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SHAKE-TABLE TESTING OF POST-INSTALLED ANCHORS IN CONCRETE AND HOLLOW BRICK MASONRY

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ABSTRACT

This paper contains the first results of an experimental campaign focused on the seismic assessment of different typologies of post-installed anchors.

The central role of these devices in anchoring non-structural elements and assuring their safety especially when installed in strategic buildings explains the importance of the knowledge on fastener dynamic behaviour. As is widely recognized indeed the anchorage performance and reliability are required for the seismic design of relevant apparatus, such as fire protection systems in schools, medical equipment in hospitals or museum artefacts. Moreover, after the recent seismic events (L'Aquila 2009, Chile 2010, Christchurch 2011, Emilia 2012), the dynamic response of non-structural elements is by now considered one of the critical issues to be addressed by earthquake engineering (Miranda et al., 2012). This subject still contributes to make the built environment a weak point in terms of life safety and the economic losses for the resilience of a community struck by a seismic event.

Tri-axial shaking table tests were carried out to study the seismic behaviour of fastening systems for use in both concrete and masonry supports. Two cross-shaped structures were built at full scale, one consisted of concrete walls and one of a RC framed structure with masonry infill panels. Two different conditions were investigated in the case of fasteners installed in concrete, namely uncracked and cracked support. Poroton® hollow bricks were used to build the specimen with masonry infill walls.

The tests were designed on the basis of the standard AC156 (2010) which provides a test setup for the seismic certification of non-structural components by shaking table tests. The experiments were realized by subsequent signals scaled at a growing ZPA (Zero Period Acceleration) to study the effects induced on the specimens at increasing seismic intensity.

The results allowed the overall seismic behaviour of each fastening element to be investigated, especially in terms of failure mode, maximum sustained acceleration and anchor slippage from support. The influence of cracks on these aspects was also deepened for the concrete structural unit. The test plan also allowed a complete comparison among different anchoring methodologies, such as mechanical, chemical and undercut anchors.

Some recent studies (Rieder, 2009; Watkins, 2011; Mahrenholtz et al., 2012) focused on the seismic assessment of metal anchors in concrete by means of shake-table testing, whereas the use of fasteners in masonry and the behaviour of plastic anchors in general were not exhaustively investigated until now (Algin, 2007; Sinica, 2010). Nevertheless these are two fields of interest because of the widespread presence of non-structural components in constructions. Therefore during

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the experimental study a particular attention has been paid to the issues of plastic anchors and installations in masonry.

INTRODUCTION

The damage observation in recent seismic events (L'Aquila 2009, Chile 2010, Christchurch 2011, Tohoku 2011, Emilia 2012) helps in the identification of the critical aspects related to the response to earthquake of non-structural components (Miranda et al., 2012). Generally these elements are included in buildings and may belong to the architectural system, to the utility system or to the building content. The failure of these elements can represent a significant danger for life safety and leads to relevant economic losses. Furthermore the consequences of this can have a severe impact for a society (Miranda et al., 2012). That is clear especially in the case of strategic facilities if a lack of functionality for the entire structure occurs (Taghavi and Miranda, 2003; ATC 69, 2008).

During an earthquake the non-structural components should withstand to relevant inertial forces, transferred through the connection to the structural elements (beams, slabs, columns, walls) or often to other non-structural elements, such as infill walls, or to relevant relative displacements among different anchoring points. In many cases those connections are realized by means of post-installed anchors which should be designed properly in order to ensure a good behaviour to the seismic actions (Makris and Black, 2001; Naumoski et al., 2002; Solomos and Berra, 2006; Hoehler et al., 2011). Among all the requirements the reliability in terms of failure modes and strength of post-installed anchors results to be fundamental to obtain a valid design in the dynamic field. The purpose of the here presented experimental campaign is to verify the seismic behaviour of various anchoring systems through shaking table testing.

TEST SETUP AND INSTRUMENTATION

The experimental campaign presented in this paper included seismic tests on shaking table with two different structures in order to study the dynamic behaviour of various anchor types installed in concrete and masonry. As a consequence of this, a first RC structure followed by a second RC frame with reinforced masonry infill walls were built (Figure 1). The structural design was accomplished on the basis of numeric modelling and preliminary analytical studies (Mazzon et al., 2013).

On each wall of both structural units under testing some masses, realized through squared steel plates, were fixed by a single anchor connection in the centre of each element. The weight of these elements was designed for each different anchor typology according to the mechanical resistance of the fasteners as provided by the manufacturer (Mazzon et al., 2013). According to the current assessment provisions for the use of metal anchors in concrete in seismic applications (ETAG 001, 2013 – Annex E), each concrete wall was previously cracked in a vertical section in order to study the dynamic behaviour of fasteners in both cracked and uncracked support conditions.

The experimental campaign was carried out on the Structural Dynamics and Vibration Control Laboratories at the ENEA Research Centre in Rome. The design of the structural units under testing as well as the choice of the input signal induced to the table, in terms of maximum displacement, velocity and acceleration, were developed also considering the technical characteristics of the testing system (Mazzon et al., 2013a). The time histories in the 3 main directions were generated through synthetic procedure with SIMQKE software (Vanmarcke et al., 1997) on the basis of the target spectrum and the recommendations included in AC 156, 2010 (Figure 2). The accelerograms were built at first on a reference value of ZPA, zero period acceleration, as in AC 156 (2010) equals to 0.40g so that to get to a spectral acceleration of the plateau for flexible components of 1.00g, with an amplification factor equal to 2.5.

Figure 1. Structural units under testing: concrete walls (left) and masonry infill walls (right)

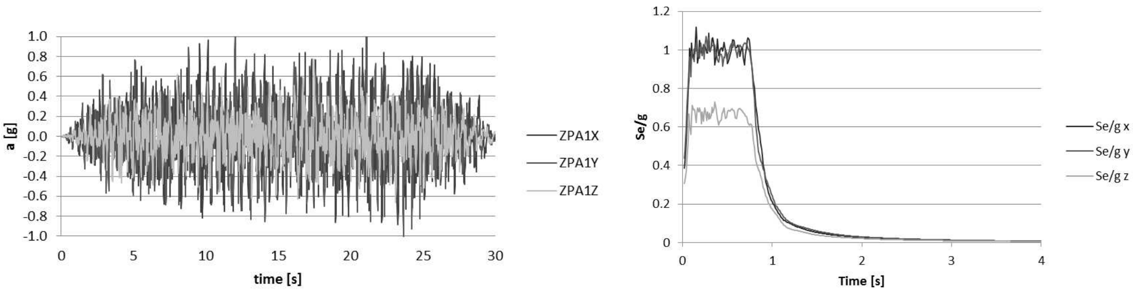


Figure 2. Tri-axial input time history generated with SIMQKE according to the target spectrum of AC156

The initial dynamic characteristics of the structural units under testing were analysed by means of a preliminary dynamic identification with a white noise input signal. The same experimental procedure was repeated for both structures. The inputs were scaled in order to obtain subsequent time histories of growing intensity in terms of ZPA up to the attainment of the anchor specimens failure or the system limits. The increase of peak acceleration was equal to 0.05g in each succeeding step but for high levels of ZPA (>0.80g) the increasing was 0.10g. For test session 5 a different loading sequence was selected and the seismic intensities related to those at which the anchors showed the failure during the test session 4 were selected.

Between two subsequent steps a random signal was run to identify the evolution of the dynamic characteristics of both the support units and the anchored components under testing.

Both structural units under testing were monitored in acceleration and displacement. In detail three different typologies of devices were mounted on the tested elements: accelerometers, displacement transducers (potentiometers) and an optical system for displacement control.

The accelerometers were used to record accelerations at the base of the structures and, for each wall, at the height of steel plates fixing. A number of 15 and 22 accelerometers was mounted on the concrete and on the masonry infill walls structural units respectively (Figure 3).

The displacement measures, especially for the out-of-plane slip of the anchor elements from the support, were monitored through potentiometers. Other displacement sensors were used in the concrete unit in order to monitor the crack width close to the fixing points. A number of 12 potentiometers were used in the concrete structural unit and 2 in the masonry infill walls unit.

The spatial positioning system 3D-Vision allowed the motion of several relevant points on the structures and on components to be monitored in terms of displacements as well as to have a redundant slip measure (Figure 4). In particular 5 markers were attached to each steel plate, to monitor the movement of the mass, in addition to a couple of markers fixed on the concrete surface above the steel elements, to control the support. A total number of about 80 markers was used in every test session.

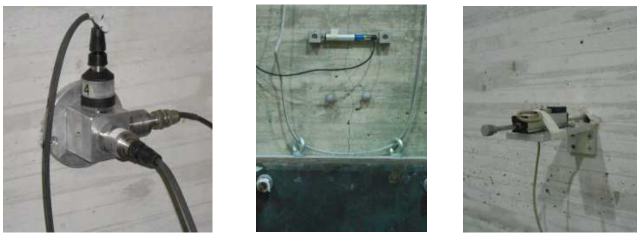


Figure 3. Accelerometers and potentiometers mounted on the units under testing

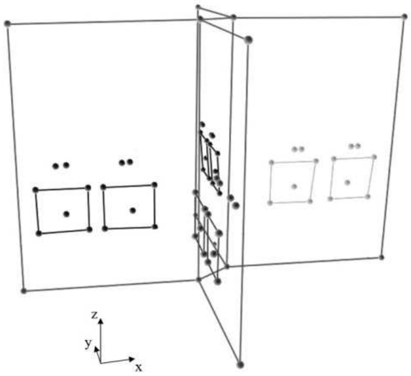


Figure 4. Layout of the unit under testing recorded through spatial positioning system 3D-Vision

ANCHOR TYPES

A total of 38 specimens of various types of anchors underwent to shaking table tests. Among those specimens 23 were installed in concrete walls, on cracked and uncracked condition and 15 were installed in the hollow brick infill walls. The specimens under testing belong to 6 anchor typologies: 4 mechanical and 2 chemical fasteners. Among the mechanical specimens expansion and undercut anchors were tested only in concrete. Two additional types of anchors were both plastic expansion-based, they differ in the fact that one has the screw and the plastic sleeve passing through the fixture (type A) while the other one has only the screw which holds the fixture (type B). Finally two chemically bonded anchor typologies were included in the testing, one in the concrete applications and the other coupled to a perforated plastic sleeve in the masonry applications.

The mass of fixtures for each anchor type was chosen to be the same whether the anchor specimen was installed in cracked or uncracked concrete. The mass values were selected in order to study in detail the load-displacement behaviour of the specimen, especially for the first testing steps. The mass values were defined also to allow a comparison among different anchor typologies belonging to the same macro-category (i.e. metal anchors had the same mass value).

For masonry applications the masses were chosen according to the fastening static design provisions included in the ETAG 029 without considering any resistance reduction factor for dynamic loading. Further details on anchor selection and design are presented in (Mazzon et al., 2013a).

Table 1. Experimental test sessions

Series	Base material	Number of input steps	ZPA max
TEST SESSION 1	UC[1]/CC[2]	19	1.10g
TEST SESSION 2	UC[1]/CC[2]	19	1.00g
TEST SESSION 3	UC[1]/CC[2]	20	1.10g
TEST SESSION 4	HBM[3]	19	1.20g
TEST SESSION 5	HBM[3]	5	1.10g

[1]UC = Uncracked concrete;
[2]CC = Cracked concrete;
[3]HBM = Hollow brick masonry.

Table 2. Concrete anchors features: d_0=nominal diameter; h_{ef}=embedment depth; d_h=hole diameter

Anchor type	d_0 [mm]	h_{ef} [mm]	d_h [mm]
Undercut	M10	60	14
Metal expansion	M12	80	18
Plastic expansion (type A)	10	50	10
Plastic expansion (type B)	8	50	8
Chemical bond	M16	85	18

Table 3. Masonry anchors features: d_0=nominal diameter; h_{ef}=embedment depth; d_h=hole diameter

Anchor type	d_0 [mm]	h_{ef} [mm]	d_h [mm]
Plastic expansion (type A)	10	50	10
Plastic expansion (type B)	8	50	8
Chemical bond	10	85	15

Table 4. Specimens and fixtures characteristics

Anchor type	Base material	Mass [kg]	Number of specimens
Undercut	UC[1]	400	2
	CC[2]	400	2
Metal expansion	UC	400	3
	CC	400	3
Plastic expansion (type A)	UC	250	3
	CC	250	3
Plastic expansion (type B)	UC	85	2
	CC	85	1
Chemical bond	UC	400	2
	CC	400	2
Plastic expansion (type A)	HBM[3]	85	6
Plastic expansion (type B)	HBM	50	5
Chemical bond	HBM	200	4

[1]UC = Uncracked concrete;
[2]CC = Cracked concrete;
[3]HBM = Hollow brick masonry

TEST ANALYSES AND RESULTS

A first evaluation considers the comparison between accelerations captured directly by the accelerometers and those computed from the displacements recorded through the spatial positioning system. The values of the acceleration measures at the ground level allow a verification of the input signal while those from sensors fixed at a certain height provide information on the structural units response. The values recorded on the masses give an indication on the dynamic behaviour of different fixtures. These values mainly depend on the connection condition which developed during the testing. Therefore indirectly it is possible to observe the behaviour of post-installed anchor specimens in addition to the immediate experimental observations, i.e. specimens failure modes and maximum peak acceleration suffered.

The considered tri-axial accelerations refer: (1) to the sensors for the control of the testing system, (2) to accelerometers attached to the shaking table and (3) to the accelerometers fixed to the walls at the fixtures height, in addition to (4) to the acceleration values obtained from the displacement of markers. The most relevant ones are those installed at the base beam of the structures and those on the steel masses.

The aim of this first processing phase was to go backward to the design stage of the experimental campaign evaluating and discussing the setup decisions and validating the assumptions considered previous to the testing.

EXPERIMENTAL OBSERVATIONS

Concrete (TS1, TS2, TS3)

Each tested anchor typology manifested a different behaviour. In this way the occurrence of typical failure modes related to anchor types can be observed. The damages experienced by the various parts of the anchoring system and by the support surface allowed a response for every specimen to be studied.

Metal expansion anchor M12 never reached collapse in both concrete conditions, withstanding to all the steps during the three test sessions up to the maximum level of scaled input signal (Figure 5). Nevertheless in both cases relevant shear deformations on the stud and a crushing of the external sleeve were shown by the specimens, especially by those installed in cracked concrete. In addition a concrete detachment below the specimen installation point as well as a hole enlargement were noticed.

The chemical anchor with M16 bar highlighted different behaviour depending on the support surface conditions (Figure 5). For the specimens installed in non-cracked concrete no failure and no damages of the fastening system were observed after the test sessions. On the other hand the application in cracked concrete showed a pull-out failure with a 4cm deep concrete cone. Also a shear deformation of the bar was recorded. Therefore it can be pointed out that the crack width is a crucial issue to be deepened especially for chemical anchors, as this aspect influences prominently the specimens performance as already demonstrated in past studies (Hoehler, 2006). Further analyses, especially focused on the influence of the cracked support, will allow an in depth interpretation of the obtained results.

Undercut anchor specimens with M10 stud were used to fix a mass of 400kg, like the three previous types (Figure 6). This type never attained failure in both support conditions, namely cracked and uncracked concrete. However relevant shear deformations of the bar and sleeve opening were observed. Also the hole showed a significant damage for the most of the specimens under testing.

The plastic expansion anchor with diameter of 10mm (type A) fixed a mass of 250kg in the concrete test sessions (Figure 6). In uncracked conditions the failure was reached in one case (G3) due to the steel failure of the screw, while in other cases (G1, G2) it overcame the maximum scaled input signal without any failure. Whereas in cracked concrete – with a Δw of 0.35mm – the specimens failure was always reached because of slipping (H1, H3) or of shear breakage of the screw (H2). The specimen H1 showed also a damage in the plastic sleeve as a secondary mechanism, while the failure of specimen H2 was related to a slipping of the entire fastening system. Anchor specimens in both support conditions caused damage of the base material surface around the fixing point.

Plastic expansion anchor with a diameter of 8mm (type B) reached failure in two specimens over three due to shear breakage of the screw after plastic sleeve slipping (Figure 7). One of the two (E3) was installed in cracked concrete and the other (F3) in non-cracked concrete. In the third case (I3) the specimen installed in non-cracked concrete did not reach the failure and showed a 2mm slipping.

Figure 5. Expansion metal anchor after the test in cracked concrete (A2) and non-cracked concrete (B2); Chemical anchor after the test in non-cracked concrete (C1) and cracked concrete (D2)

Figure 6. Undercut anchor after the test in cracked concrete (E1) and non-cracked concrete (F2); plastic expansion anchor type A after the test in non-cracked concrete (G1) and cracked concrete (H2)

Figure 7. Plastic expansion anchor type B after the test in cracked concrete

Masonry (TS4, TS5)

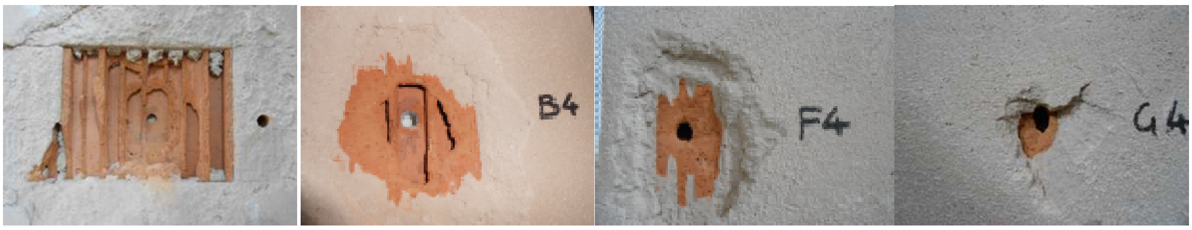
In general after the test sessions with installation in masonry anchor specimens showed low level of slipping for all the tested typologies. The observed failure modes for the fixing in lightweight hollow bricks were highly related to geometrical and mechanical characteristics of the base material.

The failure of the chemical anchor with a M10 stud, affected a wide area of the brick where it was installed (Figure 8). In particular the breakage of the external shell and a partial failure of the inner web were observed in the bricks of fixing. For one specimen (B4) also a partial separation between the resin and the steel stud was observed. For another specimen (E5) no failure was reached at the end of the testing session (ZPA = 1.10g).

Plastic expansion anchor with a 10mm diameter (type A) showed a pull-out failure as a consequence of the hole damage on the brick shell, causing the detachment of a relevant part of plaster around the fixing point (Figure 8). Several tested specimens (F4, G4, H4, A5, B5) manifested a similar failure mode.

The plastic expansion anchor with a 8mm diameter (type B) showed in all cases a slipping of the plastic sleeve, though with final collapse caused by the shear failure of the screw (Figure 9). The slipping of this fastener was measured as less than 10mm in the worst case.

The different mass of the fixtures for the various anchor typologies does not allow an immediate comparison among all the tested anchors. Nevertheless, as a general consideration, it can be noticed that all the specimens installed on masonry and subjected to a lower number of steps with a single input step (TS5) showed higher resistance levels rather than the respective value after several subsequent seismic steps (TS4). For chemical anchors as for type A plastic anchors a 20% reduction was identified. Whereas type B plastic anchors did not show relevant variations in their behaviour.



(a) (b) (c) (d)

Figure 8. Failure modes on masonry infill walls: Chemical anchor (a, b); plastic expansion anchor type A (c, d)

Figure 9. Plastic expansion anchor type B after the test in masonry infill walls

MEASURED ACCELERATIONS

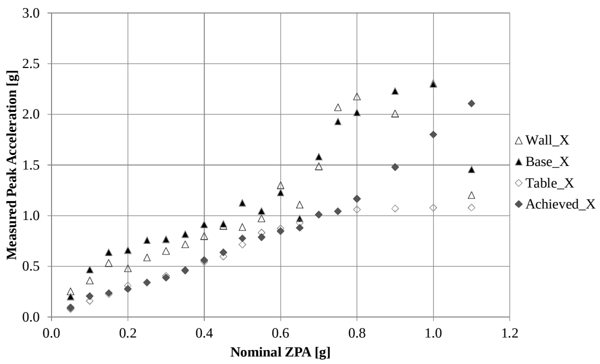
The analysis of the structural units response subjected to the input signal is a preliminary fundamental consideration to be developed for a complete understanding of the connection trend behaviour. The purpose is to verify the amplification which the anchored elements were subjected to during the shaking as well as to verify the results about the amplification ratio between base and anchoring height obtained from the design of the experimental campaign.

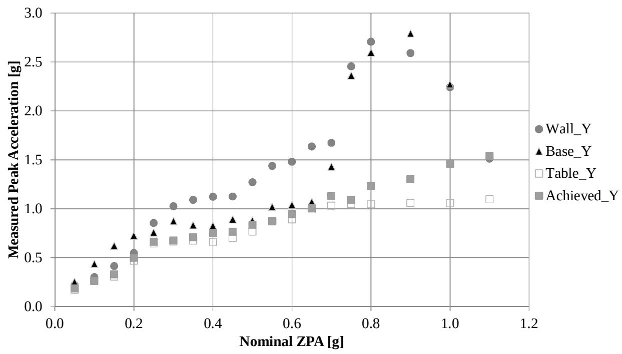
Two FE Models were created in order to predict the stiffness of both structures and thus the foresee accelerations acting at the wall fixing height (Mazzon et al., 2013b). It is therefore needed to validate the designed testing layout according to the expected accelerations at different heights. The amplification acceleration ratio allows the influence of the structure and its filtering action to be evaluated.

Figure 10 and Figure 11 show the trend of the measured accelerations with reference to the nominal step for the case of a test session on the concrete and masonry unit respectively. The charts underline as the input (“achieved” signal) and the values recorded on the shaking table (“Table” signal) substantially agree along the whole test except for the last steps on some sessions.

A more noticeable difference can be noticed if the input/table signal and the valued recorded on the support at the fixing points (“wall” signal) are compared. In that case the influence of the structure can be clearly identified and in general this induces an amplification of accelerations and a modification of frequencies. This modification along the test is especially evident for the case of the masonry infill wall unit. This is probably due to the continuous increasing damage induced on the infill walls that cracked and split out parts of the top row of all the masonry panels.

In the case of the concrete unit a substantial difference between the overall trend of accelerations at base and fixing levels becomes evident only at the higher steps.





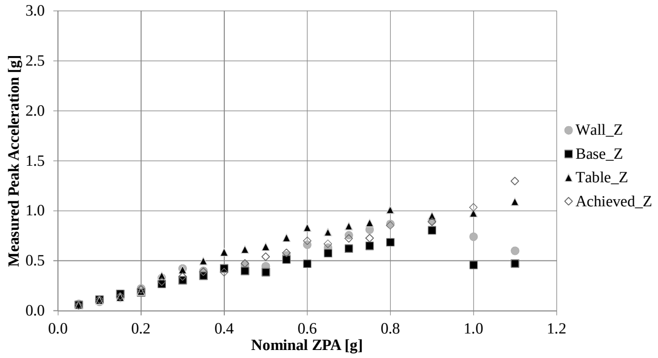


Figure 10. Example of measured peak accelerations for the concrete unit (test session 3)

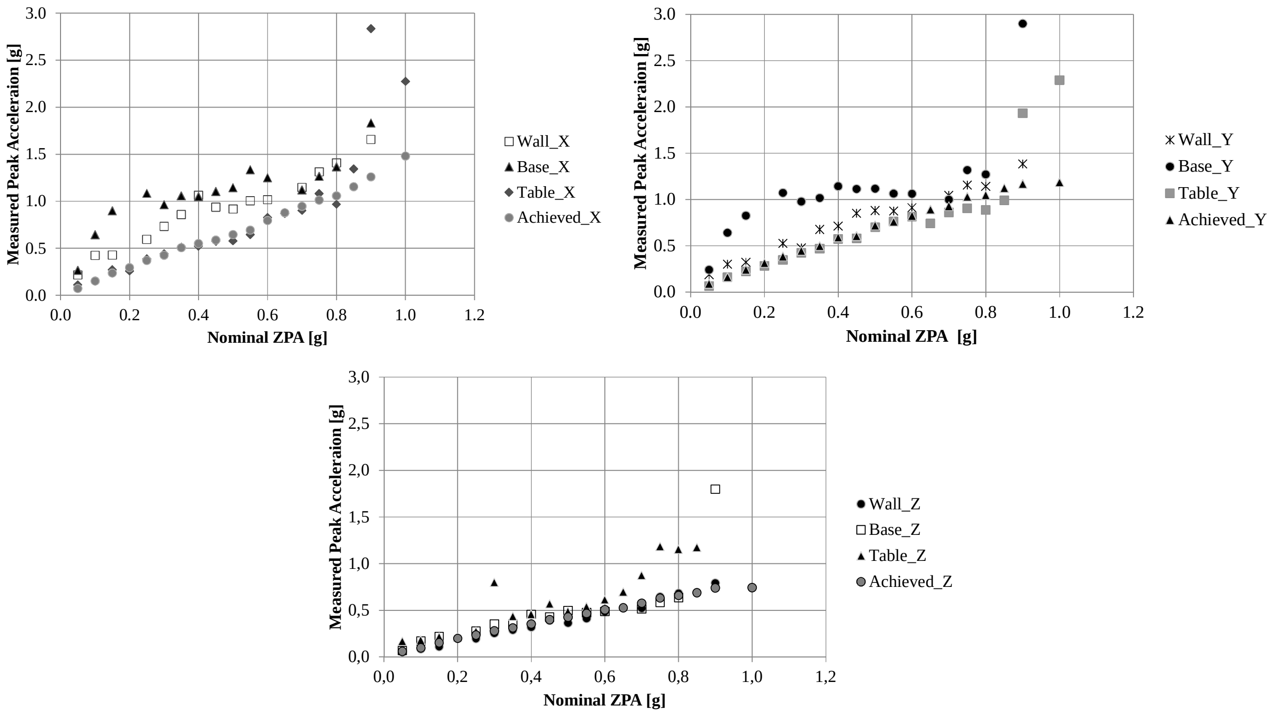


Figure 11. Example of measured peak accelerations for the masonry infill walls unit (test session 4)

ANALYSES OF ACCELERATIONS

In this section a study on the relation between accelerations measured on the structural unit walls, at fixing height, and on the fixtures is presented. This kind of investigation allows the presence of variation of trend behaviour of specimens to be recognized, i.e. whether after a certain number of testing steps the specimen behaviour modified depending on the decreasing of stiffness, that is related to the progressive damage of the fastening system. Such finding leads to get information on where a discontinuity point, related to specimen slipping from the base material surface, can be found.

Concerning the testing in concrete the general behaviour manifested by all the specimens is linear (Figure 12) with almost no differences between those installed in uncracked (B, C, F, G) and cracked concrete (A, D, E, H). A slightly evident trend of decreasing in fixture acceleration in relation to the highest ZPA steps of support acceleration can be also noticed.

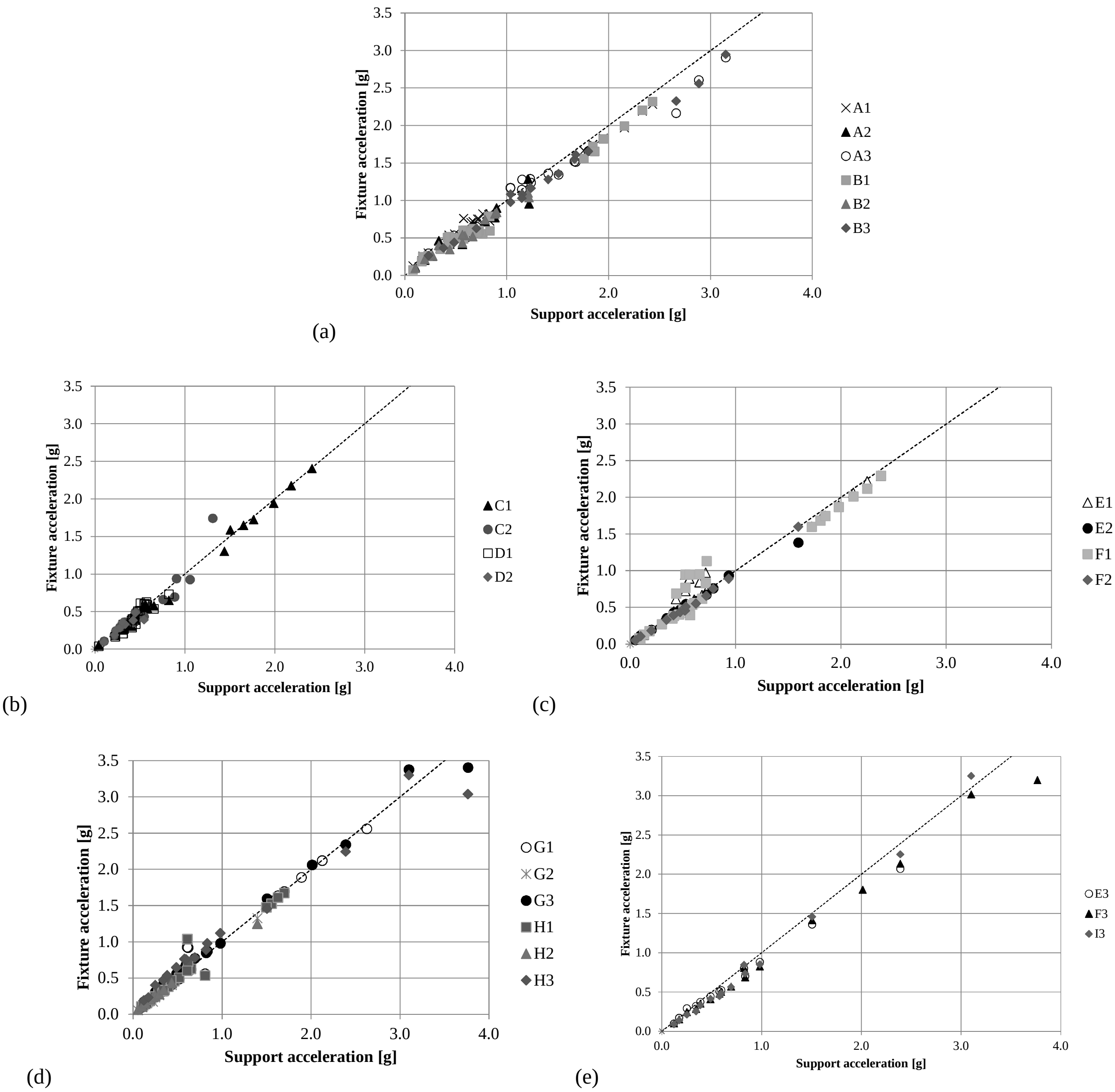


Figure 12. Maximum recorded acceleration on the fixture versus maximum recorded acceleration on the support at each testing step for concrete application of metal expansion anchor (a), chemical anchor (b), undercut anchor (c), plastic expansion anchor type A (d) and plastic expansion anchor type B (e)

As regards the testing in masonry it can be observed more differences in the relation trend through the time history steps than what noticed in the concrete structural unit.

Each anchor type showed a different behaviour especially for test session 5 when the value of fixture acceleration is always less than the acceleration measured on the wall, at the same height. In those cases also the type of wall restraint has to be taken into account. A further study can be carried out in the future in order to relate the behaviour of specimens to the behaviour of the masonry infill wall they are installed in.

Concerning the chemical anchor (Figure 13a) after the first steps with low ZPA when the relation is linear, the amplification of acceleration measured on the fixture starts decreasing. Plastic expansion anchor type A (Figure 13b) shows a behaviour similar to the previous anchor type in test session 4, i.e. a linear trend of relation, but a more significant decrease of fixture acceleration in test session 5, when the wall behaviour has also to take into account. Finally, plastic expansion anchor (Figure 13c) distinguishes among other types as the acceleration ratio from the beginning is greater than 1 and it stays over the bisecting line excepted few points of test session 5, where also the wall behaviour may affect the data. This finding means that the fixture in case (c) was more free to move due to connection behaviour of that particular anchor type.

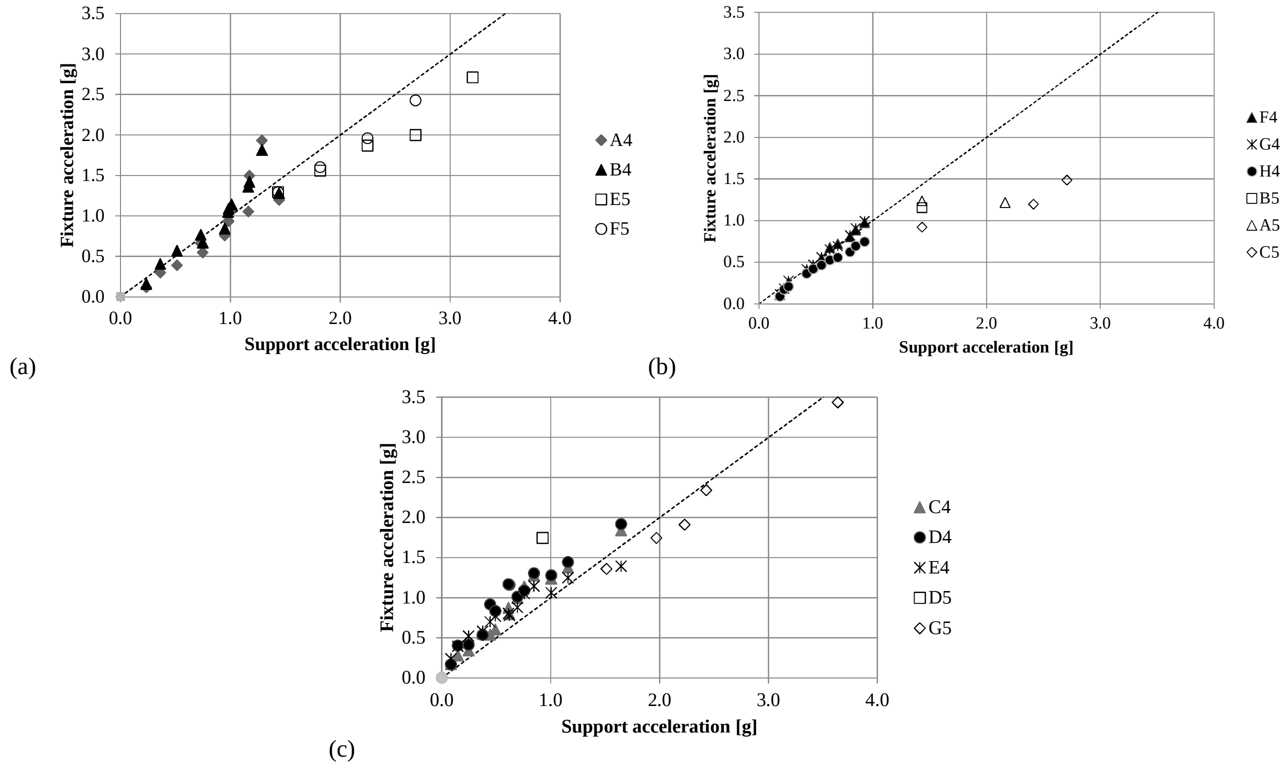


Figure 13. Maximum recorded acceleration on the fixture versus maximum recorded acceleration on the support at each testing step for masonry application of chemical anchor (a), plastic expansion anchor type A (b) and plastic expansion anchor type B (c)

CONCLUSIVE REMARKS

The preliminary analyses of accelerations presented in this paper after the shake-table testing of post-installed anchors reveal the progressive damage of the structural units. This overall behaviour is more evident for the RC structure with masonry infill walls. Nevertheless also in the concrete unit a slightly variation of the acceleration ratio among the considered structural elements can be recognized.

The linear trend observed on the acceleration ratio between mass and support underlines as the anchor specimens were able to transfer the whole acceleration from the structure to the fixture. This was analysed in terms of peak measured acceleration, up to almost the last testing steps. The trend among the measured accelerations was indeed mainly linear for the concrete structural unit. Concerning the masonry infill wall structural unit there is a difference in the outcomes of a particular anchor type (plastic expansion type B) which provided the fixture with an amplification of peak acceleration, as the mean of the data points lays above the bisecting line.

The presented analyses also allow a difference in the behaviour of different anchor typologies to be studied. While the anchors installed in concrete manifested in most cases an overall linear trend, the plastic expansion anchors showed a variation on their overall behaviour. This was more evident for the installation in the masonry support, rather than that in concrete.

The above presented analyses of acceleration are a fundamental step for the computation of loads acting on the different anchor typologies. In the case of fastenings that manifested an overall linear trend the possible relative acceleration will not have a relevant influence on the computation of the acting load. Differently the relative acceleration should be taken into account when the ratio deviates from the linear trend. These results will constitute the basis for the development of further analyses to evaluate the force acting on the tested anchors and to relate these with the measured slip values. This will lead to a more comprehensive evaluation of the overall dynamic behaviour of the selected specimens.

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