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SHAKING TABLE TESTS ON POST-INSTALLED TRADITIONAL AND DISSIPATIVE FASTENERS IN UNCRACKED AND CRACKED CONCRETE

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Abstract

In consideration of the increased community expectations towards the reduction of post-earthquake damage to non-structural elements, even for strong seismic events, and in the context of performance-based design, this paper focuses on the experimental investigation of the seismic behavior of fasteners and practical implementation to improve their performance.
In the last decade several laboratory tests have been carried out to better understand the seismic behavior of anchors and a new concept of low-damage solution has been proposed. This earthquake-resistant fastener, referred to as EQ-Rod, relies upon the use of supplemental damping to reduce the acceleration demand and consequently the force applied to the non-structural component placed on the floors of multi-storey reinforced concrete buildings.
Building on this original research, the paper presents a second experimental campaign carried out at the Structural Laboratory of the University of Rome "La Sapienza" to extend the investigation and propose solutions to a larger variety of fastening systems (expansion and chemical anchors) and focusing on the behavior in both un-cracked and cracked concrete.
A comprehensive set of uniaxial shaking table tests have been performed using a specific apparatus and considering a test matrix with spectra compatible accelerograms.
The experimental tests provided satisfactory confirmation of the beneficial effects of the concept of dissipative anchor rod to seismically protect the non-structural components and suggestions are provided to further improve the system.

Keywords: Non-structural system, Post-installed fastener, Earthquake-Resistant Rod, Shake table tests, Seismic Performance.

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1 INTRODUCTION

Non-structural components are typically connected to reinforced concrete buildings using post-installed fasteners, which are usually preferred by designers for their flexibility, easy handling and large field of possible applications compared to cast-in-place anchors.

In the research field, the study of the seismic behaviour of this type of anchors is spreading, with the aim of better understanding through experimental and numerical investigations both the seismic performance of anchors and the effect onto the attached non-structural system. Following the higher community expectations towards the reduction of post-earthquake damage, economic losses and downtime, mainly due to non-structural systems, the study and improvement of the seismic behavior of post-installed anchors/fasteners is becoming fundamental.

Over the past few decades, large amount of work has been carried out to study the behaviour of different types of individual or groups of post-installed anchors, subjected to quasi-static and dynamic forces or displacement-controlled loading protocols, either in uncracked or cracked concrete [1, 2, 3, 4, 5]. In recent years, the dynamic behaviour of post-installed fasteners has been also investigated through shake table tests, including tests performed using tri-axial shake table excitations [6], or uniaxial shaking table tests on anchors installed in regions where cracking of the structure is expected due to the seismically induced demands [7].

In the current context of performance-based seismic design and with the aim of improving fastening techniques, a comprehensive experimental and numerical campaign has been carried out at the University of Canterbury to develop a new generation of post-installed fasteners referred to as EQ-Rod, able to reduce the damage onto the non-structural component under severe seismic events [8]. This type of fastener relies upon the use of supplemental damping, either viscous and/or hysteretic, added in series or in parallel to a traditional fastener to reduce the acceleration demand and consequently the force applied to the non-structural component and represents a first generation of low-damage system for this type of component (Figure 1).

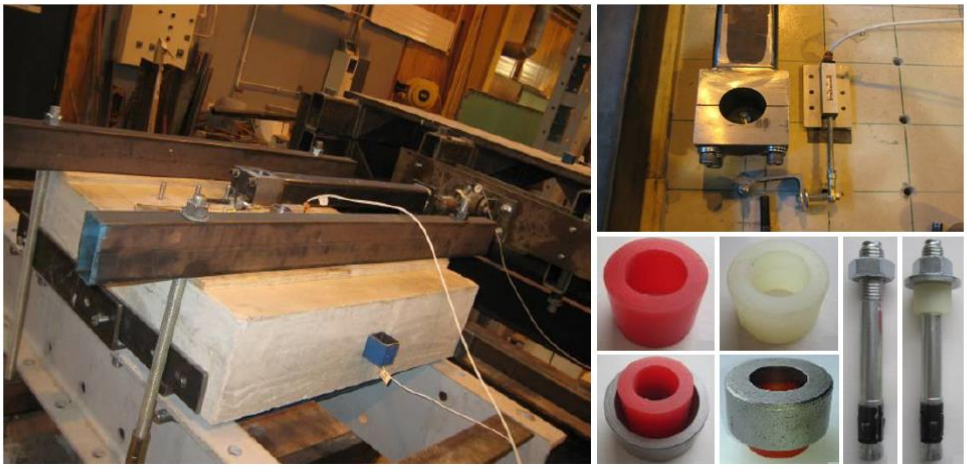

Figure 1: Shake-table test details on traditional and EQ-Rod fasteners (left and top-right) and configurations adopted for the supplemental damping devices (bottom-right) [8, 9].

Building on this original research, the paper presents the findings of a second experimental campaign carried out at the Structural Laboratory of the University of Rome “La Sapienza” with the aim of extending the previous investigation and propose solutions to a larger variety of fastening systems (traditional and low-damage expansion and chemical anchors), focusing on the behavior in both un-cracked and cracked concrete.

2 INNOVATIVE EARTHQUAKE-RESISTANT FASTENERS

Fasteners can be grouped in function of the way they transfer tension loads to the anchorage material [10]. Load-transfer mechanisms are typically identified as: 1) mechanical interlock, where the load is transferred by bearing the fastener onto the anchorage material; 2) friction, due to fasteners that have a geometry that generates an expansion force, which in turn produces a friction force between the anchor and the sides of the drilled hole; 3) bond, where the tension load is transferred to the anchorage material by a chemical interlock.

During an earthquake, a fastener may be subjected to tension, shear, combined tension-shear, and combined shear and bending cycling loading [10]. Referring to a non-structural component anchored to a reinforced concrete structure using a fastener, during the seismic motion the anchor loads develop due to the inertial response of the non-structural element to the acceleration of the building floor to which it is attached.

The seismic behaviour of the acceleration-sensitive non-structural component is typically described by floor acceleration response spectra, which provide the maximum associated acceleration as a function of the fundamental period of vibration of the element. The response spectra depend on the system viscous damping (non-structural component + connections), therefore by increasing the value of the damping the demands on the non-structural component can be reduced. Taking into account this concept and in order to achieve a significant reduction of the seismic demand and increase in performance, the idea of adding supplemental damping to the fasteners started to develop and a first innovative damage-resistant fastener was developed [8, 9], the so-called EQ-Rod fastener. An external supplemental damper is added to a traditional anchor, increasing the system damping, and this results in reducing the amplitude of the spectral response and the acceleration on the non-structural element under a given ground motion (Figure 2).

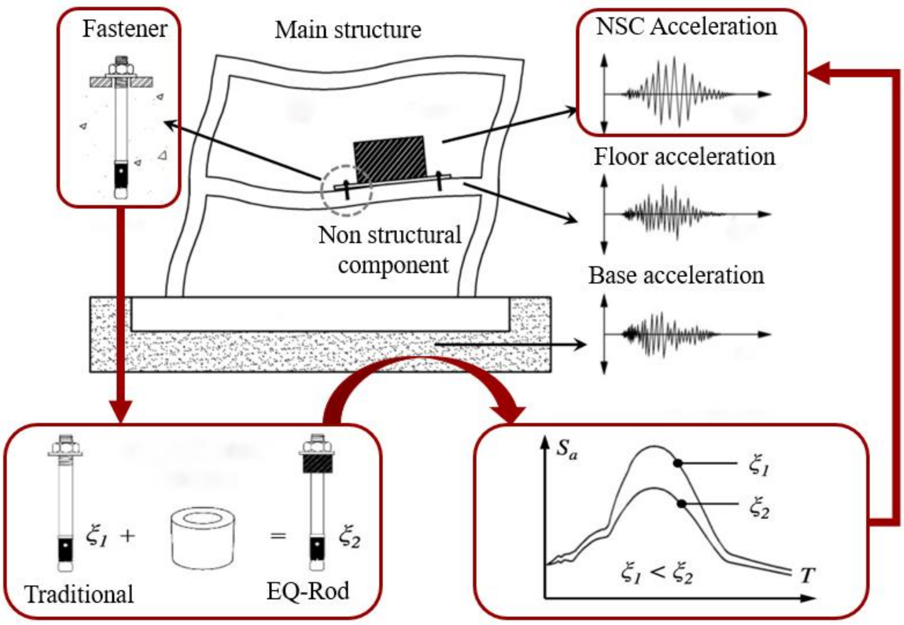

Figure 2: Effect of supplemental damping on fasteners in reducing the seismic demands of the attached non-structural component (modified after [8]).

3 RESEARCH MOTIVATION

Following on the first initial yet comprehensive experimental campaign on the EQ-Rod solution for post-installed fasteners, further investigations are needed to explore the beneficial effects of the concept of dissipative anchor rod to seismically protect the non-structural components for a greater variety of fastening systems (expansion and chemical anchors) in both un-cracked and cracked concrete.

The shaking table tests carried in 2008 at the University of Canterbury focused on the response of expansion fasteners in uncracked concrete. As a follow-up it was considered important to extend the application of the low-damage solution to other types of anchors and system conditions. In fact, fasteners can be located in a crack that either forms during an earthquake or has formed at some prior time and the crack width can typically change over the duration of an earthquake, therefore investigations are also needed to apply the low-damage strategy in cracked concrete.

In such a context, a new low-damage prototype (EQ-Rod 2.0) has been proposed and a new Research and Development project has been carried out between the University of Rome “La Sapienza” (Research Leader), the University of Natural Resources and Life Sciences (Vienna, Austria), and Fischer (Fischerwerke Artur Fischer GmbH & Co. KG).

The paper describes the shaking table test setup, the testing protocol and the key results and findings of the experimental investigation carried out at Sapienza University

4 EXPERIMENTAL CAMPAIGN

Uniaxial shake table tests have been carried out at the Structural Engineering Laboratory of the University of Rome “La Sapienza” through a specific testing protocol capable of simulating the dynamic response of fasteners under seismic actions.

The experimental campaign involved different phases: 1) preparation of the ad-hoc test setup and monitoring system; 2) preliminary tests on different types of anchors to confirm the correct functioning of the whole testing apparatus, including fastener installation, loading protocol, control and acquisition system, post-processing of the results; 3) finally, further and comprehensive experimental tests have been performed according to a detailed test matrix on cracked and uncracked blocks.

Six different types of M12 anchors – i.e. two categories, expansion (FAZ II) and chemical (Superbond) anchors, in three configurations, traditional, EQ-Rod 2.0, traditional with mortar filling - have been tested under real recorded earthquake ground motions, through shear loads to the anchors, to investigate the anchor behaviour as well as the accelerations and displacements transferred to the attached non-structural component.

4.1 Test setup

The experimental Single-Degree of Freedom (SDOF) test setup comprises of three main parts: a concrete block representing the floor slab; a driving mass representing the attached non-structural element (NSE); the anchorage system. The shake table reproduces the selected input motion transmitted to the floor concrete block where the anchor rod is installed and connected through a lever arm to the driving mass, that is excited (Figure 3).

The 1.5m x 1.5m shake-table at the University of Rome “La Sapienza” is a uni-axial earthquake ground motion simulator (MOOG n. L081-324-011), consisting of guiding rails designed for a maximum stroke (travel) of ± 200 mm and a maximum payload capacity of 2 tons.

The concrete floor slab on which the anchor is installed is represented by a cracked or uncracked concrete block (80x80x30 cm, f_{ck}=20 MPa) rigidly attached to the shake table. Lateral sliding is prevented by steel angles fixed on the shake table in both directions.

A driving mass of 1046 kg, made by assembling steel plates, represents the non-structural mass attached to the anchor rod. The mass is located on low-friction linear rail guides (LLT of the SKF Group), fixed on an exterior steel frame, to allow the movement along the shaking direction. These guides have precision-ground raceways and a carriage with four rows of balls in an X-arrangement, the dynamic coefficient of friction of the whole system is approximately μ_d=0.5% while the maximum acceleration guaranteed is 75 m/s^2.

A steel lever-arm connects the driving mass to the anchor and consists of L profiles of S355 steel seated to a steel plate where the load cell ends. The rigid lever arm spreads the inertia force from the driving mass to the fastener and the inertia force acts in the center of the attached element, therefore the vertical displacement of the anchor is not influenced by additional push and pull forces.

Finally, a steel plate with two different holes is located on the concrete block to install the fasteners. A larger hole, with a diameter of 24mm, is adopted for the EQ-Rod solutions, while the smaller one, with a diameter of 14mm, is adopted for the traditional anchors.

Figure 3: Details of shake-table test setup.

4.2 Test instrumentation

The load transferring to the anchor rod is measured by a load cell, with a maximum capacity of 200kN (tension and compression), installed between the driving mass and the steel lever-arm.

Three accelerometers attached to the driving mass, the concrete block and the shake table are used to monitor the system acceleration. The shake table acceleration is measured to compare the input record and the output signal of the table. The acceleration of the concrete block is needed to check that the connection between concrete block and shake table is effectively “rigid”. The acceleration of the driving mass provides information on the effect of the fastener in the transfer of acceleration to the non-structural component.

Three LVDT transducers are used to measure the relative displacement between driving mass and concrete block. In particular, the vertical displacement of the anchor rod is monitored and the horizontal displacement of both the fastener and the steel plate is measured; the difference between these horizontal displacements provides information on the gap between steel plate and fastener.

4.3 Input motions

Different types of input signals have been considered for the experimental test campaign. Initially, sinusoidal inputs, either acceleration history with constant frequency and varying the amplitude (from 0.05 g to 0.5 g) or sweep signals with amplitude of 0.15g and 0.3g, a frequency range of 1-5Hz and a time-period of 10s, were considered to study the dynamic behaviour of the fasteners. Finally, the experimental tests were carried out using time-history earthquake inputs, selecting three Far Field and two Near Fault ground motions, properly scaled. The characteristics of the selected records can be found in Table 1, while the acceleration spectra of each record are shown in Figure 4.

Input name	Year	M_w	Record ID
Cape Mendocino	1992	7	EQ_1
Landers	1992	7.3	EQ_2
Friuli	1976	6	EQ_3
Kobe	1995	6.8	EQ_4
Christchurch	2011	6.3	EQ_5

Table 1: Main characteristics of the selected input earthquake records.

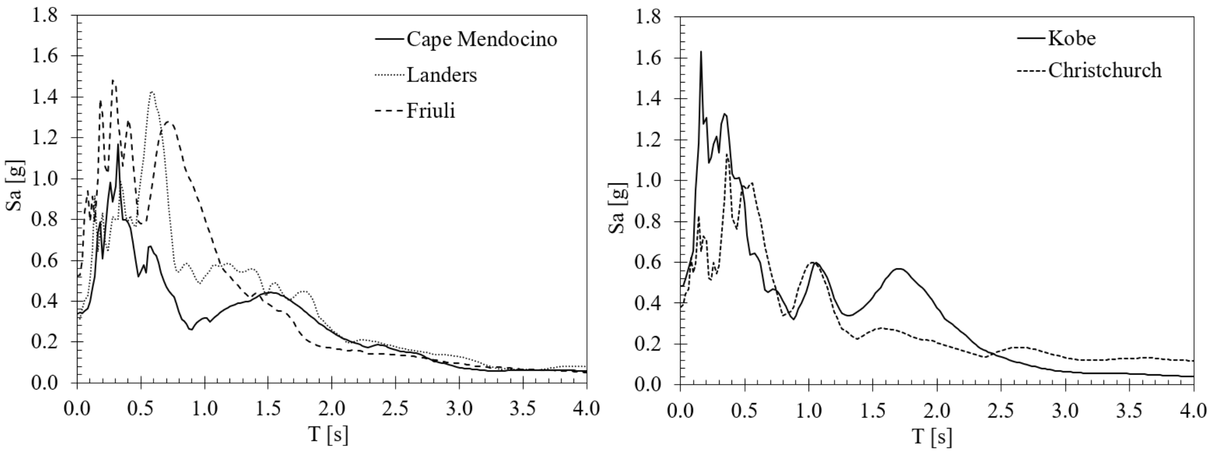

Figure 4: Acceleration response spectra for the Far Field (left) and Near Fault (right) input ground motions.

4.4 Testing protocol

The installation of anchors is a crucial phase for the experimental test. In fact, test results can be directly affected by the installation operation of the fasteners, therefore for each type of anchors the installation procedure has to be applied in a rigorous manner before performing the shaking table tests.

Each M12 fastener was installed into the concrete block following the procedure specified by the manufacturer. Regarding the concrete blocks, to study the seismic performance of anchor rods located along cracks parallel to the shaking direction, an appropriate apparatus was developed to generate these cracks (Figure 5): a bar with a sharp edge was positioned exactly between two cotters inserted in the concrete block and the crack was opened by blowing onto both cotters on the left and on the right of the bar until the crack reaches 0.5 mm width.

Figure 5: Testing protocol for crack opening.

Therefore, the shaking table tests were performed following a specific test matrix that included three different expansion anchors (*FAZ II Traditional, FAZ II EQ-Rod and FAZ II Traditional with Mortar Filling*) and three different chemical anchors (*Superbond Traditional, Superbond EQ-Rod and Superbond Traditional with Mortar Filling*) anchored in uncracked and cracked concrete blocks. The configurations with mortar filling indicated the presence of mortar into the gap due to construction tolerances between steel plate and anchor.

Referring to the five input motions previously described and their simulated aftershocks (EQ_i-50), assumed as 50% of the input motion (amplitude-only reduction, same duration), for each type of expansion/chemical fastener the experimental test matrix in Table 2 was considered.

Test ID	Input motion	Type of fastener
1	EQ_1 + EQ_1-50	Traditional
2	EQ_1 + EQ_1-50	Traditional with Mortar Filling
3	EQ_1 + EQ_1-50	EQ-Rod
4	EQ_2 + EQ_2-50	Traditional
5	EQ_2 + EQ_2-50	Traditional with Mortar Filling
6	EQ_2 + EQ_2-50	EQ-Rod
7	EQ_3 + EQ_3-50	Traditional
8	EQ_3 + EQ_3-50	Traditional with Mortar Filling
9	EQ_3 + EQ_3-50	EQ-Rod
10	EQ_4 + EQ_4-50	Traditional
11	EQ_4 + EQ_4-50	Traditional with Mortar Filling
12	EQ_4 + EQ_4-50	EQ-Rod
13	EQ_5 + EQ_5-50	Traditional
14	EQ_5 + EQ_5-50	Traditional with Mortar Filling
15	EQ_5 + EQ_5-50	EQ-Rod

Table 2: Test matrix for the FAZII or Superbond type of fasteners.

The tests in Table 2 were performed three times on different anchors of the same typology to provide at least three responses for the same input motion and derive mean and standard deviation probabilistic results. In total, the test matrix of the experimental campaign consisted of a total number of 360 shake table tests (input + aftershocks), 180 for uncracked concrete and 180 for cracked concrete.

5 EXPERIMENTAL RESULTS

The acceleration of the driving mass representing the non-structural system and the hysteretic behaviour (force-displacement relationship) of the fastener anchored in the concrete block fixed to the shake table have been determined from the experimental tests.

This paper presents only some of the main findings and discussions related to the obtained experimental tests on all the anchor types (Figure 6), while a more complete description of all the experimental data can be found in the Research Project report [11].

The efficacy of EQ-Rod prototypes in improving the seismic response of the system is determined as the capacity of reducing the acceleration demand onto the connected non-structural component (driving mass) when compared to the demand related to the application of traditional (expansion or chemical) fasteners.

Concerning the data processing, it is observed that the data obtained with the high-speed logger connected to the shake table was filtered using a low pass (6th order Butterworth filter) with a cut off frequency of 20Hz to reduce external noise.

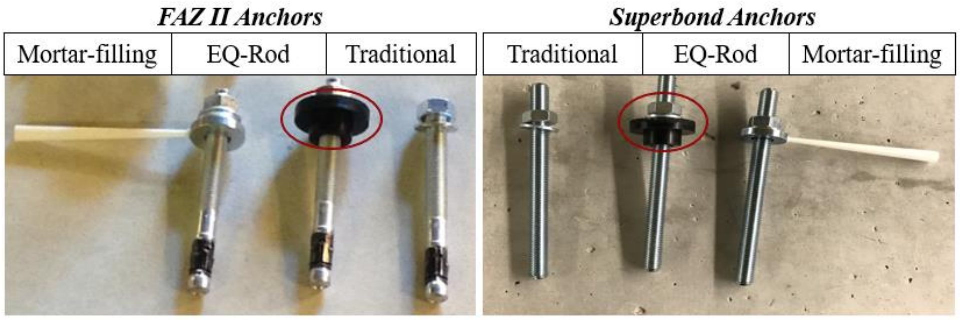

Figure 6: FAZ II and Superbond anchors.

5.1 Sinusoidal input test results

The preliminary experimental results from the sinusoidal input tests on uncracked concrete blocks are initially presented in terms of hysteretic loops for both Traditional anchor and EQ-Rod 2.0 considering either FAZ II or Superbond configurations (Figure 7).

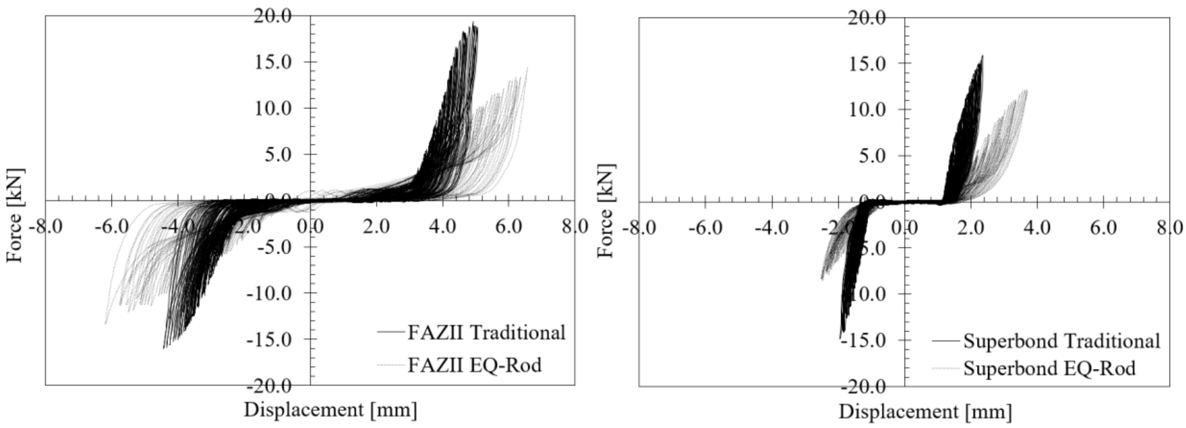

Figure 7: Comparison between FAZ II Traditional and FAZ II EQ-Rod (left) and Superbond Traditional and Superbond EQ-Rod (right) in terms of Hysteretic Loop for uncracked concrete.

The installation of each anchor followed the testing protocol, with the only difference that the application of the torque was reduced to 0 Nm - instead of 30Nm or 20 Nm - in order to simulate the complete loss of tightening torque due to long period.

Analyzing the maximum force values determined on the non-structural system, the results showed a reduction in the range of 15-25% for the EQ-Rod solution when compared to the FAZII traditional one, and 20-35% for EQ-Rod system when compared to the Superbond traditional anchor. These results were associated to the large hysteretic energy of the EQ-Rod system, thus to the greater displacements that it reached during most of the cycles.

5.2 Ground motion input test results

In accordance to the proposed test matrix, the shake table tests were carried out for all the proposed configurations in uncracked and cracked concrete. Test results in terms of force/displacement curves of the driving mass are shown for just one test of an input record (EQ_1) for all the three types of expansion anchors (Figure 8) and chemical anchors (Figure 9).

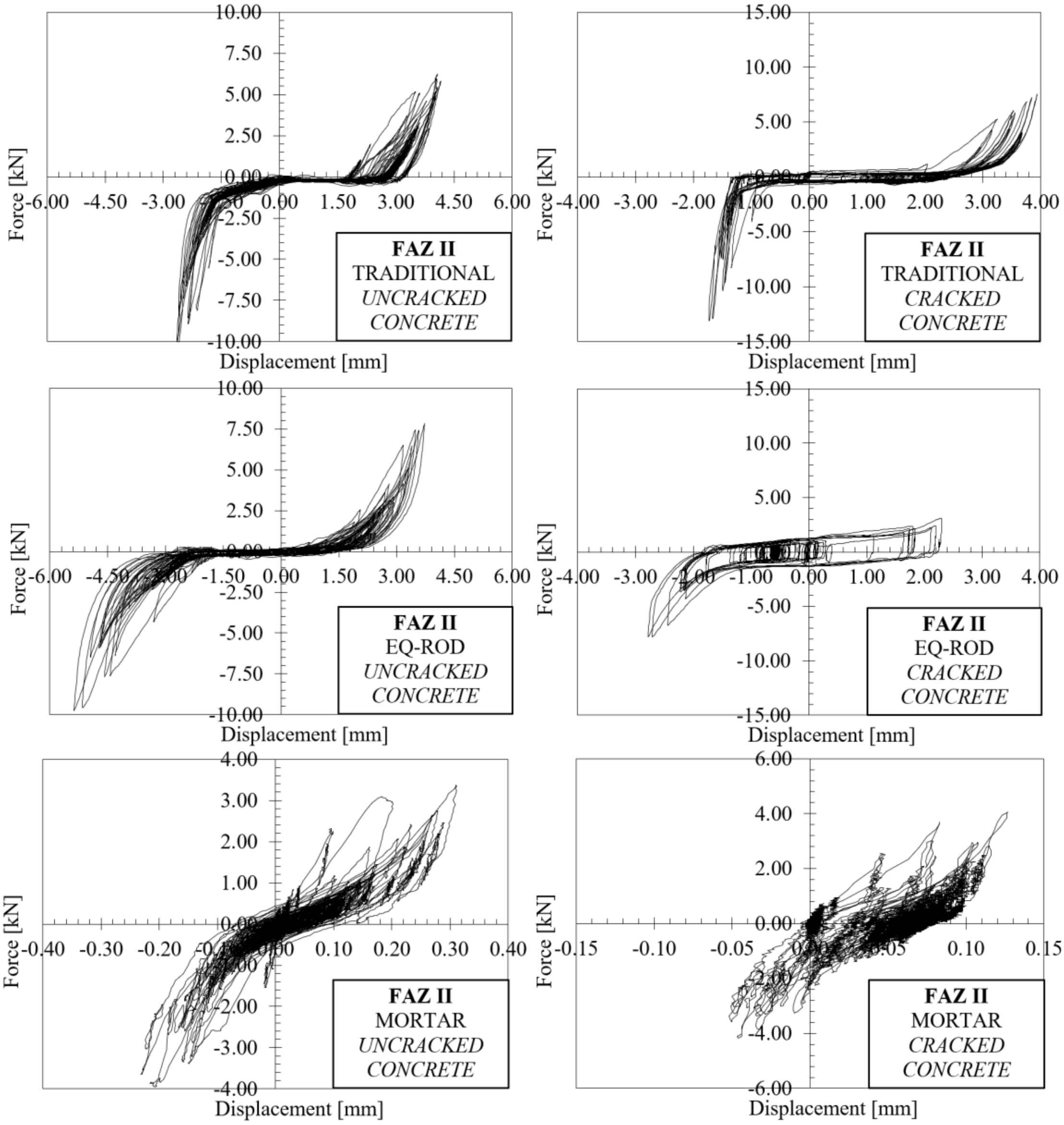

Figure 8: Force-displacement relationships for the FAZII Traditional, FAZII EQ-Rod, FAZII Traditional with Mortar Filling in uncracked and cracked concrete.

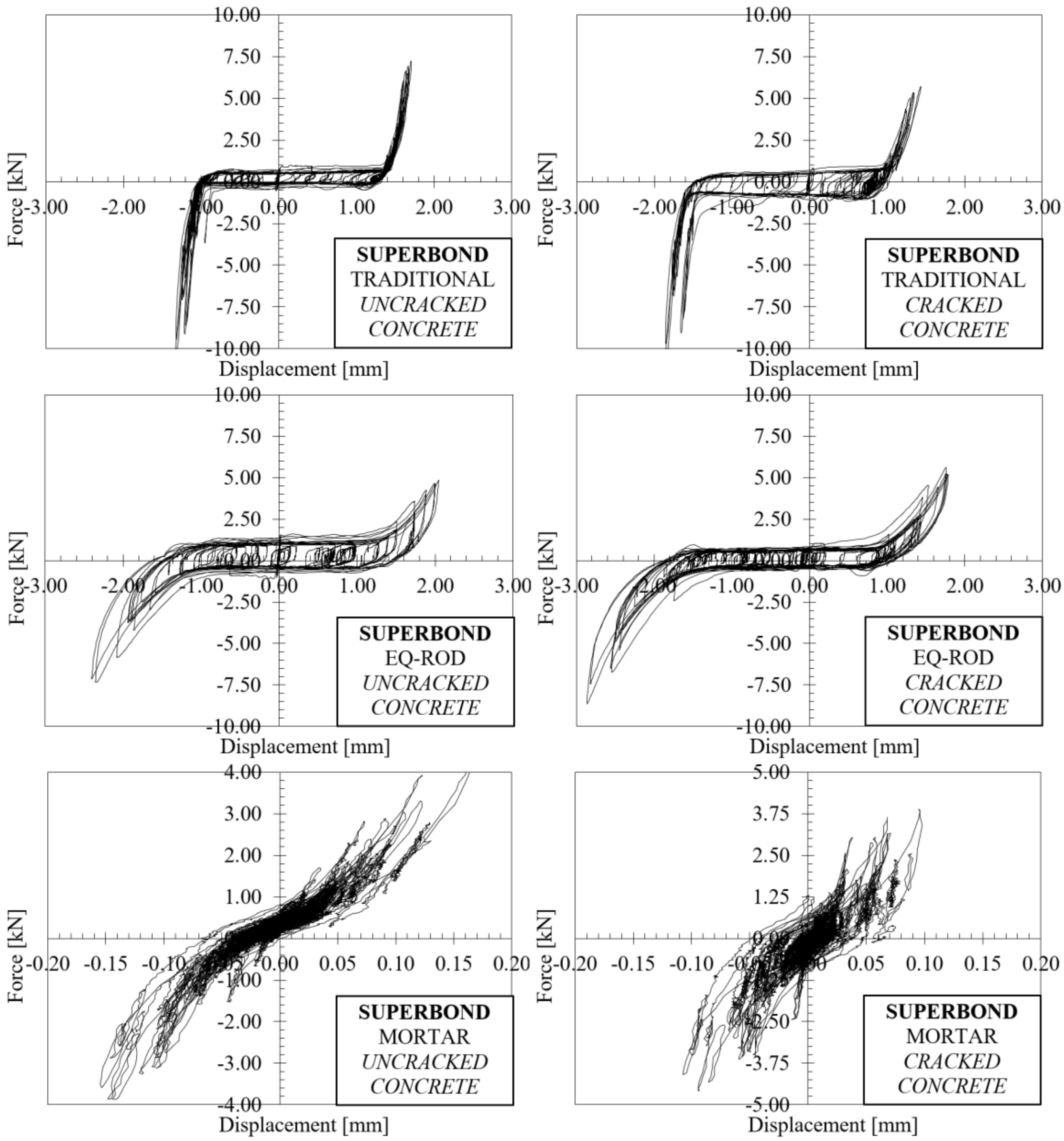

Figure 9: Force-displacement relationships for the Superbond Traditional, Superbond EQ-Rod, Superbond with Mortar Filling in uncracked and cracked concrete.

The experimental tests provided the following main results: 1) for the expansion anchors in uncracked concrete, the EQ-Rod system can provide a reduction in terms of driving mass forces and accelerations in the range of 10-15% for the input signals and of 15-30% for the aftershocks; 2) for the expansion anchors in cracked concrete the EQ-Rod reduction in terms of driving mass forces is in the range of 20-30%, while in terms of accelerations in the range of 25-40% for the input signals and 30-40% for both accelerations and forces considering the aftershocks; 3) for chemical anchors in uncracked concrete the EQ-Rod reduction is 10-25% in terms of forces and 20-30% in terms of accelerations when considering the input signals, while 30-40% for both demands when considering the aftershocks; 4) finally, for chemical anchors in cracked concrete, the EQ-Rod solution provided a reduction in terms of driving mass forces and accelerations in the range of 20-30% for the input signals and of 30-40% for the aftershocks.

The performance and benefits of EQ-Rod in cracked concrete appears in general superior to that in uncracked concrete. It should be noted that, in addition to the inherent isolation-dissipation mechanism, EQ-Rod anchor reaches larger displacements in cracked concrete and the overall system has thus lower frequencies (higher period) and attracts less forces as it moves towards the de-amplification part of the spectra.

Notwithstanding the efficiency of the proposed EQ-Rod configuration, test results also showed that a significant benefit in terms of response can be obtained by applying mortar filling, with a reduction of 40-60% for all the analyzed configurations in uncracked and cracked concrete. This high reduction is due to the lack of dynamic impact (pounding) due to the presence of gaps between steel plate/anchor and concrete/anchor. The anchor with mortar filling thus acts as a more rigid element, while EQ-Rod allows for a combination of isolation and dissipation. It appears that a combination of the two concepts (filling the gap and adding a tight-fit EQ-Rod dissipative system) would be able to provide the best and most reliable benefits.

6 CONCLUSIONS

With the aim of improving the seismic response of non-structural systems anchored to concrete structures a post-installed fastener with supplemental damping has been experimentally proposed and studied. The first prototype of this solution, referred to as EQ-Rod, was developed in 2008, while a new system, named EQ-Rod 2.0, is herein considered, conceived as an easily applicable solution useful for either expansion or chemical fasteners. The seismic performance of this system has been deeply studied through uni-directional shake table tests using specific testing protocols for both uncracked and cracked concrete.

Worth noting that due to the larger geometric tolerances between the EQ-rod and fastener rod (inner tolerance/gap) as well as due to the different material of the new EQ-Rod when compared to the initial prototype, during the tests the bearing stresses on the rubber material led sometimes to the yielding of the rubber damper with permanent deformations and amplifications of the dynamic effects and this in turns reduced the efficiency of the EQ-Rod system as a damping element under cumulative aftershocks.

However, the experimental results confirmed that the concept of adding damping to a fastener can be adopted to improve the seismic performance of the system, reducing both accelerations and forces onto the connected non-structural component. The proposed system can thus be considered as a damage-control solution for such applications.

The shake table test results provided evidence of the efficiency of the dissipative solution, yet further improvements of the system design are needed and recommended to fully exploit the novelty of the dissipative/isolation mechanism of the EQ-Rod and obtain a greater and robust reduction of the driving mass accelerations when compared to the traditional anchor (with or without mortar filling).

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] R. Eligehausen, Behavior, design and testing of anchors in cracked concrete. *ACI Structural Journal*, **130**, S123-175, 1991.

[2] R. Eligehausen and T. Balogh, Behavior of fasteners loaded in tension in cracked reinforced concrete. *ACI Structural Journal*, **92**, S35, 1995.

[3] P. Mahrenholtz and R. Eligehausen, Behavior of anchor groups installed in cracked concrete under simulated seismic actions. *Fracture Mechanics of Concrete and Concrete Structures - Assessment, Durability, Monitoring and Retrofitting of Concrete Structures*, B. H. Oh, et al. (eds), Korea Concrete Institute, Seoul, 2010.

[4] M. S. Hoehler, P. Mahrenholtz, R. Eligehausen, Behavior of Anchors in Concrete at Seismic-Relevant Loading Rates. *ACI Structural Journal*, **108**, 2, 238-247, 2011.

[5] E. Vintzéleou, and R. Eligehausen, Behaviour of Fasteners under Monotonic or Cyclic Shear Displacements, Anchors in Concrete – Design and Behavior. *ACI Special Publication*, SP 130-7, 181-204, 2012.

[6] A. Rieder, Seismic Response of Post-Installed Anchors in Concrete. *PhD Dissertation*, University of Natural Resources and Life Sciences, Vienna, Austria, 2009.

[7] P. Mahrenholtz, T.C. Hutchinson, and R. Eligehausen, Shake Table Tests on Suspended Nonstructural Components in Cyclically Cracked Concrete, *Journal of Structural Engineering*, **140**, 11, 2014.

[8] P. Quintana-Gallo, M. Moghaddasi, S. Pampanin, and K. Bergmeister, Shake table tests of post-installed fasteners in concrete with supplemental damping. ACI Structural Journal, **115**, 3, 595-606, 2018.

[9] S. Pampanin, M. Moghaddasi, P. Quintana-Gallo, A. Rieder, EQ-Rod a New Generation of Earthquake-Resistant Fasteners. *Report prepared for Fischerwerke Artur Fischer GmbH & Co. KG*, University of Canterbury, Christchurch, New Zealand, 2008.

[10] R. Eligehausen, R. Mallée, J.F. Silva, *Anchorage in Concrete Construction*, 1st Edition, Ernest and Sohn Publisher, Berlin, Germany, 2006.

[11] S. Pampanin, S. Bianchi, J. Ciurlanti, Shake table tests of post-installed anchors with supplemental damping (EQ-Rod 2.0). *Report prepared for Fischerwerke Artur Fischer GmbH & Co. KG,* Sapienza University of Rome, Rome, Italy, 2017.