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SESIMIC RESPOSE OF THREE TYPES OF POST-INSTALLED ANCHORS IN CONCRETE

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ABSTRACT:
Seventy two specimens were tested under simulated seismic tension, direct shear or combined tension and shear to study their deformations and strength. The anchors comprised post-installed undercut expansion, screw and sleeve expansion types embedded in uncracked concrete. The number and pattern of load cycles followed the ACI recommendations and the ratios of the maximum applied load to the subsequent reduced loads were maintained as recommended by ACI, but the maximum amplitude of each type of load was either 50% or 75% of the relevant static capacity of the anchor. The results of the test show that generally the anchors could sustain the above cyclic load levels without failure, with only one exception, i.e. when subjected to direct shear load equal to 75% of the static shear capacity of the anchor. In the latter case, irrespective of the type of anchor, all the anchors failed within the first 8 load cycles. In each case failure was essentially due to fatigue and this was the only loading case in which full load reversal occurred. In the other cases the anchor residual strength was sometimes higher and sometimes lower than its corresponding static capacity.

1. INTRODUCTION

Many types of anchors exist, and they are classified as pre- or post-installed. A post-installed anchor is placed in a hole drilled into hardened concrete and it includes adhesive, screw, undercut and expansion types (Eligehausen et al. 2006). The objective of this study is to test three types of anchors under simulated seismic load in order to determine their load-deformation characteristics and ultimate capacity. Each of the tested anchors is qualified for seismic applications by its manufacturer. The American Concrete Institute (ACI) Committee 355 in its report, viz. ACI 355.2-04 (ACI 2004), specifies the procedures for pre-qualification of post-installed mechanical anchors in concrete, including their qualification for seismic applications. However, the procedure is not intended to determine the actual ultimate capacity of an anchor nor its load-deformation characteristics. Furthermore, ACI recommends that the anchor tests be performed in cracked concrete because some tests have shown (Zhang 1997, Kim et al. 2004) anchors to have lower capacity in cracked versus uncracked concrete and in practice concrete is normally cracked due to applied/environmental loads, drilling operation or seismic forces. However, other tests (Rodriguez et al. 2001) have shown that some types of anchors in cracked concrete can have higher capacity under ramp-type dynamic load versus static load. The latter investigators noted that if an anchor were subjected to a pulse-type load with amplitude lower than the static failure capacity of the anchor, it would not fail under low cycle fatigue and this was the reason for their selection of the ramp-type load. On the other hand, Kim et al. (2004) applied the simulated seismic load specified in ACI 355.2-04 to sleeve type anchors and subsequently tested them monotonically to failure to find their residual capacity. They observed that in tension the residual capacity was higher than the static capacity while in shear it was nearly equal to the static capacity. Thus, it was concluded that the simulated seismic load had no deleterious effect on the capacity of the anchors. Since the maximum amplitude of the ACI simulated seismic loading is only 50% of the mean tension or shear capacity of the anchor based on static tests in cracked concrete, this loading is somewhat low and may not be representative of actual seismic loads to which an anchor may be subjected. Hence, in this study the basic load pattern of the ACI was retained, but the amplitude of the load was varied, and the effect of the load amplitude on the anchor capacity was investigated. The results of this study can be used to derive a capacity reduction factor under seismic loads as function of the maximum amplitude of the seismic load. Although the current tests were performed in uncracked concrete, it is recommended that the effect of crack be separately addressed by performing similar tests in cracked concrete.

2. TEST PROGRAM

2.1. Test specimens and Materials

Three types of anchors were tested, namely screw, undercut expansion and sleeve expansion, designated as SA, UE and SE, respectively, and as illustrated in Fig.1.

Figure 1 (a) Screw (SA) , (b) Sleeve Expansion (SE), (c) Undercut Expansion (UE)

They were all made of high strength carbon steel with nominal diameter of 9.5 mm, with embedment depth of 51 mm, 41 mm and 38 mm for the SA, EU and SE anchor, respectively. These embedment depths correspond to the minimum embedment recommended by the anchors manufacturer. They were installed in reinforced concrete cylinders with a 250 mm diameter and 350 mm height. The average 28 day compressive strength of the concrete was approximately 32 MPa.

3. TEST SET-UP AND LOADING

3.1. Test set-up

As stated earlier, the anchors were embedded in concrete cylinders. To fix the cylinders to the loading frame during the test, two threaded rods were embedded in each concrete cylinder as illustrated in Fig. 2. The anchors were tested under either tension, combined shear and tension, henceforth referred to as combined loading, or under direct shear, as illustrated in Fig.2 (a), (b) and (c) respectively. The combined load was applied vertically to an anchor installed perpendicular to an inclined plane whose normal made an angle of 30^{o} with the vertical, Fig. 2(b). Since a 30^{o} inclined plane was used, the axial tension to shear ratio was approximately 1.73. This ratio is to some extent arbitrary, but no single ratio can represent all possible shear and tension combinations. In the future, tests with different ratios could be performed to determine the tension-shear interaction diagram. Note that during the test, the anchor was always gripped very close to the concrete surface in order to minimize bending of the anchor rod. The direct shear load was applied as in Fig. 2(c) using a steel plate.

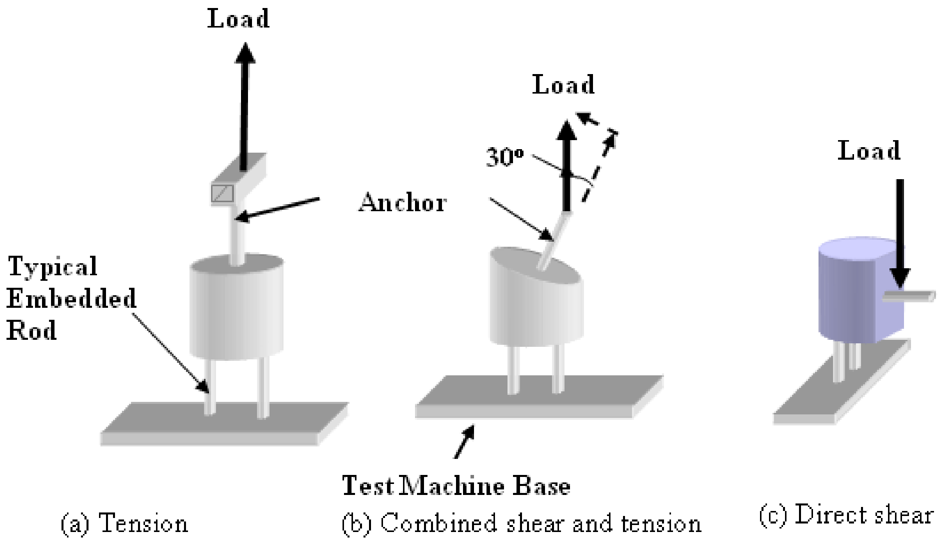


Figure 2 Typical test set-up and applied loadings

3.2. Simulated Seismic Load

The simulated seismic load is basically the same as recommended by ACI 355.2-04 and other standards organizations. For the tension and for the combined loading tests it is a pulsating load, Fig. 3(a), while for

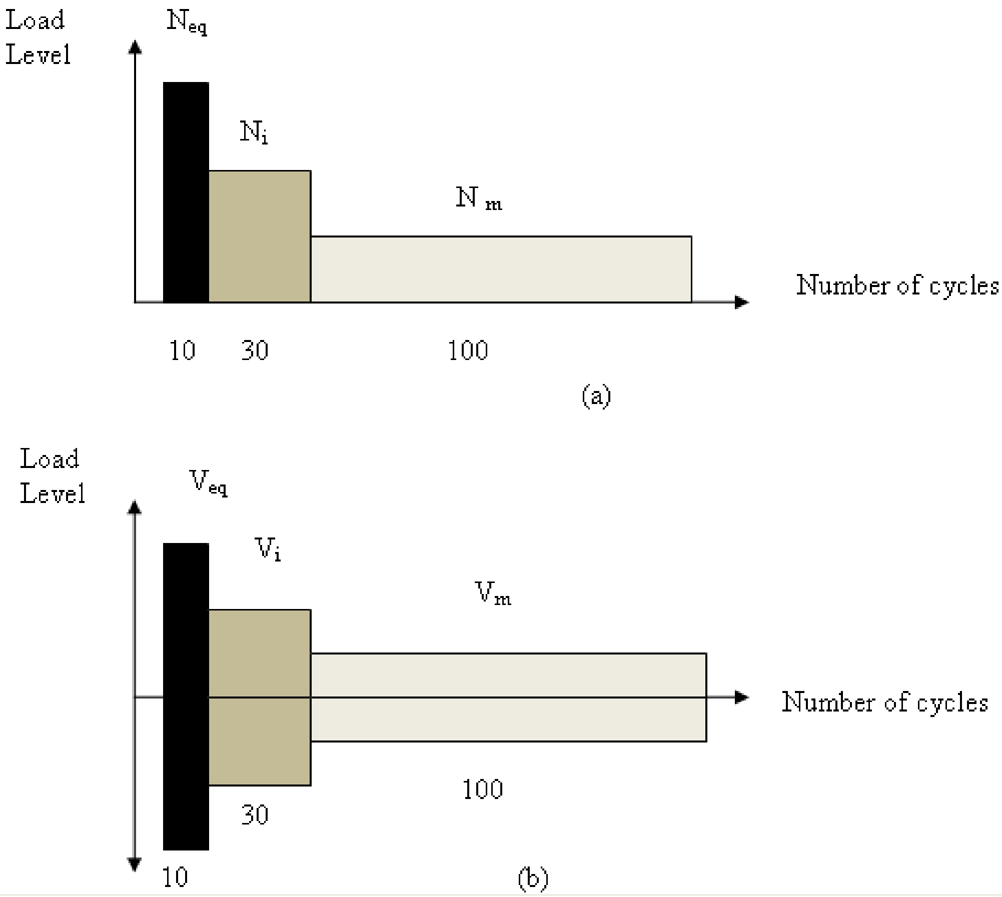


Figure 3 Cyclic loading profile for (a) Tension or combined tension and shear tests, (b) Direct shear tests

direct shear it is a cyclic load as in Fig. 3(b). The number of cycles for each load level is shown on the horizontal axis in Fig. 3 while the amplitudes of the three load levels are $N_{eq}(V_{eq})$ = maximum applied tension (shear) load, equal to 50% or 75% of the mean tension (shear) capacity obtained from monotonic static tests; $N_m(V_m) = N_{eq}(V_{eq})/4$; $N_i = (N_m + N_{eq})/2$; $V_i = (V_m + V_{eq})/2$. Using 75% of the mean static strength is more severe than the 50% specified in the ACI 355.2-04, but our objective is to obtain the anchors response under strong seismic excitations. Hence, in the current testing program, for each anchor type first monotonic static tests were performed on three repeat specimens under each loading condition to determine its average strength based on results of the three repeat specimens. Subsequently, either 50% or 75% of the relevant static value was applied as the maximum amplitude of the cyclic and pulsating loads. Note that all tests, including our reference static tests, were performed using uncracked concrete. In summary a total of 72 specimens were tested.

4. TEST RESULTS AND DISCUSSION

The average failure load of three replicate specimens for each anchor type is given in Table 1. It should be stated that some specimens subjected to pulsating or cyclic loading failed before the completion of the full 140 cycles shown in Fig. 2. For those that did not fail, their residual strength was found by testing them to failure under monotonically increasing load.

4.1. Static test

For the three anchor types, typical anchor tensile force-axial displacement, anchor shear force-lateral displacement (slip), and for combined loading anchor resultant force-resultant displacement graphs are shown in Fig. 4(a) , (b) and (c), respectively. The three repeat specimens for each anchor type loaded in tension showed similar results, generally with less than 10% difference among their ultimate capacities. On the other hand, when subjected to direct shear, the SA anchor specimens exhibited difference of up to 50% among the replicate specimens while the SE and UE anchors exhibited more consistent results, with a maximum difference of less than 10% among the capacities of the three specimens. Furthermore, the average tensile and shear capacity of each anchor type was greater, by at least 10%, and in some cases by more than 40%, than the suggested value of the manufacturer. For combined shear and tension, similar results were obtained but the UE anchor strengths exhibited the largest inter-specimen variability. Measured strengths under combined tension and shear were significantly (up to 48%) less than predicted by the following interaction equation suggested in Hilti (2005)

$$\left(\frac{N_c}{N}\right)^{\frac{5}{3}} + \left(\frac{V_c}{V}\right)^{\frac{5}{3}} = 1 \qquad (4.1)$$

where N and V are the pure tensile and pure shear capacity of the anchor, respectively, and N_c and V_c are the corresponding capacities under combined action. If a linear interaction relationship were to be assumed, i.e. assuming the power in Eqn.4.1 to be 1.0, in no case would the predicted strength be more than 15% greater than the measured strength. Hence, Eqn. 4.1 requires further scrutiny.

4.2. Simulated seismic tests

Figure 5 shows some typical loading profiles and load-displacement curves captured for the specimens tested. Note that the loading profiles are those recorded by the testing machine and they match reasonably well the input profile. The large force at the end of a loading profile represents the residual strength of the anchor and signifies that the specimen sustained the simulated seismic load without failure, and that failure was due to monotonically increasing load applied at the end of the cyclic loading. The latter failure load, termed residual strength, is reported in Table 4.1. Notice that among the 27 specimens tested under the seismic load with a maximum amplitude of 0.5R (50% load case), where R is the relevant static capacity, only two specimens failed prematurely prior to the completion of the 140 cycles. The latter two specimens may be treated as statistical outliers because the replicates of those two specimens did not fail prematurely. The premature failure may be ascribed to random variations in the testing procedure, material properties and/or manufacturing of the test specimens. The changes caused by the cyclic load to the average static tensile, shear and combined load capacities of anchor SE -- excluding the results of the specimen that failed prematurely -- are -5.9%, -40.3%, and +88.8%, where negative signifies decrease and positive increase. For anchor UE the corresponding values are +2.1%, -3.2% and +121.1% while for anchor SA they are -17.5%, -3.2% and +35.6%. It is clear from these results that combined cyclic loading increases the residual capacity of the anchor dramatically. There is no obvious explanation for this behavior, but it does require further investigation. Note that Rodriguez et al. and Kim et al. also reported an increase in anchor capacity due to dynamic loads. On the other hand, the effect of cyclic loading with 0.5R maximum amplitude on the shear and axial load capacities is generally small.

Anchors subjected to the seismic load with maximum amplitude of 0.75R exhibited the following behavior. None of the anchors failed under cyclic tension or combined load while all, except one SA specimen, failed due to cyclic shear within the first eight cycles. The changes in the tensile and combine load capacities of anchor SE are +17.17% and +14.11%. For anchor SA the corresponding values are +13.57% and -7.3% while for anchor UE they are +8.4% and +48.5%. Among the capacities of the three replicate specimens of anchor UE subjected to combined loading there were large differences, ranging between 9.7 and 39.9 kN; consequently, the average value in this case could be misleading. Further testing is needed to reliably determine the effect of combined cyclic loading on the ultimate capacity of this type of anchor. The important observation that can be made is that in general simulated seismic tension or combined loading with maximum amplitude up to 75% of the pertinent static capacity of the anchor does not cause major reduction in its capacity and it can even increase it. By contrast, seismic shear with similar amplitude causes dramatic reduction in its capacity and leads to premature failure within the first 8 cycles.

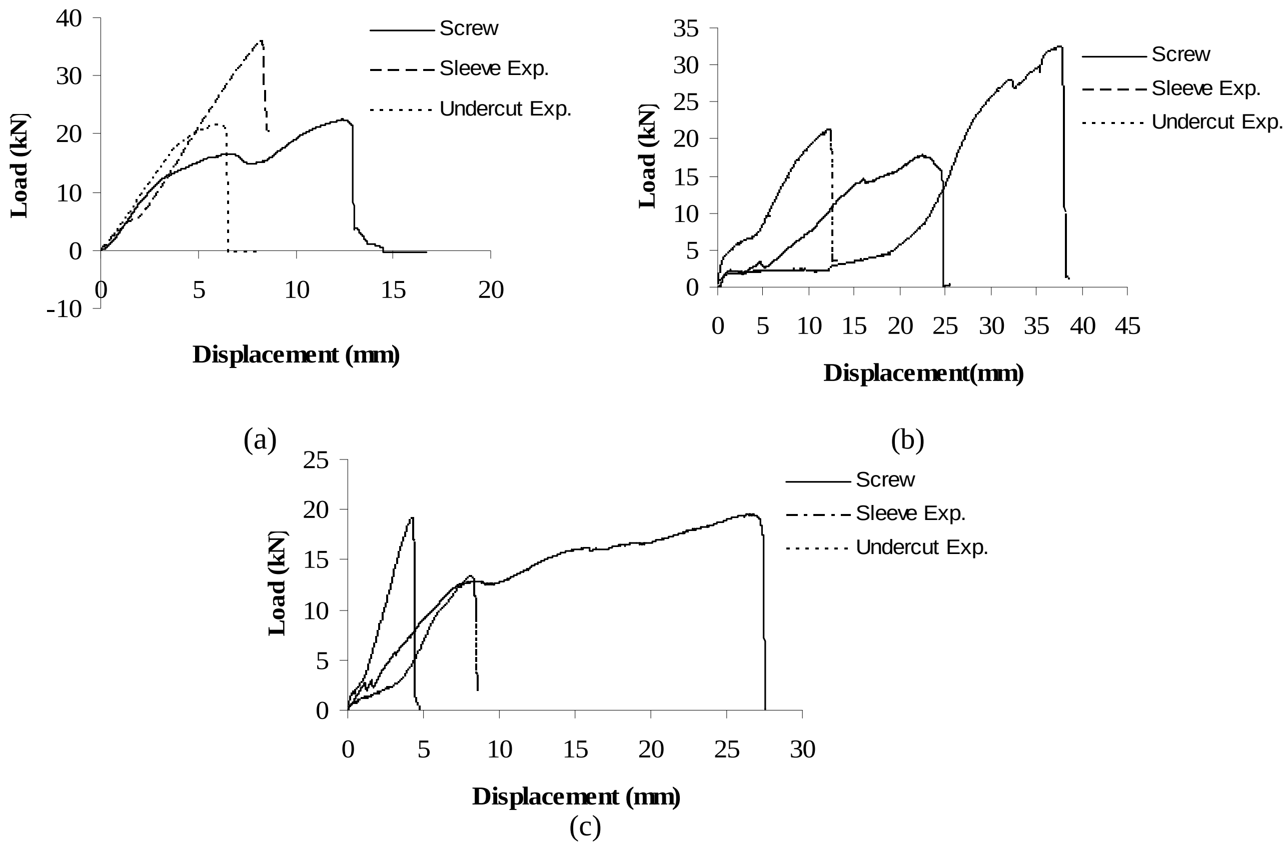
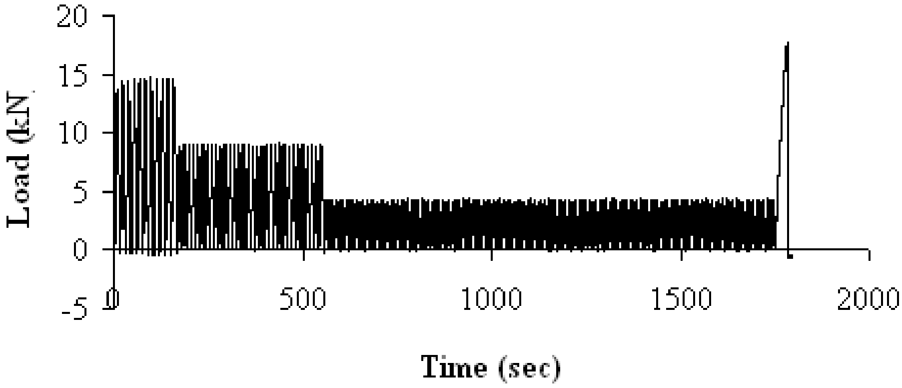


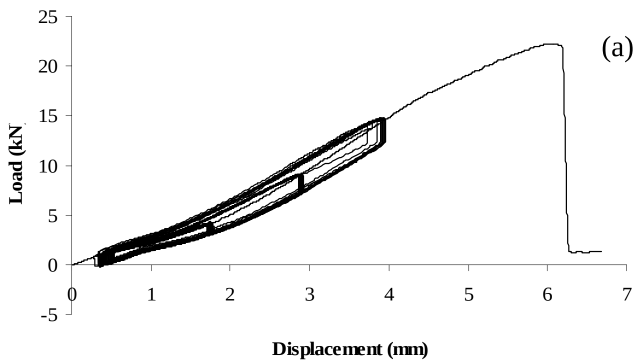
Figure 4 Static test results (a) Typical anchor tensile force-axial displacement, (b) Anchor shear force-lateral displacement, and (c) Anchor resultant force-resultant displacement under combined load

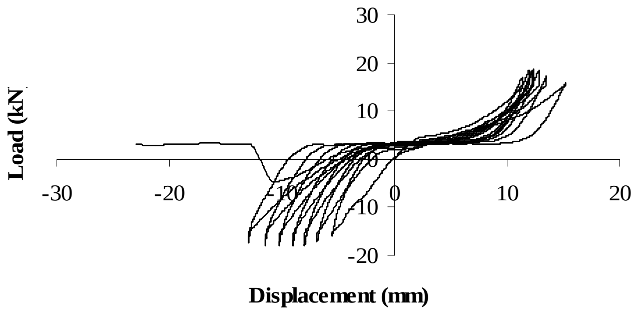
Table 4.1 Average failure load for the tested specimens

Anchor Type	Static Strength (kN)			Residual Strength (kN)					
	Tension	Shear	Combined	Tension		Shear		Combined	
				50%	75%	50%	75%	50%	75%
Sleeve Expansion (SE)	25.85	23.88	21.97	24.31	30.29	14.25	19.43	41.49	25.07
Screw (SA)	32.56	23.79	18.81	26.88	36.98	23.54	25.8	25.5	17.43
Undercut Expansion (UE)	20.87	24.48	14.43	21.3	22.63	23.69	19.2	31.91	21.43

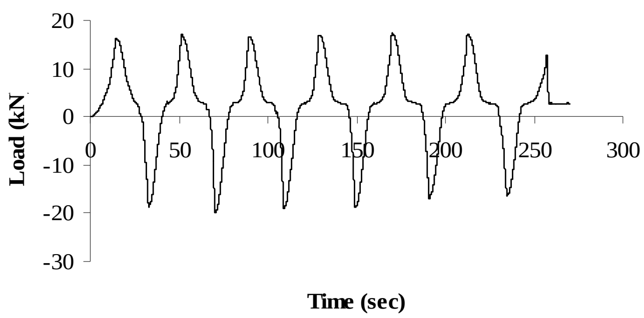


(a)





(b) (c)



(d)

Figure 5 (a) Typical loading profile for 50% cyclic tension test ,(b) Load-displacement curves for undercut expansion anchor subjected to 50% cyclic tension, (c) Load-displacement curves for screw type anchor subjected to 75% cyclic shear, and (d) Typical loading profiles for 75% cyclic shear test.

5. CONCLUSIONS

Based on the results of static and simulated seismic tests conducted on 72 screw, sleeve expansion and undercut expansion anchors, the following conclusions can be reached:

(a) The static capacity of all three types of anchors under combined tension and shear may be significantly lower than indicated by Eqn.1. A linear interaction equation, albeit still un-conservative, would be much more appropriate to use.

(b) Simulated seismic tension, shear, or combined shear and tension, with variation as recommended in ACI 355.4-02, and with a constant tension/shear ratio of 1.73, and maximum amplitude of 1/2 the pertinent static capacity, does not cause premature anchor failure. The reduction in capacity caused by this level of cyclic loading varies but does it not exceed 20%; in fact, in many cases the anchor residual strength exceeds its static capacity substantially.

(c) When the maximum load amplitude is increased from ½ to ¾ of the corresponding static capacity, the effect of cyclic loading on the residual tensile or combine load capacities is similar to that stated in (b), but the shear capacity is dramatically reduced and anchor failure occurs within the first eight cycles. Therefore, it is concluded that cyclic shear causes the most damage to an anchor and it must be properly considered when designing connections involving anchors resisting mainly shear force.

(d) Further investigation is needed to determine the full tension-shear interaction failure envelope of such anchors, and possibly other types of anchors used in seismic applications. Such tests need be performed both under static and simulated seismic loads. This can be achieved by testing each anchor type under different tension to shear ratios. Finally, more extensive testing is needed to determine the actual cyclic shear capacity of anchors qualified for seismic applications. Such tests need be performed in both cracked and uncracked concrete.

REFERENCES

Eligehausen, R., Mallee, R. and Silva, J.(2006). Anchorage in Concrete Construction, Ernst & Sohn: A Wiley Co., Berlin. 378 pp.

ACI (2004), Qualification of Post-Installed Mechanical Anchors in Concrete, Reported by ACI Committee 355, Document ACI 355.2-04, American Concrete Institute, Michigan, 2004. 19 pp.

Zhang, Y.G. (1997) Dynamic Behavior of Multiple-Anchor Connections in Cracked Concrete, Ph.D. Dissertation, Department of Civil Engineering, University of Texas at Austin.

Kim , S.Y., Yu, C.S. and Yoon, Y.S. (2004). Sleeve-type Expansion Anchor Behavior in Cracked and Uncracked Concrete. *J. Nuclear Engineering and Design*, No. 228, pp. 273-281.

Rodriguez, M, Lotze, D., Gross, J.H., Zhang, Y.G., Klinger, R.E. and Graves III, H.L. (2001). Dynamic Behavior of Tensile Anchors to Concrete. *ACI Structural Journal*, V. 98, No. 4., pp. 511-524.

Hilti (2005), " Hilti North America Product Technical Guide," www.us.hilti.com,