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Seismic risk mitigation in industrial plants with structural fastening systems

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ABSTRACT

The updating of European Standard EN 1992-4, edited in September 2018, has provided a relevant review regarding the design of fastening systems for using in concrete. A deep change has also concerned structural anchorages in application field, as result as it needed to furnish a regulation regarding their use in terms of design and verification against seismic hazard. For this reason, the code requires to verify all of elements of a building, both primary and secondary structural elements and no-structural and for facilities components. Therefore, every fastener system is involved in seismic verification.

Fasteners are classified both following load transfer mode, that it can be mechanical interlocking, friction and bond, and the way of installation (cast-in and post-installed). In the last years, even after issuing of 18/2012/UE European indication, great attention has been focused by industrial sector on seismic risk problem in industrial plants, and on possible solutions of mitigation as well. Several typologies of existent industrial equipment, containing dangerous substances given that inflammable, explosive and toxic, are connected to foundation structures by means of anchorage systems adoption that sometimes don't completely result enough to resist against seismic actions, significantly increasing seismic risk value of the plant.

1 INTRODUCTION

1.1 *State of the art*

Fastening systems application has represented in the last years a very important topic for design of structural engineering in seismic area because, if on the one hand their widely diffusion is confirmed, and on the other only recently, technical code has been updated for this purpose.

During the Ninetys, many authors have published several scientific documents, (e.g.: Eligehausen and Balogh 1995 and Fuchs et al. 1995) regarding the fastening application in reinforced concrete: in particular Eligehausen R. has taken the lead in order to develop studies of fastening systems issue. Therefore Eligehausen and co-authors in Anchorage in Concrete Construction (2006) have widely examined modern fastening technology. This handbook represents a milestone because the authors have satisfied all aspect of application of anchors in concrete, from a historical review to design of fasteners passing through classification of fastening systems and their principles and the analysis of behaviour of themselves applying to concrete.

After, other authors (Nuti and Santini 2008) deeply focused on performance of anchors in seismic conditions. In particular, they detailed and discussed the main themes aiming at fastening systems designing for buildings in seismic area: different failure modes considerations, influence of cracking and analysis of ductility capacity.

Fastening systems classification is clearly provided not only by Eligehausen and co-authors in Anchorage in Concrete Construction (2006), but also in PhD dissertation document by Hoehler (Behavior and Testing of Fastenings to Concrete for use in Seismic Applications in 2006).

First at all, fasteners are differentiated by the way of the transfer loading: mechanical interlocking, friction and bond. For this latter typology, Cook and other several researchers offered experimental and numerical investigation on adhesive anchors (Cook et al. 1993, Cook et al. 1998, Cook et al. 2001), providing technical papers on ACI Structural Journal.

Fastening system can be also classified by the way they are installed: cast-in fastener and post-installed. Cast-in anchors (Heath et al. 2018) are applied in the mould before concrete casting; on the other hand, post-installed (Mahrenholtz et al. 2015) system is installed into the cured anchorage material.

Considering load-bearing behaviour, as described in just mentioned documents by Eligehausen and co-authors (2006) and by Hoelher in 2006, fastener systems characteristics are analysed both under seismic tension loads (Petersen et al. 2018a) and testing shear action (Petersen et al. 2018b).

It's important underline that anchors performance are also discussed following their failure mode: in particular, Delhomme and co-authors in 2010, examined failure mode through experimental pull-out test carried out on a joint between metallic component and concrete block. After, other authors (Gurbuz et al. 2011) presented pull-out experimental results on anchor in concrete. In the same document, they also provided a predictive model collecting data from other experimental pull-out tests published in scientific literature.

Even experimental campaigns are available in the current state of knowledge: Zeman and co-authors (2015) demonstrated anchors capacity under seismic action by means of tests under alternating shear load cycling. After, in 2016, the influence of the supplementary reinforcement application on fasteners group with multiple anchor rows was studied by Sharma and other researchers. Thanks to these results, a model has been further developed in order to predict performances and failure modes of this system realized by anchorages with this supplementary reinforcement.

1.2 Anchors system legislation overview

In European Union, the use of metal anchors in concrete structural elements follows standard in according to ETAG 001 code "Guideline for European technical approval of metal anchors for use in concrete". In particular, Annex C "Design methods for anchorages" proposes the design and verification procedure regarding metal anchors applied to the concrete. Fasteners system design is based on partial safety coefficients, wherein design actions values have not to overcome design resistance ones.

$$S_D \leq R_D \tag{1}$$

where:

S_D = design actions value

R_D = design resistance value.

Three typologies of design methods are described: A, B and C. By means of method "A", $S_D \leq R_D$ formulation has to be satisfied both for all of loading directions (tensile and shear) and for all of failure modes (steel failure, pull-out failure, Concrete cone failure, splitting failure due to anchor installation, splitting failure due to loading, concrete pry-out failure, concrete edge failure).

The design method "B" is based on a simplified approach: the design value of the characteristic strength is not depending from loading direction and failure mode typology. If the case of anchoring groups occurs, the most stressed anchor has to be verified in terms of (1) formulation.

At the end, also in method "C" a simplified approach rules design procedure, wherein only a F_D design resistance value is provided, not depending from loading direction and failure mode typology.

Annex B "Tests for admissible service conditions detailed information" describes the test programs in order to determine the admissible service conditions. More specifically, the definition of pre-qualification tests of the metal anchors under seismic action was regulated in Europe thanks to publication of Annex E of the ETAG 001. Aiming at studying anchors performance under seismic loads, depending on severity level of the tests, two seismic categories, C1 and C2, are distinguished: C1 seismic category provides anchor resistance in terms of strength; meanwhile, in category C2, the anchoring capacity is expressed both in terms of strength both of deformation.

The EOTA TR 045 standard should be also mentioned: basically, it describes the procedure for the design of the anchors, for transferring seismic actions to the concrete, according to the rules defined in Annex E of the ETAG 001.

From September 2018, the reference standard code has become the "European Standard EN 1992-4", which provides a design method for anchoring (structural and non-structural elements to structural components connection), used for actions transferring on concrete.

In the USA, the implementation of metal anchors is regulated in ACI 355.2, wherein post-installed mechanical anchors tests are explicated under static and cyclic loading and describes test program and requirements for the assessment of them for using in concrete. Thus, from ACI 355.2, AC193 and AC308 of International Code Council (ICC) acceptance criteria are edited. In particular, ACI 193 comprises anchors tests and AC308 describes tests and design of chemical anchors.

Concerning to anchors design, similar to philosophy of TR 045 European standard, American code defines indications in ACI 318 – Appendix D document (e.g., in D.2.2 cast-in and post-installed fasteners are considered). At the same way, chemical anchors performances are evaluated according to AC308.

In the last two decades, Federation Internationale du Beton (FIB) has also provided documents on fastening system: in 1999 “Textbook on behavior, design and performance” is published; after, FIB provided “Fib Guide for the Design of Fastening in concrete” (2007). Then, “Design of anchorages in concrete. Guide to good practice” is made available in 2011 for scientific and professional purposes.

2 THE SEISMIC RISK IN INDUSTRIAL PLANTS

Industrial plants are complex systems and this complexity is due to the numerous connections, equipment and components, together with the complexity of their operations that makes them particularly vulnerable to Natural Technological accident (Na-Tech). Past earthquakes world over, such as 1994 Northridge-USA, 1995 Kobe- Japan, 1999 Kocaeli-Turkey, 2008 Wenchuan-China, 2010 Chile, 2011 Tohoku-Japan and 2011 and 2011 Van-Turkey earthquakes, have evidenced that naturals phenomena may cause severe damages to equipment items, resulting in loss of containment, thus in multiple and extended releases of hazardous substances.

In all these earthquakes, older and heavy industrial facilities, especially those with taller structures that partially to totally collapsed, were more affected by the earthquake than newer facilities. Losses associated with business interruption were more severe for these types of facilities. For light industrial facilities, building damage turned out to be the primary reason for direct and indirect losses. For refineries and other chemical processing facilities, non-building structures turned out to be the most vulnerable, with tanks being the most susceptible to earthquake and fire damage.

If industrial facilities store large amount of hazardous materials, accidental scenarios as fire, explosion or toxic dispersion may be triggered, thus possibly involving working people within the installation and/or population living in the close surrounding or in the urban area where the industrial installation is located. Many industrial installations are placed in seismic prone areas, often near the urban centres, have many years of services and the equipment are often designed according to past seismic codes. This latter is an important aspect because influence directly the seismic vulnerability of the industrial components. Moreover, it is important emphasize that the past seismic regulation often underestimated the seismic hazard of the sites and allowed the use of simple seismic analysis method sometimes not applicable to the complex industrial facilities.

At the European level, there is no specific law or any type of guidelines regarding Na-Tech risk assessment and management. However, there are several laws indirectly mentioning Na-Tech, through the rules governing industrial establishments handling hazardous materials, landfill sites and waste treatment plants. The reference for the prevention of chemical accident in the European Commission is the Seveso Directive III (2012/18/EU). The aim of the Seveso Directive is the prevention of major accidents which involve dangerous substances and the limitation of their consequences for human health and the environment, with a view to ensuring a high level of protection throughout the Union in a consistent and effective manner. The European Directive calls for the analysis of natural causes in minimum data and information to be considered in the safety report. The accidental risk analysis of “natural causes” which may lead to a chemical accident implies the consideration of the potential threat of natural hazards in the hazard analysis, and carrying out preventive measures to reduce the likelihood of an accident.

3 ANCHORING SYSTEM IN INDUSTRIAL EQUIPMENT

The type, number and size of process units required in a process plant depends on a variety of factors including the type of the final products required. The interconnected units making up a process plant are a maze of tanks, furnaces, columns, reactors, heat exchangers, pumps, pipes, fittings, and valves.

The seismic vulnerability of many of these equipment is strongly dependent to the resistance of the base anchoring system adopted. Among these, basing on their process function and constraints condition, it is possible to identify:

- Vertical cylindrical vessels which are directly anchored to foundations and free along the height. This category includes columns, reactor, stacks and flares. The base anchorage of these structure is recognized by the use of anchor bars with ended hooks that are installed during the foundation casting (shown in Figure 2-a).
- Horizontal cylindrical vessels supported by two or more saddles connected to a foundation platform through a fastening

system. One saddle is generally fixed while the other one is free to slide to allow for thermal expansion. In this category, many pressurized storage tanks and heat exchangers are included. The anchoring system is generally realized with the use of anchor bolts installed during the foundation casting (shown in Figure 2-b).

- Process furnaces and steam boilers. These equipment have function to heat or vaporize large amounts of liquid products, according to the chemical process demand. Generally, process furnaces are large structures, with few standardized shapes, mainly of cathedral type and vertical cylinder. These furnaces are kept elevated from the ground by means of short steel or reinforced concrete columns, the connection between the two structural systems is obtained through an anchor bars with ended hooks that are installed during the casting of the supporting structure (shown in Figure 1).
- Equipment directly placed on supporting structures. Many units can be placed on a support structure, among these is possible to find heat exchangers, air-cooler, pipes and pumps. Support structures are often made of steel and the columns are directly anchored to the foundation with a fastening system (shown in Figure 2-c).

One of the most common damage observed during the past earthquakes for these typologies of structure, is the failure of anchor bolts at the base due to the excessive traction and shear stresses.
For example, during the Loma Prieta earthquake (California, USA, 7 October 1989, Magnitude 6.9) a refinery was seriously damaged, where the most important effect was on the anchor bolts of about 20 vertical vessels, on 50 vessels (Patel, 2012). For these reasons, the right design or the installation of a new anchoring system, instead of the older (old-existent) one, according to recent technical codes, can be a relevant intervention of seismic risk mitigation of an industrial plant.

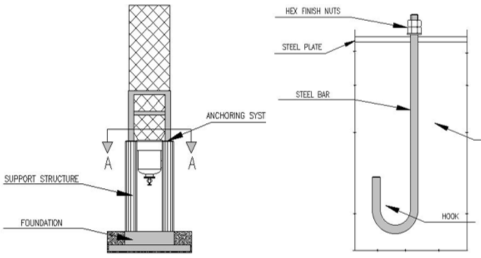

Figure 1. Typical configuration of a process furnaces anchoring system

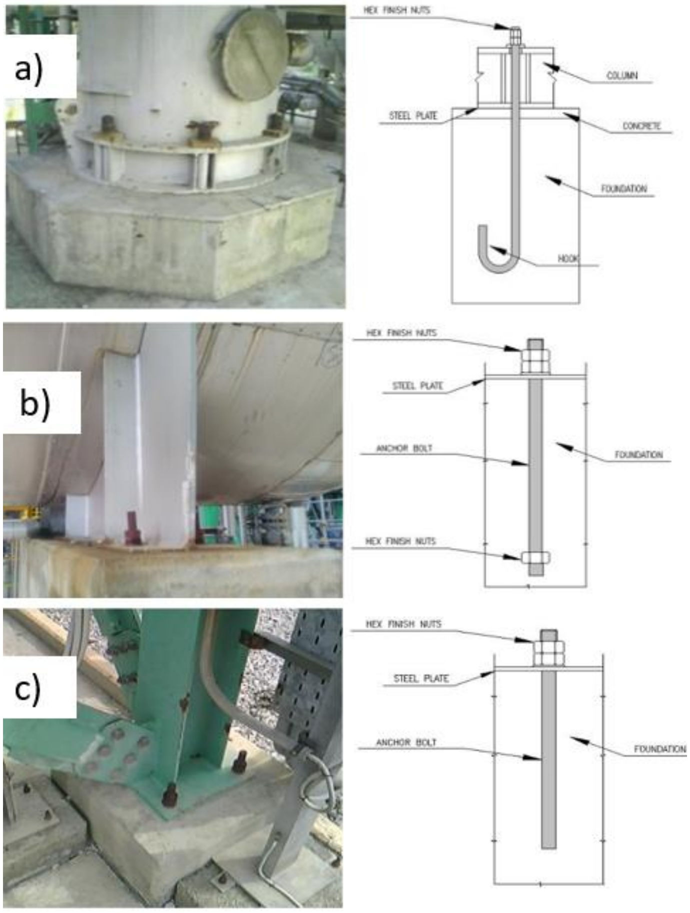

Figure 2. Typical anchorage systems of a column (a), horizontal vessels (b) and supporting structure (c)

4 CASE STUDY

In this section, the effectiveness of a new anchoring system for the seismic protection of equipment and seismic risk mitigation is showed. As case study, an air-cooled heat exchangers of a process plant ideally placed in Priolo Gargallo city (Italy) has been considered. These units are used to cool and/or condense process streams with ambient air as the cooling medium rather than water. Air-cooler and tube bundle are the principles component of a cooling system and are generally placed at the top of steel supporting structure, in which the base columns are anchored directly to the concrete foundation.
The steel supporting structure, here considered as example of application, is composed by three span along longitudinal direction and one span in the transverse direction (shown in Figure 3). Ten air-coolers weighing 18.000 kg and five tube bundles of total weight 100.000 kg, are stand at the last level of the supporting structure at around 12.50 m from the ground level. This large mass is supported by three rows of steel columns made with profiles HEA200 and IPE 220 steel beams.

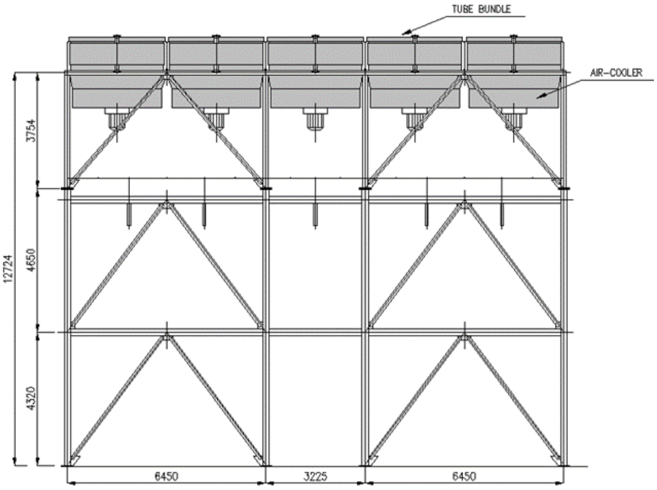

Figure 3. Longitudinal view of the structure: air-cooled heat exchangers placed at the top of a steel supporting structure

The existing base anchoring system is realized with four bolt M24, class 8.8, that connect each column to the foundation structure (shown in Figure 4).

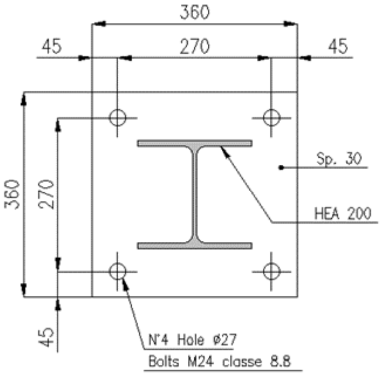

Figure 4. Plan view of the existing anchoring system

In order to evaluate the safety level of the existing anchoring system and its mean annual frequency of damaging, according to the seismic hazard of the site, time-history (T-H) analyses has been conducted using the refined FEM model shown in the Figure 5.

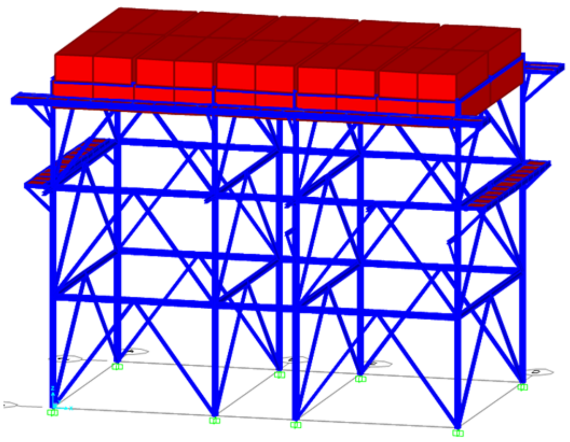

Figure 5. FEM model representation

Seismic analysis has been performed applying a set of 49 ground motion records, selected from the European Strong Motion Database (Luzi et al. 2016) according to seven site specific response spectra with increasing value of the return period (T_r=60, 75, 101, 712, 949, 1950 and 2475 yeas). Tensile and shear forces have been assessed for each anchor bolt while the resistance has been evaluated according to the European Code EN 1992-4.

In Figure 6, an example of the response in terms of shear forces, to one of accelerograms at the base of a single steel column of the supporting structure, is shown.

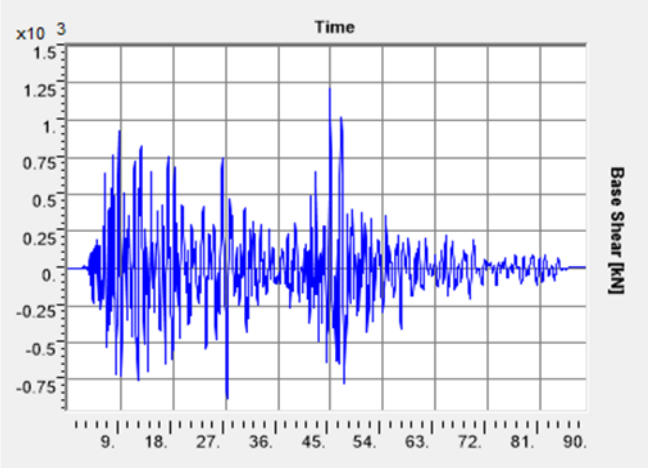

Figure 6. Example of Time-History of Base shear components for one of the record

By the Cloud Analysis method (Jalayer and Cornell, 2003) the median value (θ) of the peak ground acceleration (PGA) that cause the exceedance of the limit state representing by the damaging of the anchoring system, has been evaluated together with the logarithmic standard deviation .

Figure 7 shows the maximum response values expressed in terms of "safety coefficient" of an anchor bolt, for each ground motion, represented on a log-log plane, where a linear regression of the results is also reported.

Once the definition of the limit state has been established, that is the value of the resistance of the anchor bolt, the fragility curve can be evaluated, as shown in Figure 8, where the median value and the logarithmic standard deviation are also reported. Given the presence of numerous piping and connections, the breaking of the anchoring system at the base, with the sliding of the support structure can cause releases of hazardous materials.

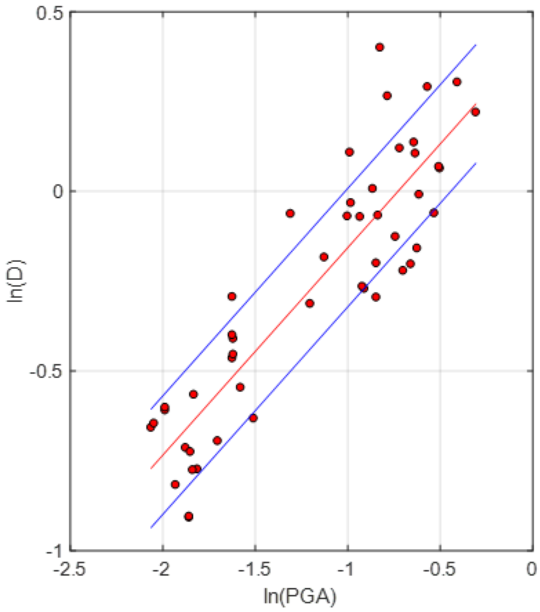

Figure 7. Probabilistic response model (Cloud Analysis)

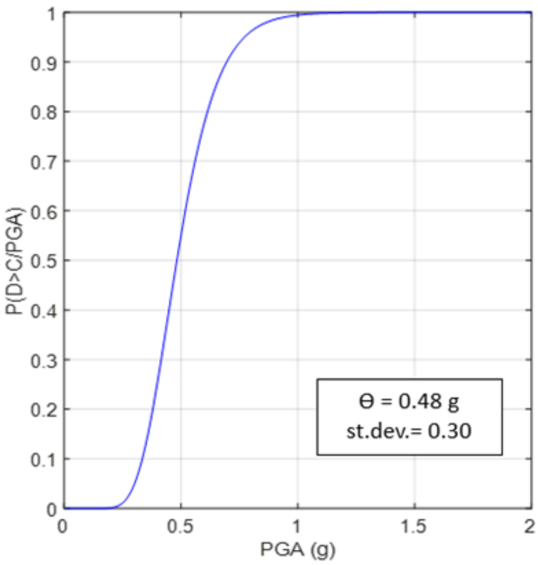

Figure 8. Fragility curve associated with the damage to the anchoring system at the base of the supporting structure

Given the parameters of the fragility function and the hazard curve of the site, the mean annual frequency λ_{DS} of the damage occurrence, equal to 2.94E-03, has been evaluated according to (Alessandri et al., 2019). The results suggest an improvement in the anchoring system, in order to obtain a decreasing of the mean annual frequency of the damage and avoid possible loss of containment. As shown in Figure 9, one of the possible mitigation actions is to increase the number of the existing bolts, so, additional four bolts M24 post-installed, class 8.8, have been added to the existing ones.

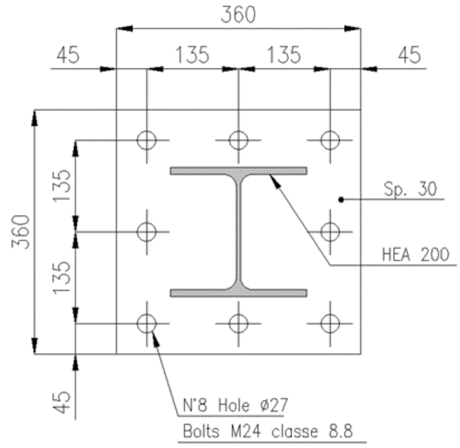

Figure 9. Plan view of the anchoring system with the addition of bolts.

As shown in Figure 10, with this simple intervention that does not require the interruption of the production activities of a plant, the seismic vulnerability of the equipment drastically decreases. The median value (θ) of the peak ground acceleration that cause the exceedance of the limit state increases up to 1.60 g.

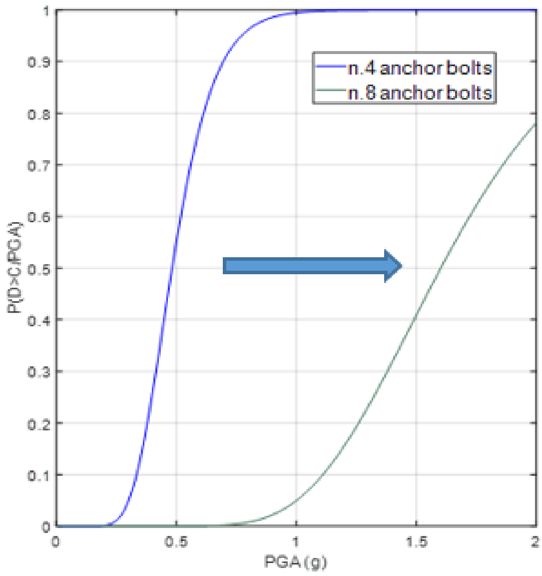

Figure 10. Translations of the fragility curve after adding the anchors bolt

Consequently, also a reduction of the mean annual frequency λ_{DS} of the damage occurrence has been obtained reaching a values of 1.05E-04.

5 CONCLUSIONS

The present document provided a widespread overview of the fastening systems development, in particular, focusing on the considerable importance concerning the diffusion of them, taking into account the new European legislation. Therefore, the value of the risk assessment for an industrial plant was demonstrated: by means of a case study, the efficiency of a correct design of the fastening system was showed. Thanks to the replacement of existing anchor elements, or adding others, the mean annual frequency λ_{DS} of the damage occurrence was decreased, contributing a significant advantage in terms of the connection performance and reduction of the seismic risk of the equipment.

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