Reliability and Design Issues of Bonded Anchors Installed Using Different Techniques

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ABSTRACT: Bonded anchors are typically installed using injection systems, where products are injected into pre-drilled holes using proprietary mixing systems supplied by manufacturers, or using products that need to be pre-mixed by hand (or with the aid of a mixing tool). In this latter situation, pouring the resulting mix into the pre-drilled holes or thrusting it through the holes is the only option.
Within this context, an overview is presented on the influence that different installation techniques have on the performance of three mixes (one to be injected and two to be prepared by the user). The performance of each mix is investigated by carrying out tests in different environments to assess the reliability of the product in typical jobsite conditions. A comparison of the different requirements concerning product certification in Europe and their correlation with the available (or still unavailable) design provisions and requirements is also carried out.

Keywords: post-installed anchors; bonded anchors; injection systems; anchor reliability; structural safety.

1 INTRODUCTION

In the last decades, the use of post-installed bonded anchors has become very common in retrofit and new constructions. Typically, bonded anchor systems consist of a bonding agent injected in a predrilled hole and a threaded rod or a rebar to connect a fixture. The behaviour of these connections has been extensively investigated (Cook 1993; Cook et al. 1998; Eligehausen et al. 2006; Kunz et al. 1998).
The peculiarity and the drawback of post-installed bonded anchors is their renown sensitivity to different installation conditions (Mattis et al. 2017; González et al. 2018; Bajer et al. 2012; Cook et al. 2001; Grosser et al. 2011; Silva 2016), which is a critical problem in job-sites (e.g., lack of awareness of the sensitivities of the products, cleaning conditions, etc.).
To provide an adequate level of safety and reliability, product qualification procedures developed in the last decade in Europe and in North America (EAD330499-00-0601 2018; EAD330087-00-0601 2018; ACI Committee 355.4 2011; ICC-ES AC308 2015) dedicate specific tests to the verification of the performance and the robustness of the products in "non-standard" conditions (e.g., reduced cleaning, overhead or horizontal installation, wet concrete conditions, etc.). In accordance with these procedures, a product undergoing the required qualification tests can be used and designed (using appropriate safety factors) in accordance with the available building codes (ACI Committee 318 2014; FIB Bulletin 58 2011; TR029 2010; TR055 2018; EN 1992-4 2018).
Other available qualification documents or standards (e.g., ASTM C881/C881M-15 2015; BS 4551:2005; BS 5080-1:1993; BS 2782-0:2004; EN 1881:2006; EN 1504-6:2007) allow products to be certified or qualified for similar applications following different requirements without addressing the most critical installation conditions, and without being tied to available design building codes.

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One of the most critical installation conditions is the mixing of the different components of a post-installed bonded anchor. In order to limit gross errors (which lead to reduction in performance and safety level) the EOTA and ACI (ICC-ES) product qualification procedures (EAD330499-00-0601 2018; EAD330087-00-0601 2018; TR 048 2016; ACI Committee 355 2011; ICC-ES AC308 2015) allow the use of systems in which the mix proportions are controlled by the packaging of the bonding material (e.g. soft-skin capsule, prepacked injection - coaxial or side by side - cartridges that use proprietary dispensers and nozzles, bulks where all components are mixed exactly as supplied, etc.), while systems where the mix proportions are controlled by the installer are not allowed or covered.
This distinction is not taken into account in other available qualification documents and many certified products that are popular in regions like China, Middle East, and South America, are used following quite peculiar mixing and installation procedures.
The use of bulk materials provided in cans and mixed by the installer, for example, is very common. In these situations, the mixing proportions of the components might not be respected, the mixing technique (usually manual for a non-well defined time) and the installation technique are typically not addressed by the manufacturers, and no suggestions are provided for the installation. Furthermore, the "dip and stick" technique, which does not require extensive training nor guidance, has become a very common practice.
This installation procedure consists in dipping a rebar or a threaded rod in the bonding agent (resulting from mixing two components in a can) and then sticking it into the predrilled hole. Usually, an installer dips the rebar back-and-forth few times in the can and in the hole and, although highly unreliable, this technique is common practice and is even suggested in some MPII (Manufacturer's Printed Installation Instructions). To the authors' knowledge, the effect of this installation technique has not been assessed in previous studies. The aim of this research was to evaluate the reliability of different installation techniques (injection with dispenser and nozzle vs. dip and stick) and verify the influence of the mixing technique (manual, mechanical, static mixer) on the performance of selected products. To this end, pull-out tests with three different bonded systems as well as clear acrylic tube tests to check the voids as related to the different installation techniques were performed in accordance with the EOTA product assessment methods (EAD330499-00-0601 2018; EAD330087-00-0601 2018).

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

The experimental program considered three different bonding agents: two epoxies (A, B) and one polyester (C) material. The bonding agent A was provided in a prepacked injection cartridge (two components mixed with a nozzle), B was a two-paste component provided in two cans, and C a two components system provided in one can (paste component) and in one bag (powder component). The MPII (Manufacturer's Printed Installation Instructions) for products B and C differ depending on the country, many parameters are not well defined (i.e. borehole size, cleaning procedure, mixing procedure), and different scopes are suggested.
The main differences among the three products are related to the mixing technique - dispenser and nozzle (A) or manual/mechanical mix of two solid components (B, C) - and installation procedures - injection (A) or manual (B, C).

Tension tests with the different products were conducted using concrete slabs with average concrete compressive strength (cube side 150 mm) between 32 and 34 MPa. The anchors consisted in 12 mm and 16 mm B500 rebars (relative rib area ir=0.069 and 0.068). The tests were performed with a Hydraulic jack with a load carrying capacity of 200 kN mounted on a testing frame with a stiff plate at the base that allowed to perform confined tests (the diameter of the hole in the steel plate was 4 mm larger than the bore-hole diameter). The load and the displacements were measured with a load cell and with two LVDTs, respectively, and acquired with a HBM Spider 8 data acquisition system (sampling 5 Hz). Furthermore, tests with acrylic tubes were performed to assess the quality of installation due to the different type of injection in deep holes conditions. Overall 132 tension tests and 24 acrylic tube tests were performed.

2.2 Installation procedure and test plan

The installation of product A was relatively easy (dispenser and the static mixer provided by the manufacturer) and allowed a quick and effortless installation, while products B and C were first manually mixed (B for 3 minutes and C for 1.5 minutes according to MPII) and installed using the dip and stick method. With no information available in the product MPII, the bar was dipped in the can and then in the hole back-and-forth three times. This choice was adopted to allow an acceptable hole filling and reduce the scatter in performance. It is noted that, in most jobsites, the rebar is usually dipped into the can and then in the hole only once.

The test plan included reference tests (RT) with a very short embedment depth (four bar diameters - 4d) to evaluate the maximum bond strength, and additional tests at different embedment lengths to define the embedment length associated to the transition pull-out/steel failure.

The reference tests were conducted in standard conditions (e.g., dry concrete, room temperature) and, due to the lack of (and sometimes contradictory) information available from the different MPII, many parameters were defined as standard by the authors for bonding agent B and C. Decisions were mainly driven by considerations of common practices in job-site, i.e. the easiest and quickest procedures for installation were chosen. All holes were drilled using a rotary hammer drill with a diameter of the drill bit according to the MPII, when available. The diameter of the hole (and drill bit) was not well defined for bonding agent C and tests with 14mm (same as for Product A), 16mm, and 20mm diameters were performed to obtain reasonable coefficient of variation.

The holes were cleaned in accordance with the MPII, when available: for product A using compressed air cleaning (CAC) and a steel wire brush (2 x blows, 2 x brush, 2 x blows), while for product B and C, since no clear instructions were given, 2 blows of CAC were adopted as reference.

Additional tests were performed to investigate the product reliability and robustness (e.g., installation direction - horizontal and overhead, and the sensitivity to hole cleaning in dry and wet substrate). Reduced cleaning was applied according to the procedure of the EAD 330087-00-0601 (2018) for the sensitivity tests in dry and wet substrate – this procedure is more severe than that of EAD330499-00-0601 (2018) and allows the use of the adhesive for post-installed rebar connections. The anchors were set and cured at ambient temperature (of about 20°C).

3 EXPERIMENTAL INVESTIGATION

3.1 Reference tests

Figure 1 summarizes the results of reference tests in terms of ultimate load and of coefficient of variation (v) as a function of the embedment length. The three products showed a limited coefficient of variation at the embedment depth of 4d, but for product C that result was achieved after several attempts because the manufacturer did not indicate the borehole size. For instance, for the bar of 12mm with a borehole of 14mm, the coefficient of variation was about 20% (not reported in Fig.1). Additional tests were performed with boreholes of 16 and 20 mm. The bond strength was similar regardless of the borehole size, while the coefficient of variation was lower with the biggest size (of about 2%). In all cases, failure between steel and adhesive was observed. Thus, the reference borehole size for product C was assumed to be equal to 20 mm.
Adhesive A showed an excellent strength in the tests with shallow embedment (4d), thus, the reference embedment depth was chosen as 5d. An embedment depth of 8d was chosen for the other products.
As shown in Figure 1, the selected embedment depths were appropriate for products A and C, while product B reached load values still far from the expected steel failure load.

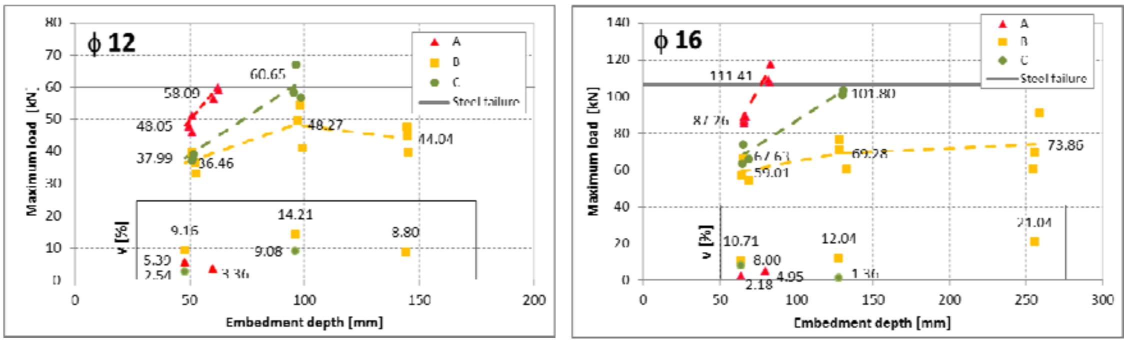

Figure 1. Maximum load and coefficient of variation (v) vs embedment depth

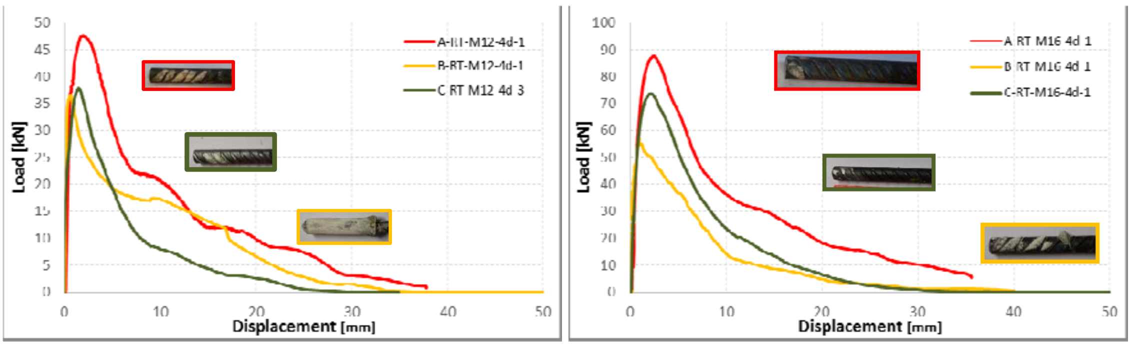

Figure 2. Load-displacement curves of all products – Embedment depth 4d

Two additional embedment depths were therefore selected: 12d for ϕ12 and 16d for ϕ16.
Since no load increment was observed when increasing the embedment depth and the coefficient of variation of the 16mm-diameter rebar was very high (Fig.1), the reference embedment depth was kept equal to 8d. Overall, the load-displacement curves (Fig. 2) showed a similar behavior with different ultimate load due to the different bond

strengths. Product B showed failure between adhesive and concrete for the 12mm diameter, but with a limited coefficient of variation (the failure mode was the same for all specimens). By increasing the embedment length, the failure mode was similar but the bonding agent did not completely fill the bore hole leaving some air pockets.

3.2 Robustness tests

Once defined the reference embedment depth, different parameters were considered to check the robustness of the bonding agents.
For adhesives B and C, the mechanical mixing technique was considered since the MPII suggested either the use of manual and mechanical mixing; afterwards, sensitivity to the cleaning technique in dry and wet condition as well as to the installation direction (horizontal and overhead) were considered.
Table 1 summarizes all test results in terms of average bond strength, τ, coefficient of variation, v, and the parameter α, defined as the ratio between the average bond strength in the considered robustness test, τ, and the average bond strength in reference tests, τ_{Ref}.

Table 1 – Robustness test results

Test		**Material**					
		A		**B**		**C**	
		d =12mm d_0=14mm	d =16mm d_0=20mm	d =12mm d_0=18mm	d =16mm d_0=22mm	d =12mm d_0=20mm	d =16mm d_0=20mm
RT-5d for A, 8d for B&C	τ_{Ref} [MPa]	24.92	26.79	13.04	10.62	16.62	15.51
	v [%]	1.66	4.18	14.70	13.85	9.73	1.13
MX-8d (mechanical)	τ [MPa]			8.12	8.35	18.24	14.73
	v [%]			11.25	9.05	10.27	16.12
	α			0.62	0.79	1.10	0.95
ID-HO-h_{Ref}	τ [MPa]		26.41		11.92		2.72
	v [%]		3.15		46.89		29.08
	α		0.99		1.12		0.18
ID-OH-h_{Ref}	τ [MPa]		24.41		9.38		3.51
	v [%]		10.40		19.38		20.90
	α		0.91		0.88		0.23
DR-h_{Ref}	τ [MPa]	23.90	25.12	10.88	8.18	13.45	13.80
	v [%]	10.45	4.31	29.06	19.20	41.75%	17.38
	α	0.96	0.94	0.83	0.77	0.81	0.89
WE-h_{Ref}	τ [MPa]	18.14	16.63			10.47	17.62
	v [%]	18.00	8.15			48.74%	4.14
	α	0.73	0.62			0.63	1.14

3.2.1 Mixing technique

The mixing technique tests were performed only with adhesives B and C by comparing manual mixing (reference test) and mechanical mixing (low speed drill and mixer

paddle). The mixing time was the same as for manual mixing (3’ for product B and 1.5’ for product C). Product C showed good performance, while manual mixing proved to be more effective for product B. The value of α (ratio between the bond strength with mechanical mixing and the one with manual mixing) for both diameters is very low (Table 1).
By following the approach of EAD 330499-00-0601(2018), the parameter α should be higher than 0.95 to assume an installation safety factor equal to 1. In this case, it seems that adhesive C is suitable for both mixing procedures (manual or mechanical), while only manual mixing should be recommended for adhesive B.

3.2.2 Installation direction – Overhead and horizontal direction

The tests were performed using rebars ϕ16. All products allow overhead and horizontal installation without specific instructions for adhesives B and C and with clear indication of the use of the piston plug for adhesive A. The advantages of using a piston plug for these and other applications are well know (Silva, 2016). However, to fairly compare the two injection methods (dispenser with nozzle vs. dip and stick), a gross error was introduced in the installation of adhesive A, neglegting the MPII and just using the dispenser and the nozzle without the piston plug.
This choice seemed reasonable because of the small effective embedment depth (5d for product A) and the general philosophy of the research, aimed at investigating typical job-site conditions (for small embedment depths, the piston plug might not always be required in job-sites). Ultimately, the performances were very good for both horizontal and overhead installations, and the parameter α was higher than the required value (0.9 according to EAD 330499-00-0601(2018)) (Table 1).
The adhesive B overall behaved well in terms of bond strength but the coefficient of variation was very high (rebar yielding was observed in one case). Adhesive C showed very low performance due to its high flowability that did not allow to properly fill the hole.

3.2.3 Sensitivity in dry and wet conditions

To evaluate the sensitivity in dry and wet installation conditions, the testing procedures according to EAD DP 330087-00-0601 (2018) were adopted (e.g., reduction in the cleaning efforts). It is noted that the procedures adopted in this study are more severe compared to the ones required by EAD330499-00-0601 (2018) in that the effect of the different installation conditions is investigated at deeper embedment depth.
As for installation direction tests, in order to have a direct comparison between the two injection methods (dispenser with nozzle vs. dip and stick) a gross error was introduced during the installation of adhesive A (injection without piston plug). Note that, in this case, a plastic pipe was attached to the static mixer in order to reach the bottom of the anchor holes (embedment depth equal to 30 cm plus 5d).
As shown in Table 1, adhesive A showed an excellent behavior in dry conditions (high average load with low coefficient of variation), while products B and C showed relatively good behavior in terms of ultimate load (the ratio α was very close to the reference value 0.8 EAD DP 330087-00-0601-2018) but the coefficients of variation were very high with respect to the expected value according to EAD DP 330087-00-0601 (2018) (up to 41%) (Table 1).

Only adhesives A and C were tested in wet concrete conditions because that application is not covered by the MPII of adhesive B. Adhesive C showed excellent behavior with the bar diameter 16 mm and very poor behavior with the bar diameter of 12 mm, while adhesive A reached low bond strength. This could be due either to the gross error in installation (no piston plug was used) or to other unforeseen borehole conditions (e.g., excessive water in the borehole). It is noted that additional tests performed using the piston plug and embedment depth equal to 10d and 20d showed a ratio between the wet concrete and the reference bond strength higher than 1 for both diameters.

3.2.4 Acrylic pipe tests

Finally, blind installation tests in clear acrylic pipes were performed to evaluate the quality of installation (e.g., hole filling) in vertical (downward) and horizontal directions. Visual inspection after installation allow to formulate explanations to some of the results obtained in previous tests (Fig. 3). The injection system fills very well the pipe without detectable voids in both installation directions. Conversely, the dip and stick method showed to be unreliable for both adhesives B and C.
A rough evaluation of the volume of adhesive inserted into the hole was assessed by weighting the system (pipe, rebar and support) before and after injection. The ratio between the volume of the inserted adhesive (weight/density) and the volume of the voids inside of the pipe (obtained by subtracting the volume of the bar – without ribs – from the volume of the cylinder), V_{fill}, was evaluated and reported in Fig. 4.
Adhesive A showed excellent performance (V_{fill} close to 1) except in one case, where the sealing of the pipe did not work perfectly and some material was lost; adhesive B, characterized by a high viscosity, showed an almost constant (low) value of V_{fill} regardless of the bar size and the installation direction; adhesive C, which was characterized by a high fluidity, showed a low value of V_{fill} for horizontal installation and for vertical installation with the bar diameter of 12 mm, while a higher ratio was observed for vertical installation of 16mm bars. Low values of V_{fill} could explain the results obtained in dry and wet concrete tests, where high coefficients of variations were observed.

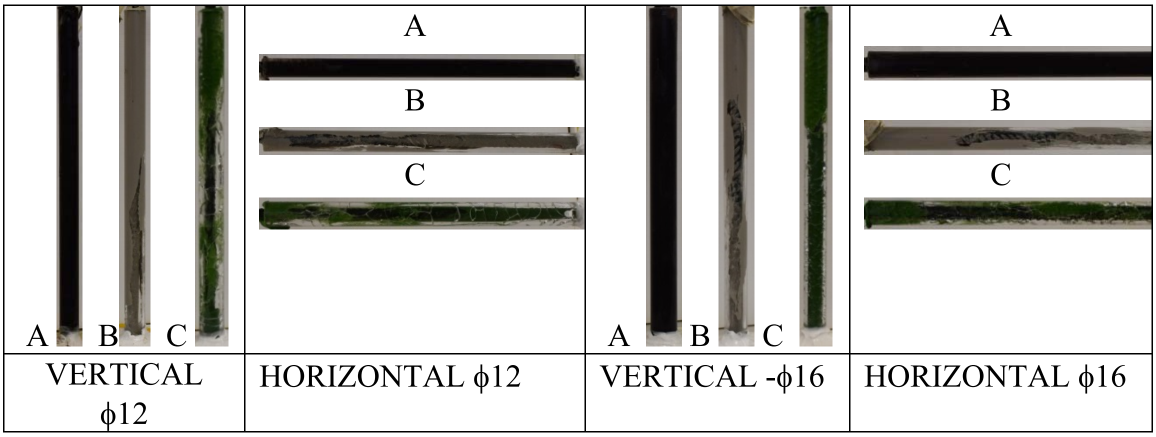

Figure 3 – Clear pipe test

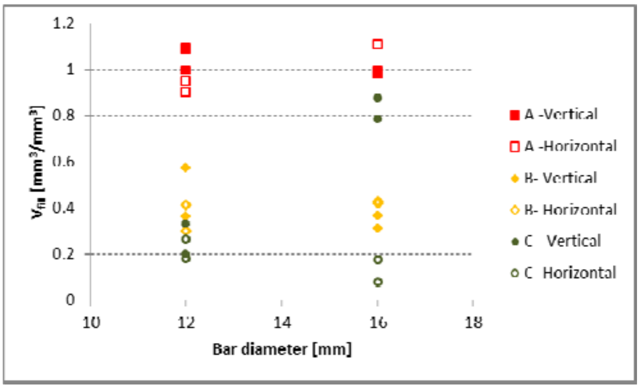

Figure 4 – Ratio, V_{fill}, between adhesive and free volume of acrylic pipe

4 DISCUSSION

The results of this investigation highlight the importance of the quality of installation and installation technique and the need to reconsider the reliability of the dip and stick method. Clearly, while some good results could be achieved in reference tests, the reliability and robustness of this installation method proved to be very low.
Adhesive A (injection system) showed low performance only in wet condition, but the additional tests in standard conditions following the MPII showed excellent performance. Adhesive B showed decent performance (average ultimate loads) but high coefficients of variation, while adhesive C showed extremely low performance in installation direction tests and in reliability tests (dry and wet concrete) for the 12mm-diameter bar.
To assess the reliability of bonded anchors, the European Assessment Document (EAD 330499-00-0601 2018) requires the determination of a parameter α, defined as the ratio between product performance in a reliability test and the reference performance, for each of the robustness tests performed. If the value of α is below the value suggested in the qualification document, the product design bond strength needs to be reduced. Following this concept, the parameters RI and RI_k (Reliability index, average and characteristic) where used to compare the overall reliability of the products tested in this study. The reliability indexes are defined as

$$RI = \frac{\sum_{i=1}^{n} \frac{\alpha_i}{req\alpha_{iEAD}}}{n} \qquad RI_k = \frac{\sum_{i=1}^{n} \frac{\alpha_{ik}}{req\alpha_{iEAD}}}{n} \qquad with\ \frac{\alpha_i}{req\alpha_{iEAD}} \leq 1 \tag{1}$$

where n is the number of robustness tests of the adhesive, α_i is the ratio between the average bond strength in each test series and the reference bond strength (Table 1), α_{ik} is the ratio between the characteristic bond strength in each test series and the reference characteristic bond strength (not properly evaluated as stated below) and req α_{iEAD} is the required value of each test according to EAD 330499-00-0601 (2018) assessment.
It is noted that the limited number of tests (n = 3) does not allow to evaluate properly the characteristic values, and that the assumption of a normal distribution with an infinite number of samples (k=1.645) was used. While this approach is not statistically meaningful, it could still be useful to provide a rough estimate of the influence of the variation on the results. Figure 5 shows the average and the characteristic ratio

$\alpha_i/req\alpha_{IEAD}$ for each test series and the reliability indexes for each product. Clearly, products B and C show much lower reliability across the board.

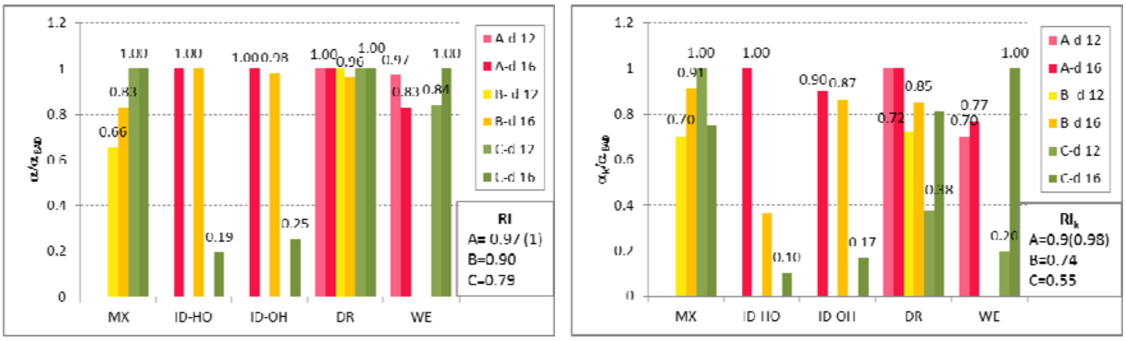

Figure 5 – Assessment of robustness tests

5 CONCLUSIONS

Based on an experimental research aimed at assessing the reliability of different products installed using different types of mixing/installation techniques and in different concrete conditions, the following conclusions can be drawn:

- In standard job conditions (i.e. deep holes, different installation directions, etc.) the injection method leads to highly reliable results compared to the dip and stick method, where the reliability of the system is very low. It is the authors' opinion that this latter method should be banned for anchoring applications.
- The MPII is a fundamental instrument for the installer, and the lack of information (i.e. borehole size, detailed instructions on the installation procedure, etc.) for products B and C (and similar) could lead to poor performance of the product.
- Specific applications, i.e. overhead and horizontal installation, require proper installation tools and qualification tests.
- Manual mixing can be effective, but the effort and level of awareness needed to install products mixed by the user is quite high compared to injection systems. This might lead to unsafe and dangerous installations.
- Injection type systems are more reliable in terms of safety, and at the same time are worthwhile in terms of installation time and product consumption (for dip and stick method a lot of material that does not fill the hole is wasted)
- More clarity should be provided on the existing qualification and certification requirements (or lack thereof) for products that are mixed by the user. In fact, while covering different scopes, such as protection and repair of concrete structures, other standards (e.g., EN 1504 (2007)) allow the certification of these products and do not follow the same (more stringent) requirements of EOTA or ACI that injection products need to go through. This discrepancy is clearly providing a lower threshold for the level of safety (published product performance and design requirements) for products that are qualified using EN 1504 (2007) and used for anchorage of reinforcing steel
- The design information needed by a professional engineer to design a connection using user-mixed products (including those qualified using, e.g., EN 1504 (2007), is very often not linked to available design building codes, might not be derived consistently, and might not provide the level of safety required in design.

REFERENCES

ACI Committee 318, (2014),Building code requirements for structural concrete (ACI318-14) and Commentary (ACI318R-14), *American Concrete Institute*, Farmington Hills, 519 pp.

ACI Committee 355, (2011) Qualification of Post-Installed Adhesive Anchors in Concrete and Commentary (ACI 355.4-11), *American Concrete Institute*, Farmington Hills, MI, USA, 55pp.

ASTM C881 / C881M-15, (2015) Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete, *ASTM International*, West Conshohocken, PA.

British Standard, BS 4551:2005 Mortar - Methods of test for mortar and screed - Chemical analysis and physical testing (+A2:2013)

British Standard, BS 5080-1:1993, Structural fixings in concrete and masonry. Method of test for tensile loading

British Standard, BS 2782-0:2004, Methods of testing plastics. Introduction

CEN, EN 1881:2006. Products and systems for the protection and repair of concrete structures - Test methods - Testing of anchoring products by the pull-out method

CEN, EN 1504-6:2007. Anchoring of reinforcing steel bar

CEN, EN 1992-4:2018. Eurocode 2: Design of concrete structures – Part 4: Design of fastenings for use in concrete.

Cook R. A., Kunz J., Fuchs W. and Konz R.C. (1998). Behavior and Design of Single Adhesive Anchors under Tensile Load in Uncracked Concrete, *ACI Structural J.*, V. 95 No.1, 9-26.

Cook R. A. and Konz R.C. (2001) Factors Influencing Bond Strength of Adhesive Anchors, *ACI Structural J.*, V.98, No.1, 76-86.

Eligehausen R., Cook R.A. and Appl J., (2006), Behavior and Design of Adhesive Bonded Anchors, *ACI Structural J.*, V.103, No 6, 822-831.

EOTA, EAD 330499-00-0601,(2018) Bonded fasteners for use in concrete.

EOTA, EAD DP 330087-00-0601, (2018) Systems for post-installed rebar connections with mortar.

EOTA TR029, (2010) Design of bonded anchors.

EOTA TR055, Design of fastening based on EAD DP 330232-00-0601, EAD 330499-00-0601, EAD DP 330747-00-0601, 2018

FIB Bulletin 58 (2011). Design of anchorages in concrete, *FIB (Fédération Internationale du Béton / the International Federation for Structural Concrete)*, Lausanne, Switzerland, 264pp.

González F., Fernández J., Agranati G, Villanueva P. (2018). Influence of construction conditions on strength of post installed bonded anchors, *Construction and Building Materials,* 165, 272–283

Grosser P., Fuchs W., Eligehausen R., (2011) A field study of adhesive anchor installations, *Concrete International* V. 33, N. 1, 57-63.

ICC-ES AC308, (2015), Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements, *ICC Evaluation Service*, LLC, Brea, CA, 67 pp.

Mattis L., Silva J. (2017). Inspecting Adhesive Anchors, *Concrete International*, V. 39, N. 6, 59-64

Silva J., (2016) Overhead Installation of Injection-Type Adhesive Anchors, *Concrete International*, V. 38, N. 7, pp. 40-49.