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A statistical analysis on the application of seismic isolation on existing buildings without local interventions

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ABSTRACT
After the recent seismic events, many data about buildings damages and ground motion records were collected. The damage information, collected through the AeDES form, are now made available by the Italian Civil Protection on the Da.D.O. web-platform. The ground motions records data are available from various sources, among them one of the most complete is the database ESM (Luzi et a. 2016). In this paper, an analysis of data available on the Da.D.O. database is performed, with the aim to assess the reinforced concrete buildings which have suffered limited or no damage after L'Aquila earthquake of 2009. The GMs records are used in order to evaluate the intensity measure at a large territory scale and to roughly assess the seismic intensity suffered by each considered building. The overlap of this information allows the assessment of the minimum capacity exhibited by the building, this information is further used to define an innovative methodology in order to find the reinforced concrete (RC) buildings that are best suited for seismic isolation retrofit.

1 INTRODUCTION

The recent seismic events that hit the Italian territory (L'Aquila, 2009, Emilia 2012, Centro-Italia 2016, Ischia 2017) have shown the inadequacy of the existing building heritage to resist to seismic events, even of moderate intensity. To this, it should be added that, as demonstrated also in many studied, such as (Kam et al. 2011; Zambrano et al. 2014; Alexander 2017), the reconstruction costs are really high, becoming very often no more sustainable by communities. Notwithstanding the huge scientific production about the intervention techniques, there is a lack of methodologies aimed to retrofit existing buildings through optimal targeted investments for maximizing the benefit-cost ratios of interventions at both large and small scale.

Among the interventions, different traditional and innovative retrofit techniques have been widely developed. For instance, one may mention the techniques based on the introduction of energy dissipation systems (Christopoulos et al. 2008; Sorace and Terenzi 2008; Di Sarno and Manfredi 2010; Ariyaratana and Fahnestock 2011; Braconi et al. 2012; Dall'Asta et al. 2017; Braga et al. 2019), or else the local interventions through composite materials (Hedayati Dezfuli and Alam 2014; Gattulli et al. 2017). Moreover, among these techniques the seismic isolation strategy (Buckle and Mayes 1990; Nagarajaiah et al. 1993; Braga et al. 2005; Jangid 2005; Lignola et al. 2016; Bhagat and Wijeyewickrema 2017), is considered one of the most effective, because it allows a consistent reduction of the lateral forces transmitted to the superstructure, with a significant reduction of the seismic demand on the structural elements. However, very often this technique implies further local interventions in order to fulfil the performance requirements requested by the design codes. This sensibly reduces the convenience of this technique because the interventions may become too much expensive and invasive. Therefore, an index measuring with accuracy the on-site actual response of a building would be very useful in design seismic isolation, especially if it will allow us to avoid further local interventions.

To this end, useful suggestion may rise from the large amount of information about the observed damages on existing buildings suffered during the recent seismic events. These information are provided by the data collected in the AeDES forms (Baggio et al. 2009) compiled during the usability surveys performed after all the seismic events by the Italian Department of Civil Protection. Nowadays, these data are almost fully available for the researchers in the Observed Damage Database (Da.D.O.) (DPC 2015; Dolce et al. 2017). Moreover, thanks to the accelerometric network widespread within the Italian territory, many information are now available in order to assess the ground motions (GMs) intensity measures (IMs) in a big part of the territory struck by a strong earthquake.

The goal of this work is to exploit the large amount of data deriving from past experiences to identify the buildings that are best suited for seismic isolation without the need of further local interventions. By using the data available from the 2009 L'Aquila earthquake, the buildings having suffered null or low damages are identified from the Da.D.O. database. In addition, the maximum spectral accelerations suffered may be estimated by the means of the available GMs records of the ESM database (Luzi et al. 2016). These accelerations can be considered as an index of the minimum capacity exhibited on-site by the considered buildings (D'Amato et al. 2019). Consequently, by assuming some reasonable configuration of seismic isolation systems, the real spectral demand for this hypothetical isolated buildings is estimated. If this acceleration, provoking null or limited damages, results higher than the one expected in presence of seismic isolation at the base, then the considered building is suitable for being retrofitted through seismic isolation strategy without the need of further local interventions. Therefore, with the criterion proposed, a selection of real tests for seismic isolation applications without interventions may be performed within the Da.D.O. database. The elaboration of all the data is still in progress. Some preliminary results regarding also the seismic damages of the buildings may be found in a companion paper (D'Amato et al. 2019).

2 DATABASE INFORMATION

2.1 Building damage database

The AeDES form (Baggio et al. 2009) collects several information about ordinary buildings affected by a seismic event, such as the building typology and characteristics, the observed damages and the usability assessment. Within the Da.D.O. database (DPC 2015; Dolce et al. 2017), are now made available the data about 74049 buildings hit by the L'Aquila earthquake of 2009. The data are provided and divided into 8 sections:

1. Building identification
2. Building description
3. Typology
4. Damage to structural elements and emergency interventions performed
5. Damage to non-structural elements and emergency interventions performed
6. External damage due to other constructions, networks, slopes and emergency interventions performed
7. Foundation and ground conditions
8. Usability judgement

The first 7 sections are totally filled while the section 8 is not filled because it contains data that cannot be disclosed publicly.

2.2 GMs database

The main shock of the L'Aquila earthquake of 6 April of 2009 (M_W=6.1) has been recorded by 62 accelerometric station available in the Engineering Strong Motion Database (ESM) (Luzi et al. 2016). Within the ESM database, the geographic location of each stations (Figure 1) and their topographic and stratigraphic properties are available. As known, the accelerometric histories are recorded along two arbitrary axes (typically East-west and North-South directions) , thus the two horizontal records may be correlated. In order to remove such inconsistency, the principal direction of each couple of records have been rotated along their principal axes, by following the procedure proposed by (Rezaeian and Der Kiureghian 2010). The so-manipulated records have been used as a new GMs database.

Figure 1. Accelerometric stations that recorded the L’Aquila earthquake of 2009.

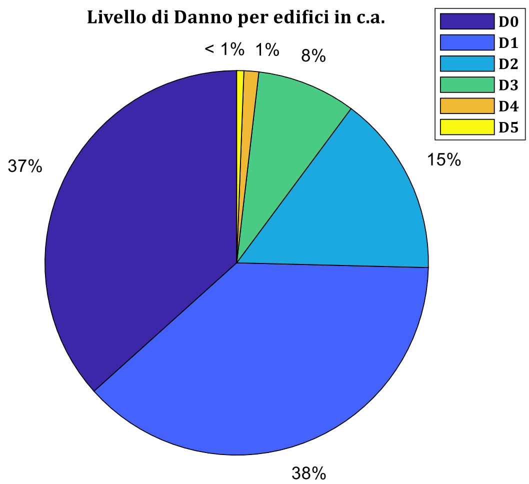

Figure 2. Percentage breakdown of damage levels of R.C. buildings after L’Aquila earthquake of 2009.

3 PROPOSED METHODOLOGY

The methodology to identify the buildings suitable for seismic isolation retrofit without the need of further local intervention is articulated in three phases:

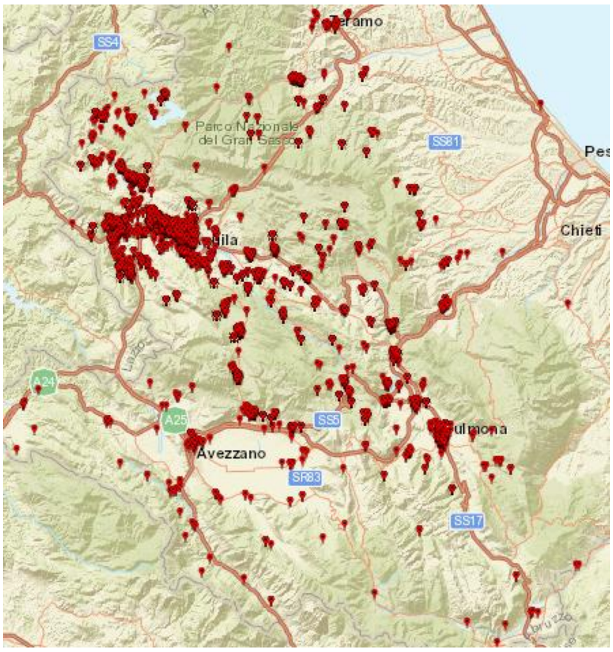

Figure 3. R.C. buildings with damage D0-D1 after L’Aquila earthquake of 2009: geographical location.

1. Selection of the buildings with null or limited damage;
2. Assessment of the seismic action suffered by each building;
3. Test on the suitability of seismic isolation as retrofit technique.

In the following the three different steps are described by taking into account the Reinforced Concrete (R.C.) frame buildings typology.

3.1 *Assessment of building with limited or null damage within the Da.D.O. database*

By using the structural and non-.structural damage information derived from the AeDES forms, a synthetic damage parameter (Grunthal 1998) can be assessed for each building. Within the literature there are many procedure to assess such synthetic damage. Some authors assess the damage level by a weighted average of the damage of each component (Di Pasquale and Goretti 2001; Lagomarsino et al. 2015) while other authors assess the damage level by considering only the maximum observed damage on each component (Rota et al. 2008; Del Gaudio et al. 2016). In Figure 2 it is shown the percentage breakdown of damage levels assessed for the reinforced concrete buildings available in the considered sample and by considering only the method based on maximum damage. The buildings with null or low damage (i.e D_0 or D_1) are 10175, whose location within the territory is shown in Figure 3.

3.2 *Intensity measures assessment through EGMs database*

By using GMs database described in section §2.2, the attenuation law of several Intensity Measures (IMs) can be calculated by regression. As an example, in Figure 4 the attenuation law for the spectral acceleration Sa(T=0.3s) is shown. By using such attenuation relationships, the estimated response spectrum at each site can be estimated.

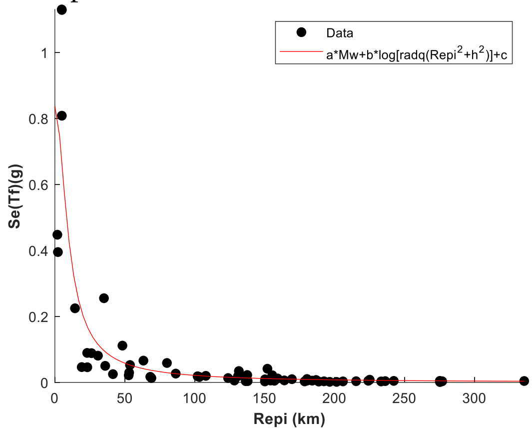

Figure 4. Attenuation law for the spectral acceleration S_a(T=0.3s) obtained from the data available within the ESM database (Luzi et al.,2016).

3.3 *Test on the suitability of seismic isolation as retrofit technique*

The basic idea of the proposed method is to test within the database the buildings suitable for seismic isolation. It consists in verifying that the spectral acceleration experienced by an undamaged building is higher than the expected one predicted with the site hazard law and supposed acting on the same building assumed equipped with a seismic isolation system. This condition can be formalized with the following ratio:

$$\frac{S_a^{GM}(T_f)}{S_a^C(T_i)} \geq 1 \tag{1}$$

where $S_a^{GM}(T_f)$ is the spectral acceleration of the spectrum of recorded ground motion for the period of the fixed base building T_f, and S_a^C (T_i) is the spectral ordinate of the design code spectra for the

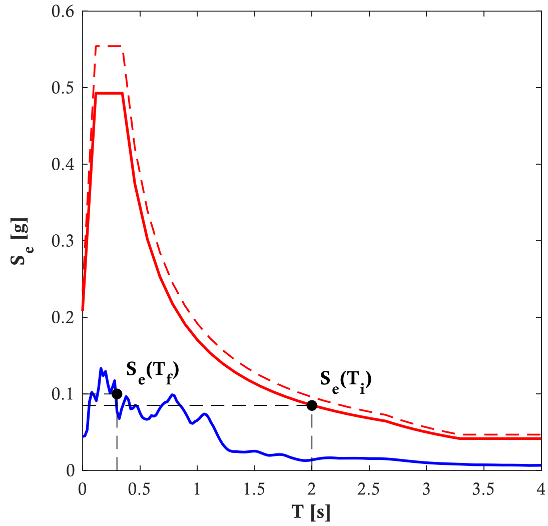

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Figure 5. Example of test on a RC building with T_f=0.3s, T_i=2s.

period of the isolated building, T_i. Both the spectral acceleration of the code, S_a^C, and the spectral acceleration derived from the recorded ground motion, S_a^{GM}, need to be assessed or adjusted by considering the exact location of the building, the topographic and stratigraphic effects and the characteristics of fixed base and isolated building.

The code spectrum is defined by considering the geographic coordinates of the site, thus obtaining the a_g, F_0, T_C* parameters from the Italian hazard database (INGV 2007) by considering a return period of 475 years. Further, the spectrum is modified according to the requirements of (NTC 2018) to consider the stratigraphic and topographic category (S_s and S_t parameters, respectively) and the regularity in height (k_r parameter). The period of the fixed base building, T_f, is determined by using the simplified expression available within the former Italian code (NTC 2008). For the spectrum of seismic isolated buildings, the equivalent damping of the isolating system (ξ parameter) needs to be assumed, whereas a behaviour factor q_0=1 is always adopted.

In Figure 5 it is shown the case of a positive test (i.e. Eq. 1 verified) performed on an example building. The blue line is the response spectrum estimated at the site from the recorded GMs, the red dashed line is the elastic code spectrum and the red solid line is the design spectrum by considering a damping ratio of the isolating system ξ. If the Eq. 1 is verified, the acceleration experimented by a building that exhibited no damage with period T_f, is higher than the design spectral accelerations of the building with a seismic isolation system with period T_i.

4 CONSIDERABLE BUILDINGS FOR SEISMIC ISOLATION

4.1 Preliminary tests

In order to check the effectiveness of the proposed methodology, a preliminary test is performed by considering some pilot buildings ideally located in the same place of the accelerometric stations. In this way, the uncertainties about the intensity measures assessment is strongly reduced and a first estimation of the sites and areas where the proposed methodology can provide reliable results is possible.

In Figure 6 and Figure 7 the results of the tests performed at the sites of each accelerometric stations for the L'Aquila earthquake are shown, by considering buildings with T_f=0.2s and T_i=1.5s or T_f=0.4s and T_i=2s, respectively. The green markers are used for the sites where the Eq. 1 is verified; otherwise the red marker markers are used for the sites where the Eq.1 is not verified. It can be seen that the test is positive in many sites close to the epicentre while the test is quite always not verified for higher epicentral distance. This is mainly due to the fact that the recorded spectral accelerations in those sites are too low to give any significant information about the effective building capacity. In Figure 8 the results of the test in function of the epicentral distance is shown. As proof of what previously stated, it can be seen that for an epicentral distance lower than 20km, the test is always verified, while for the stations placed in between 20km<R<50km the test is verified in only a few stations. Finally, for R>50km the test is always not verified.

Figure 6. Test for buildings placed in proximity of the accelerometric stations with S_s=B, S_t=1, k_r=1, q_0=1, $\xi eq=20\%$, T_i=1.5s, T_f=0.2s.

Figure 7. Test for buildings placed in proximity of the accelerometric stations with S_s=B, S_t=1, k_r=1, q_0=1, $\xi eq=20\%$, T_i=2s, T_f=0.4s.

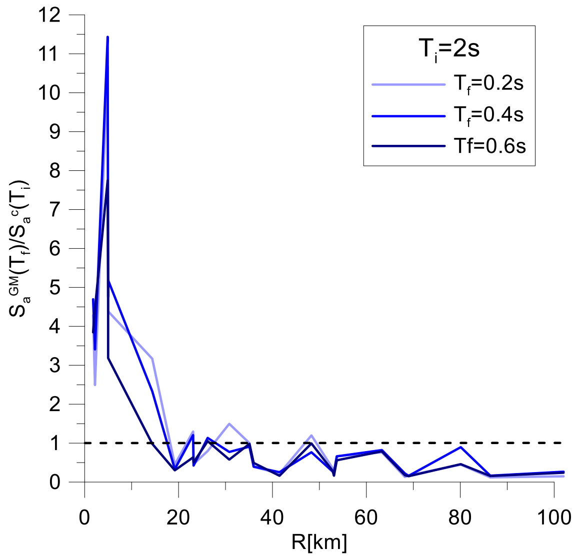

Figure 8. Results of the preliminary test in function of the epicentral distance R of the stations and for different fixed base periods, T_f and by assuming T_i=2s and ξ_{eq}=15%.

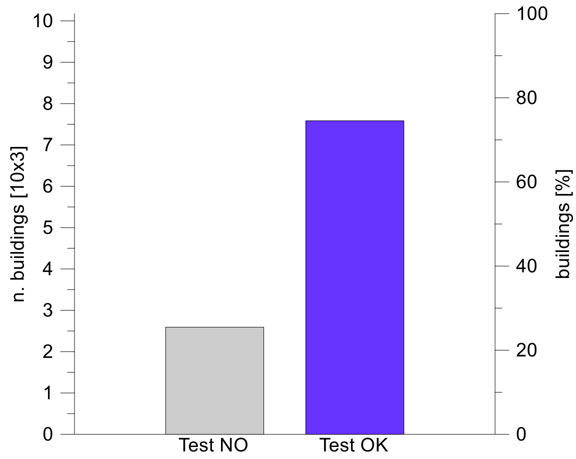

Figure 9. Results of the test on the whole database.

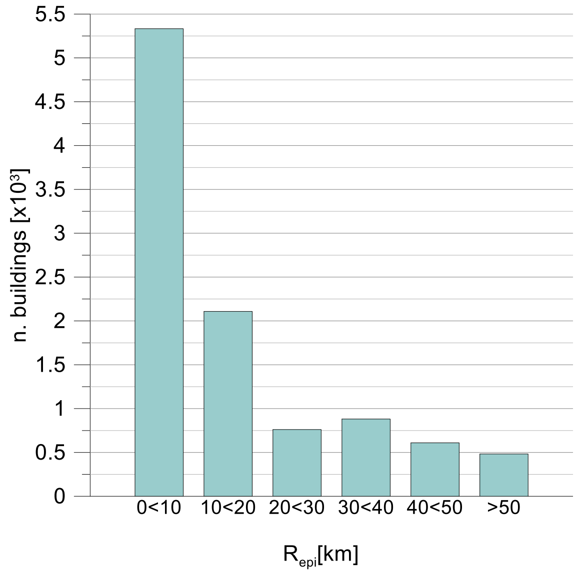

Figure 10. Number of RC buildings with damage D_0 or D_1 in function of the epicentral distance.

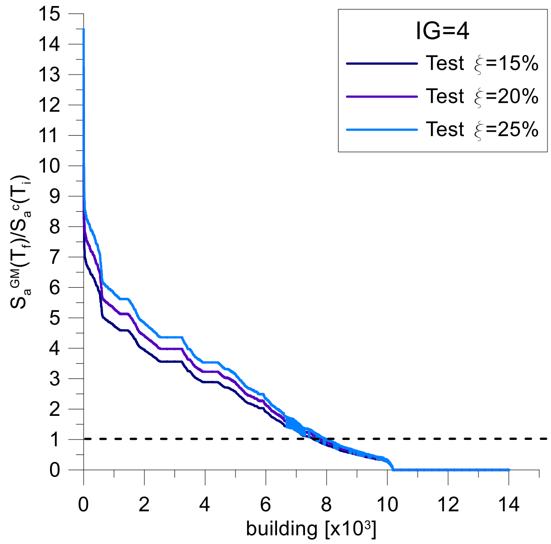

Figure 11. Ratio between the spectral acceleration suffered by the fixed base building and the design spectral acceleration of the isolated system for each building represented in descending order.

4.2 Results on the whole buildings sample

In Figure 9 are shown the results of the procedure applied to the whole buildings database and by considering an isolation grade (IG) equal to 4 (i.e. T_i/T_f=4), a damping ratio of 15% and a behaviour factor q_0=1. It can be seen that over the 70% of the RC buildings pass the test. This result is consistent with the preliminary test because the most of the buildings investigated fall into the epicentre area, as shown in Figure 10. On this aspect it should be stressed that the data refers to the buildings that have an AeDES form. Therefore it is reasonably to assume that the totality of the buildings have been verified close to the epicentre, whereas with increasing distance from the epicenter, several undamaged building have no AeDES form and are thus not considered herein. In Figure 11 the value of the ratio between the spectral acceleration suffered by the fixed base building and the design spectral acceleration of the isolated system is shown, by considering three different values of ξ_{eq}: 15%, 20%, and 25%.It can be seen that the value of the considered damping ratio, poorly influence the number of positive tests. In Figure 12 the same acceleration ratio is shown for the case of $\xi_{eq=}$ 15% by grouping the data in 7 intervals. It can be seen that, besides the building that don't satisfy Eq.1 (i.e. where the ratio is lower than 1), the biggest part of the building sample has ratio between 2 and 3 and in any case, the 90% of the investigated sample has a ratio lower than 5.

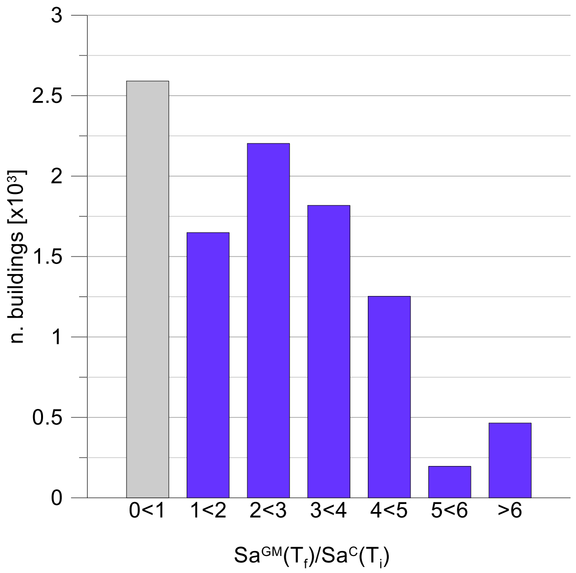

Figure 12. Ratio between the spectral acceleration suffered by the fixed base building and the design spectral acceleration of the isolated system for each building and for ξ=15%, represented for intervals.

5 CONCLUSIONS

In this paper it has been shown how the available statistical information about the past earthquakes may give useful indication in order to define an intervention strategy on the existing building heritage. It has been shown that over 10000 RC buildings placed in the proximity of the epicentre of the L'Aquila earthquake of 2009 have suffered null or limited damages. By estimating the acceleration suffered in each site, it is possible to state that these buildings are able to withstand with very low damage at least that level of shaking. In other words, it is possible to estimate the minimum capacity exhibited by these buildings. By considering the fixed base building as the superstructure of a base isolated system, it has been shown that this minimum capacity is higher than the demand required by the code spectra in the case of intervention with seismic isolation systems for over 7000 buildings, thus about the 70% of the undamaged building sample.

It can be concluded that, by adopting seismic isolation systems as intervention technique, the full retrofit of a big part of the existing buildings could be obtained without the need of further interventions, with a significant reduction in intervention costs and times. In conclusion, even if the results are affected by strong epistemic and intrinsic uncertainties, they provide some indications about the actual capacity of existing RC buildings and about the optimal choice of strategies and techniques of interventions. Therefore, they could be used in the future within the framework of methodologies and strategic plans aimed at the seismic risk mitigation at both small and large scale.

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