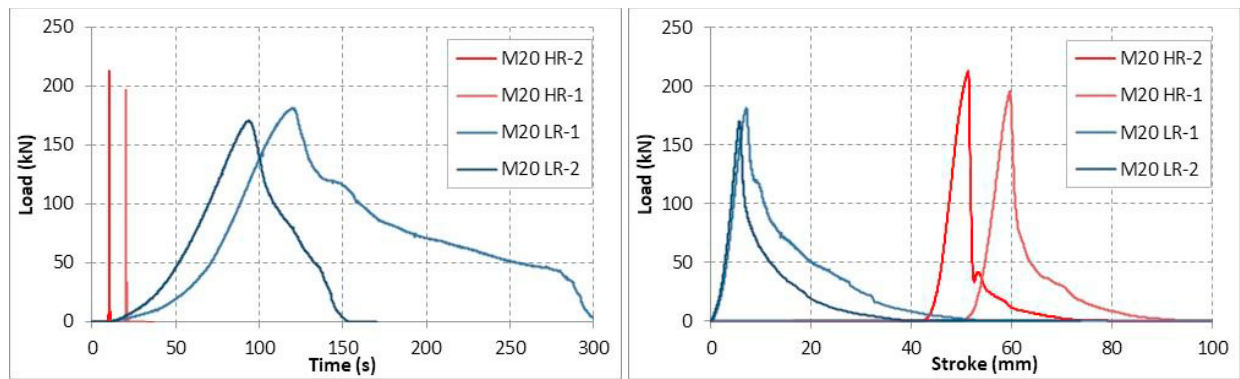


Fig. 4. Pull-out tests (Confined) - Load vs time and load vs stroke

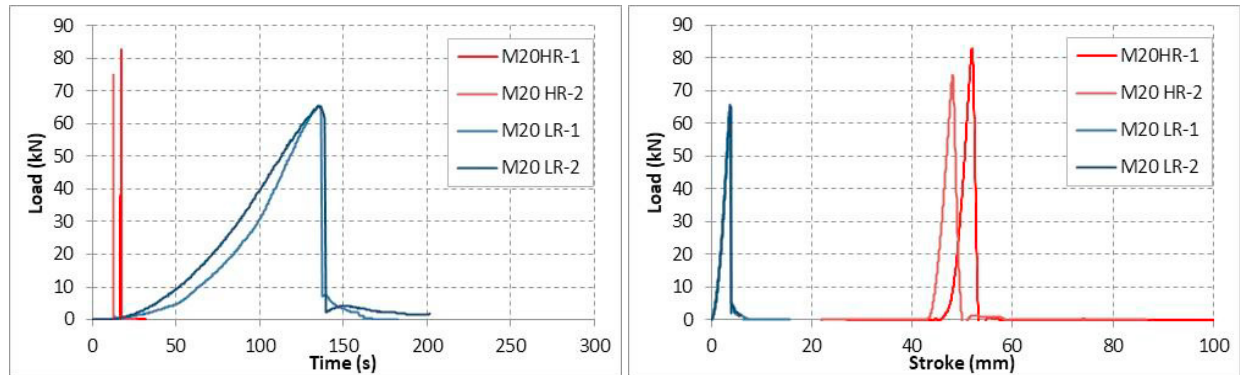


Fig. 5. Tensile tests (Unconfined) - Load vs time and load vs stroke

As expected, confined tests exhibited pull-out failure while unconfined tests showed concrete cone failure (Fig. 6). No clear differences in the failure modes were observed between low and high-rate tests.



Fig. 6. Confined and unconfined failure modes

5. Design code context and practical recommendations

Based on the regulatory framework outlined above, the following practical points are recommended when designing safety-barrier anchorages on bridge curbs, especially where Eurocode-based checks appear conservative:

- Use EN 1992-4 as the reference for resistance verification of fastenings (steel failure, pull-out/bond, concrete cone, splitting, and edge-related failures), and document the assumed concrete condition (cracked/non-cracked) and governing failure mode.
- Ensure the selected product is covered by an ETA for the relevant service conditions; use the characteristic resistances and application limits from the ETA/EAD documentation [16].
- Define the barrier performance and containment level with reference to EN 1317, and state how the corresponding design actions are derived (test-based values vs. code-prescribed equivalent static forces).
- For impact and accidental design situations, align action models with EN 1991-2 and the National Annex; explicitly state load application points and distribution to posts/anchors.
- For curb-edge baseplates and anchor groups, justify the assumed load distribution (rigid vs. deformable fixture) and, where possible, support it with stiffness considerations or conservative bounds (upper/lower).
- When interpreting impact scenarios, treat loading-rate effects as configuration-dependent; if dynamic increases are considered, justify them with test evidence (as in previous section) and avoid unconservative blanket amplification.

6. Discussion

The observed loading-rate sensitivity ($\tau_{HR}/\tau_{LR} = 1.17\text{--}1.23$) supports the hypothesis that dynamic effects can contribute to the discrepancy between conservative analytical verifications and non-critical experimental evidence in curb-edge barrier anchorage. Because rate effects depend on anchor system and govern failure mechanism, experimental characterization should be used to justify any dynamic increase factor or to motivate conservative design choices.

Additionally, the way impact actions are defined and distributed to posts and anchors in design codes is expected to strongly influence the predicted demand on individual anchors in curb-edge configurations.

7. Conclusions

Following a brief review of the relevant literature and the execution of a targeted experimental investigation, this study has shown that, for the examined anchorage configurations ($h_{ef} \approx 80$ mm), an increase in loading rate results in higher average bond stress at failure, τ_m , for both M20 test series.

The observed dynamic increase factors, $\tau_{HR}/\tau_{LR} = 1.17$ for confined configuration and 1.23 for unconfined configuration, confirm the presence of a not negligible rate effect.

Post-test visual inspection consistently revealed concrete cone-type breakout as the governing failure mechanism in unconfined tests. Although limited in scope, the results highlight the relevance of loading rate effects in anchorage behaviour and suggest that such effects, together with appropriate impact load modelling, should be considered in curb-edge barrier anchorage design when reconciling analytical predictions with full-scale experimental evidence.

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