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Seismic behaviour of post-installed anchors in concrete – A case study

Σεισμική συμπεριφορά αγκυρίων στο σκυρόδεμα – Μελέτη περίπτωσης

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ABSTRACT: Post-installed concrete anchors are applied for the fixture of structural components (column – beam connections, steel column foundations) and non-structural components like facade elements, suspended ceilings and electrical equipment. They play a significant role regarding the operability of eminent buildings like hospitals and nuclear power plants during and after an earthquake. Hence the anchors are expected to transfer reliably cyclic seismic actions between steel and concrete. Additionally, many seismic retrofitting techniques would not be possible without the use of post-installed anchors.
Realistic seismic conditions have been simulated in a MDOF shake table test with different types of anchors in cracked concrete. The findings about the behaviour of the anchors under seismic conditions can be used to calculate the resistance of the fastening between existing structures and additional retrofitting elements.

ΠΕΡΙΛΗΨΗ : Τα αγκύρια στο σκυρόδεμα τοποθετούνται είτε για τη σύνδεση δομικών στοιχείων (ενώσεις δοκών – υποστυλωμάτων, θεμελιώσεις μεταλλικών κατασκευών), είτε για τη στερέωση μη δομικών στοιχείων στο σκυρόδεμα (προσόψεων, ψευδοροφών, ηλεκτρολογικού εξοπλισμού). Παίζουν πολύ σημαντικό ρόλο όσον αφορά τη λειτουργία κτιρίων μεγάλης σημασίας, όπως νοσοκομείων και σταθμών πυρηνικής ενέργειας, μετά από ένα σεισμό και κατά την εξέλιξή του. Επίσης, πολλές εφαρμογές αντισεισμικής επισκευής και ενίσχυσης δε θα ήταν δυνατές χωρίς τη χρήση αγκυρίων.
Συνθήκες σεισμικής διέγερσης σε MDOF σεισμική τράπεζα για διάφορους τύπους αγκυρίων σε ρηγματωμένο σκυρόδεμα έχουν προσομοιωθεί ρεαλιστικά. Τα ευρήματα των πειραμάτων σχετικά με τη σεισμική απόκριση των αγκυρίων μπορούν να χρησιμοποιηθούν για τον υπολογισμό της φέρουσας ικανότητας της σύνδεσης μεταξύ υφιστάμενων κατασκευών και πρόσθετων στοιχείων στις αντισεισμικές επεμβάσεις.

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INTRODUCTION

Post installed metal anchors met a broad development in the recent years, in the field of research as well as in practice. Some practical applications of metal anchors are present in a wide range of techniques of seismic retrofitting of reinforced concrete structures. On the other hand, performance of anchors under seismic actions is currently a crucial topic of research. In the present study, an experimental investigation on the seismic behaviour of anchors is presented. Furthermore, based on this investigation, together with current codes and literature, an application of seismic retrofitting is proposed, while particular aspects of the seismic behaviour of anchors are pointed out.

SHAKE TABLE TESTS

Current testing guidelines (ACI 2004) consist of cyclic testing of the fixture that is subjected to a load history consisting of a number of repeated cycles of increasing load amplitude that first characterize the response in the elastic range and then take the anchor in the inelastic range. Typical tests are conducted unidirectional in shear and tension. The advantage is the simple test procedure, but the amplitude of the cyclic loads is set rather arbitrarily. According to ACI standard the application of post-installed anchors is limited outside of plastic hinges.

In order to represent more realistic seismic conditions various anchor types M12 with existing ETA and similar static resistance have been tested on the 3-axial shake table in the laboratory of ISMES in Italy (BG). At first fine hair cracks were opened by hammering in steel wedges with sleeves in the tubes according to fig.1, then the anchors were installed in the cracks, loaded with the steel weights and prestressed with the prescribed torque. The hole clearance between attached steel plate and anchor was 2 mm. In order to simulate the long time loss of prestressing force, after 10 minutes the torque was reduced by the half and the cracks were opened until a width of 1.5 mm. This large crack width is expected to simulate the damage of concrete in the post-yielding range during a strong earthquake. The special geometry of the sleeves enabled the opening of cracks exhibiting a constant width throughout the whole depth of the concrete member of the strength class C20/25. The concrete specimen acting as a wall was attached rigidly to the shake table (fig. 2). Within this test arrangement the anchor is loaded by an axial load N_x and a shear load V_{yz} dependent on the dimensions a and h and on the seismic input (fig. 3).
A sine sweep test yielded a significant amplification of the steel masses only at frequencies beyond 35 Hz, hence the system may be considered as stiff. The input signal for the ground acceleration was in accordance with the IEEE 693 standard (1997) which is commonly used for seismic qualification tests of electrical equipment. It consists of three incoherent synthesized signals with peak acceleration of 0.5 g in x- and y- direction and 0.4 g in z-direction, a frequency content between 1.2 Hz and 37 Hz, a duration of 32 seconds and a damping of 2%.

The dimension of the steel masses was determined by a simplified calculation according to the CEN TS draft (2004) and using the static resistance of the anchors with reduced partial safety factor γ_{Mc} = 1.7[1] for pullout failure and γ_F = 1.0 for the action side. The interaction was verified using the approach of Mesureur (2004) and lead to a total mass of 300 kg per anchor. Starting at 1/8 of the nominal level the amplitude was increased and the whole ground acceleration was again imposed to the structure. This procedure was repeated until large deformations or failure of the anchors occurred. The acceleration of the steel masses was measured by 3-d piezoelectric accelerometers and the axial and vertical displacement of the anchors by LVDTs.

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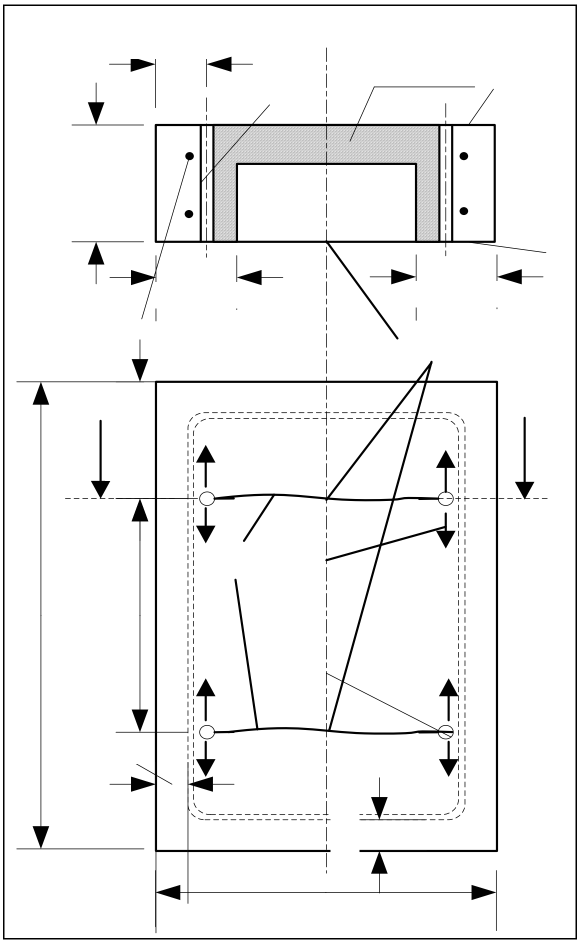

Figure 1: Cracked concrete test specimen

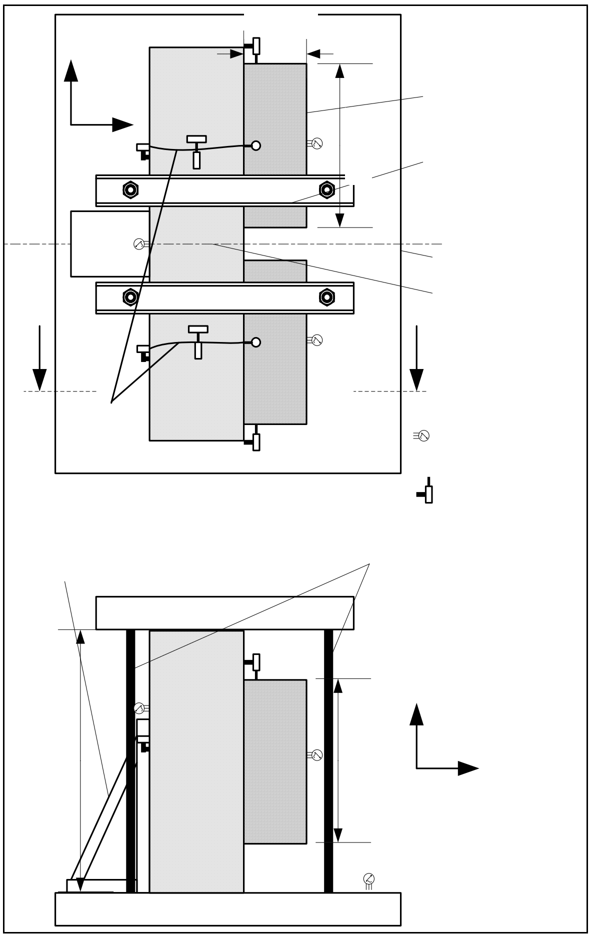

Figure 2: Test setup

RESULTS AND ANALYSIS

In fig. 4 the plastic deformation of the different anchor types in axial and vertical (z-) direction are plotted as a function of the seismic level. Both axial and vertical displacements are the highest for the bonded anchor and the lowest for the undercut anchor at each seismic level.

[1] At the time of test planning the partial safety factor for concrete failure according ETAG 001 was γ_{Mc} = 1.8

A-A

120mm.

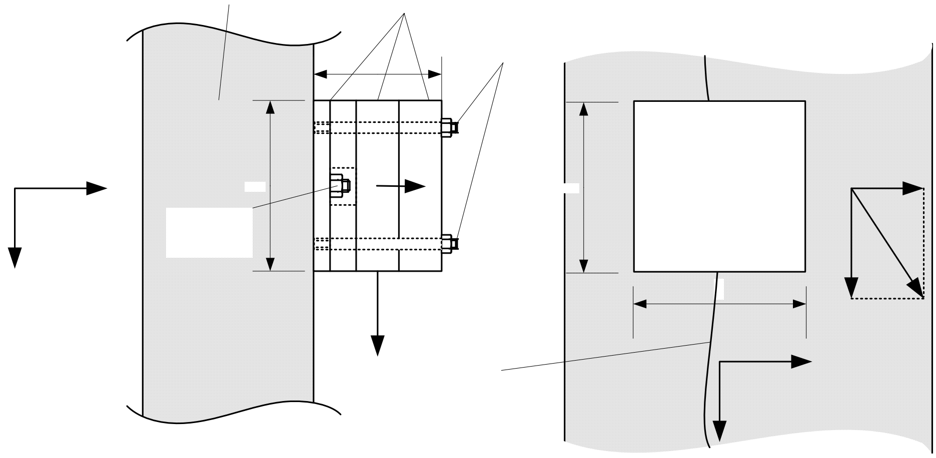

Figure 3. Loads on the anchor

The undercut anchor and the expansion anchor failed by superficial concrete crushing and subsequent bending of the anchor bolt and shear deformations up to 20 mm at 1100% resp. 800% of the design peak ground acceleration α_{nom}. For the undercut anchor the damage of concrete seems to be decisive for the bending effect, since a dust cloud could be observed immediately after failure. The failure mode of the bonded anchor was complete pullout at 800% of α_{nom}.

The various parameters for determining the action forces (z/h, T_a/T_1) were chosen rather conservative and therefore the measured amplification on the steel blocks compared to the ground motion is much less than the calculated value in compliance with CEN, resulting in very high seismic level at failure. Nevertheless the proposed value for the behaviour factor q_a, which is a measure for the ductility, seems to be on the safe side in the draft of CEN TS.

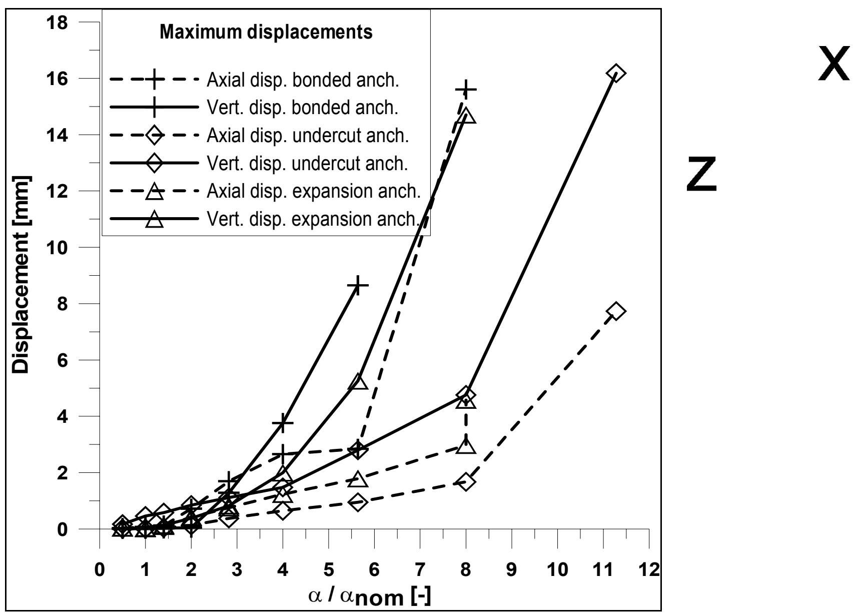

Figure 4. Plastic displacements of anchors

Since the deformation represents a cumulative damage due to increasing seismic intensity you may assume that the real resistance of the anchors is higher but it can't be determined from this test results. The main conclusion from the tests is more comparative, i. e. the difference between the various anchor types: the bonded anchor exhibits a higher susceptibility with respect to seismic loading in strongly damaged concrete (1.5 mm wide cracks) than the expansion and undercut anchor. This means that in case of very strong earthquakes expansion and undercut anchor systems may show enhanced reliability. However, within this context it should be noticed that crack widths of 1.5 mm are very unlikely to occur out of plastic hinges and therefore the test results are quite conservative.

An interesting feature could be observed: one undercut anchor suffered practically no damage during the whole tests. The reason was crack branching so that at the position of the anchor the crack width reached only about 0.5 mm. This result is a clear indication, that the seismic performance of anchors is crucially influenced by the degree of damage of the concrete. Current proposals (Hoehler et al. 2008) assume 0.8 mm wide cracks outside of plastic hinges and therefore further investigations with other crack widths are necessary.

In any case, the test results described above and the ones presented by Hoehler (2008) agree on the very good seismic performance of undercut anchors in terms of maximum displacements. Furthermore, the latter one indicates also high values for the residual axial capacity of this type of anchors among other types of post – installed anchors.

APPLICATION FOR SEISMIC RETROFITTING

Based on the encouraging performance of post – installed anchors with existing ETA in the shake table tests, a proposal for seismic application is given in this paper. Metal anchors are used for a wide range of techniques of seismic retrofitting of reinforced concrete structures. One of the main applications is internal steel bracing of frames, usually in an X – arrangement (Fig 5), that can mainly increase stiffness and occasionally bearing capacity and ductility of a structure.

Usually in practice bracing is applied to concrete indirectly through a steel frame fitted to the concrete one, but there are also proposals to connect steel braces directly on the concrete members through cast in place metal anchors (Maheri 2003). In the following, a connection with post – installed anchors is investigated, since it would be an attractive selection due to the ease of construction, the low total cost and the potential of replacement of the strengthening elements.

In any case, safe load transfer between steel and concrete members is a crucial part of the design. Consequently, the load transfer mechanism and so the type of anchor plays a very important role. On the basis of the above described shake table tests and also according to other authors (Hoehler et al. 2008) this demand might be fulfilled in a proper way by the use of post-installed undercut anchors. This is due to the fact that the plastic deformation of the anchor in case of overloading and hence the slackness between the steel braces and concrete is minimized with the undercut anchor. At the same time, it is indicated that the bearing capacity of this anchor type under cycling load is nearly equivalent to the one for monotonic load. As a consequence the continuous flow of seismic forces and the stiffness of the system will be guaranteed.

A possible connection of steel braces to concrete is described as follows: The brace is joined to a gusset, which in turn is welded to two (beam/column) connecting plates. The connecting plates are then fastened to the frame members using post – installed anchors (figure 6). The present study aims to investigate the use of post – installed anchors in such a connection also regarding their response to seismic loads.

For the design of a fastening, procedures are provided by different organizations. “ETAG 001 - Guideline for European Technical Approval of Metal Anchors for Use in Concrete – Appendix C” published by the European Organization for Technical Approvals (EOTA) is recently edited and quite representative of the current trends in the design of anchorages. However, in ETAG 001, no specific provisions for the design under seismic actions apply.

An illustrative case for the design of a fastening between a reinforced concrete frame and a steel X – bracing is presented below. Focal point of this study is the evaluation of the applicability of the connection with post installed anchors and the detailing of the fastening according to ETAG 001 with references to other codes and recent literature. For the structural analysis of this retrofitting intervention, an elastic analysis for a linear model, loaded with quasi – static seismic loads is employed in order to simply estimate a representative load that acts on the fastening.

Configuration of the analyzed structural system

The analysed structure is presented in figure 5. For the considered seismic action, design spectrum is $\Phi_d(T) = 0{,}225 \cdot g$, for q=4 (behavior factor) and A= $0{,}36 \cdot g$ (design ground acceleration). For this seismic action and structure, shear base V_0 = 299,25 kN is calculated and is triangularly distributed. In order to fulfill the requirements against buckling, optimal steel profiles to be used in this application are hollow, wide flange (H) or double angle (L) cross sections. The used profile is a hot formed square section QHR 60x4. The buckling length is limited by a joint connecting the braces at their center. Criterion of the solution is that the interstorey drift γ is kept below 5 ‰ (maximum horizontal storey displacement of 9,375 mm). In compliance with that, the diagonal has to transfer a maximum tension load of S_{sd} = 66,0 kN (utilization ratio n = 0,35), which was also taken as the axial load for the check against buckling (utilization ratio n = 0,80).

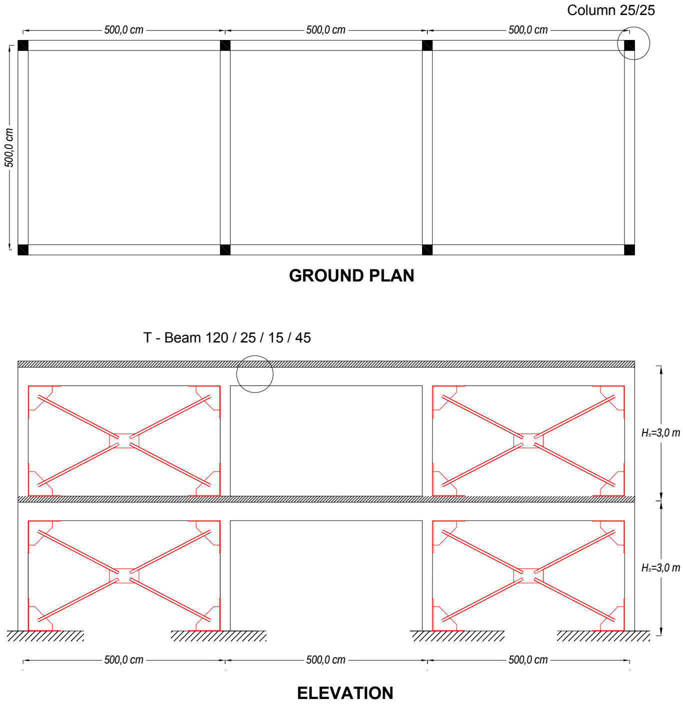

Figure 5. Configuration of the analyzed RC Structure retrofitted by use of steel X-Braces

Critical aspects of the problem

Anchor behaviour under seismic actions is characterised by uncertainty and thus some design principles are applied. Current codes suggest either to avoid overstressing or to pursue ductile (steel) failure of the anchorage. Overstressing is usually avoided by designing the anchorage for loads greater than the ultimate strength of the attached element. In many cases, however, buckling of the compression members is by far predominant and design of the braces is depended on buckling check. This effectively means that the ultimate strength of the diagonal of the brace under tension is much higher than the buckling resistance of the compressed diagonal; consequently capacity design of the anchors based on this ultimate tensile strength can be very demanding. On the other hand, brittle concrete failure modes are inevitable due to small dimensions of the concrete members. Therefore, a proper failure mechanism (e.g. local weakening) between anchors and braces should be provided. In the following, this measure is presumed.

Another requirement of current codes is to not use anchors in plastic hinge regions of concrete members. In the present study, this provision is covered by assuming cracked concrete at the anchorage and strengthening of the RC joint by the connecting plates as well. Apart from that, this retrofitting technique drastically reduces the expected moments on the joints of the frame and thus the formation of plastic hinges.

Detailing of the fastening

Details of the connection are shown in figure 6. Constructional dimensions and particularly the distances of the anchors from each other (s) and the member's edges (c) have a great influence on the fastening's capacity (ETAG 001). Especially in this application where dimensional margins are tight, the arrangement of anchors plays an important role. Generally, distances (s) and (c) was tried to be as big as possible so that each anchor's capacity is less diminished. Furthermore, the anchor's diameter must be selected in a way that the corresponding minimum allowed distances (s_{min}) and (c_{min}) according to each product's approval are not exceeded. Selection of the anchor's type is also affected by the forementioned values. Arranging the anchors should take into account the installation demands: for a usual ratchet wrench, a distance of approx. 30 mm from a nearby lateral surface (gusset) should be provided. The fastening's capacity, mostly in tension loading, is highly influenced by the anchors' embedment depth (h_{ef}) as well. The selection was M12 undercut anchors, with h_{ef} = 80 mm. The spacing of the anchors in the longitudinal member's direction were chosen s = 3· h_{ef} = 240 mm. Anchors placed in this distance do not influence each other and can be calculated separately. Anchors with spacing s = 70 mm have a reduced capacity and must be calculated as a group. So, the connection can be considered as 8 independent groups of anchors. Undercut and chemical anchors employ generally shorter spacing than other types of anchors. Furthermore, only special types of chemical anchors are approved for use in cracked concrete. Finally, abovementioned investigations taken into consideration, undercut anchors should be selected for this case.

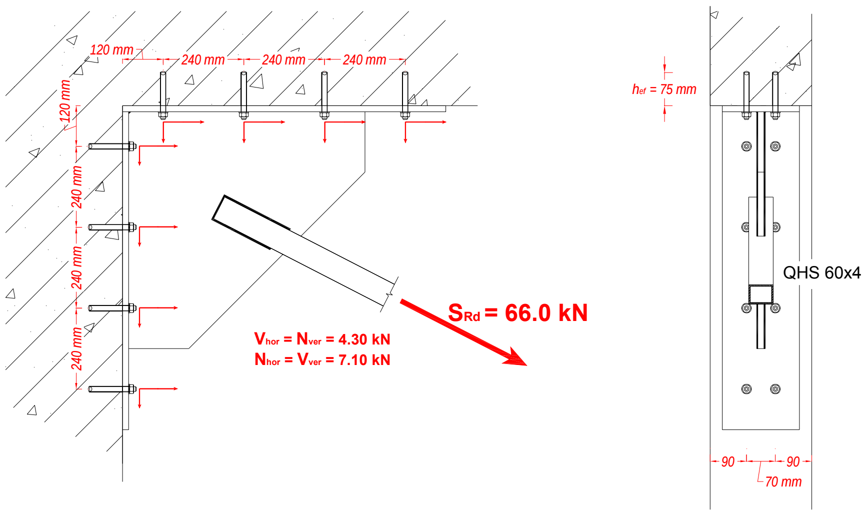

Figure 6. Representation of the proposed Brace – Concrete Frame connection. The load of the steel brace as well as the distribution of the loads to each anchor are also noted

Design of the fastening between steel and concrete

For each group the following checks should be conducted (table 1). Material safety factors for concrete related failure are considered γ_{Mc} = 1,50. Concrete's class is considered C16/20 and cracked concrete according to the provisions of ETAG 001 (w = 0.5 mm) is assumed.

Table 1. Checks to be conducted

Failure Type	Tension Loads
Steel	$N_{Sd}^{h} \leq N_{Rd,s}$
Pull-Out	$N_{Sd}^{h} \leq N_{Rd,p}$
Concrete Cone	$N_{Sd}^{g} \leq N_{Rd,c}$
Splitting	$N_{Sd}^{g} \leq N_{Rd,sp}$
	Shear Loads
Steel	$V_{Sd}^{h} \leq V_{Rd,s}$
Concrete Pry-Out	$V_{Sd}^{g} \leq V_{Rd,cp}$
Concrete Edge	$V_{Sd}^{g} \leq V_{Rd,c}$

Afterwards, the combined tension – shear resistance should be checked according to the equation:

$$(\beta_N)^a + (\beta_V)^a \leq 1$$

with a = 1.0 on the safe side, while ETAG 001 and other relative codes suggest higher values. β_N and β_V are the ratios between design action and design resistance. Literature suggests that these factors are also held below 0.8, in order to cover installation discrepancies.

Superscript (^{h}) refers to design values of loads acting on a single anchor and superscript (^{g}) refers to resultants of loads acting on an anchor group (noted in figure 6), while the resistance design values are calculated respectively. It should also be mentioned that the ETAG 001 does not cover the design for concrete class lower than C20/25 and, where needed, an approximation was made by multiplication of concrete related resistances with the factor:

$$k = \sqrt{\frac{f_{ck,i}}{f_{ck,25}}}$$

Finally, all resistance values have been reduced by 25% as a safety provision for seismic actions as suggested in literature.

In table 2, the design resistance values, the corresponding β – ratio and the fulfilment of the requirements are presented. As seen in this table, for the particular set of anchors, concrete – related failure instead of steel failure is predominant. This is consequent to small concrete member's dimensions, so limited edge distances (c), which means that requirements for ductile - steel failure are unlikely to be fulfilled. Therefore, failure of the anchorage must be avoided by certain measures as mentioned above. Additionally, resistance of the anchors is considered reduced due to seismic loads, while interaction between shear and axial forces needs to be considered.

Table 2. Design resistance values and utilization ratios

Failure Type	Tension Loads		
	N_{rd}	β_N - $N_{horizontal}$	β_N - $N_{vertical}$
Steel (single anchor)	22.93	0.154	0.094
Pull-Out (single anchor)	16.67	0.218	0.133
Concrete Cone (anchor group)	16.26	0.568	0.344
Splitting (anchor group)	16.26	0.568	0.344
	Shear Loads		
	V_{Rd}	β_V - $V_{horizontal}$	β_V - $V_{vertical}$
Steel (single anchor)	26.96	0.119	0.197
Concrete Pry-Out (anchor group)	32.52	0.198	0.328
Concrete Edge (anchor group)	77,32	0.056	0.092
Max. Tension – Shear Interaction: $(\beta_N)^1 + (\beta_V)^1 \leq 1$		0.766	0.672

CONCLUSIVE REMARKS

Design of a direct connection of a steel X brace to a concrete frame by use of post installed anchors must take into consideration a lot of details and extensive safety measures. A main reason for that is the lack of precise knowledge on the response of post – installed anchors to seismic loads which is currently one of the most challenging questions in the research area of fastenings. Still, particular conclusions are so far derived up to time from research in the Institute of Structural Engineering, from recent literature and from design provisions and technical approvals: First of all, post installed anchors have a very good response to seismic loading. Next to that, the proposed fastening for seismic retrofitting can be considered as a feasible application. Finally, it should be mentioned that undercut anchors demonstrate a sufficiently better performance in comparison to other systems and are mostly recommended for seismic applications such as the retrofitting of structures.

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