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SEISMIC RELIABILITY OF ELASTOMERIC BASE ISOLATORS

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Abstract: In this study, the seismic reliability of laminated elastomeric base isolators is assessed. The reliability is quantified by the development of fragility curves, which are constructed analytically by performing incremental nonlinear time-history analysis (IDA) of a base isolated residential building, built in L'Aquila, Italy, to replace a severely damaged building after the 2009 earthquake. The horizontal deformation of the isolation bearings is used as the engineering demand parameter and peak ground acceleration (PGA) is the chosen intensity measure. The curves that resulted from the analysis show that the elastomeric base isolators exhibit low probability of exceeding the limit states. Combining the fragility of the structures with the seismic hazard data for the site, the probability of an isolator sustaining extensive damage is limited to 1% for 475 years return period, which indicates high reliability of the device. The probability of slight and moderate damage is also low, but slight damage can be observed even for low levels of peak ground acceleration.

Introduction

Seismic or base isolation as a measure of earthquake protection of structures was conceived more than 100 years ago. With this method, additional flexibility is introduced between the structure and its foundation in order to achieve decoupling of the two components. In this way, the period of the structure is elongated, so resonance with excitations is avoided, and the input seismic load is decreased. The building can then be designed for lower forces, contributing to the economic advantage of the method. This was initially achieved by using natural rubber bearings. The devices have evolved in time to provide stability and efficiency even in high shear strain rates, as well as high damping to avoid uncontrollable displacements.

Base isolation is, nowadays, considered as an economic and practical alternative to conventional methods of seismic engineering to enhance better performance under seismic loading. However, the limited time since the method's vast practical implementation does not allow for deterministic conclusions regarding its safety and reliability. Can the safety of structures, which will potentially undergo severe ground shaking, rely on seismic isolation systems? How fragile are these systems and how can that be quantified?

Methodology

In this study, the reliability of one type of base isolators is assessed. To this end, fragility curves were developed, to represent the reliability of the examined device. The curves were developed analytically by performing incremental nonlinear time-history analysis of a sample base-isolated structure. The horizontal deformation of the isolation bearings was used as the engineering demand parameter and peak ground acceleration (PGA) was the chosen intensity measure. A model of the sample base-isolated building was created using SeismoStruct (Seismosoft, 2013) and subjected to twenty earthquake records scaled to ground motion intensity levels ranging from 0.2g to 2g using a 0.2g step (10 intervals). Thus, 200 time-history analyses were performed in order to collect sufficient damage data for each intensity level and develop fragility curves of the base isolator in a reliable manner. Figure 1 summarizes the methodology followed.

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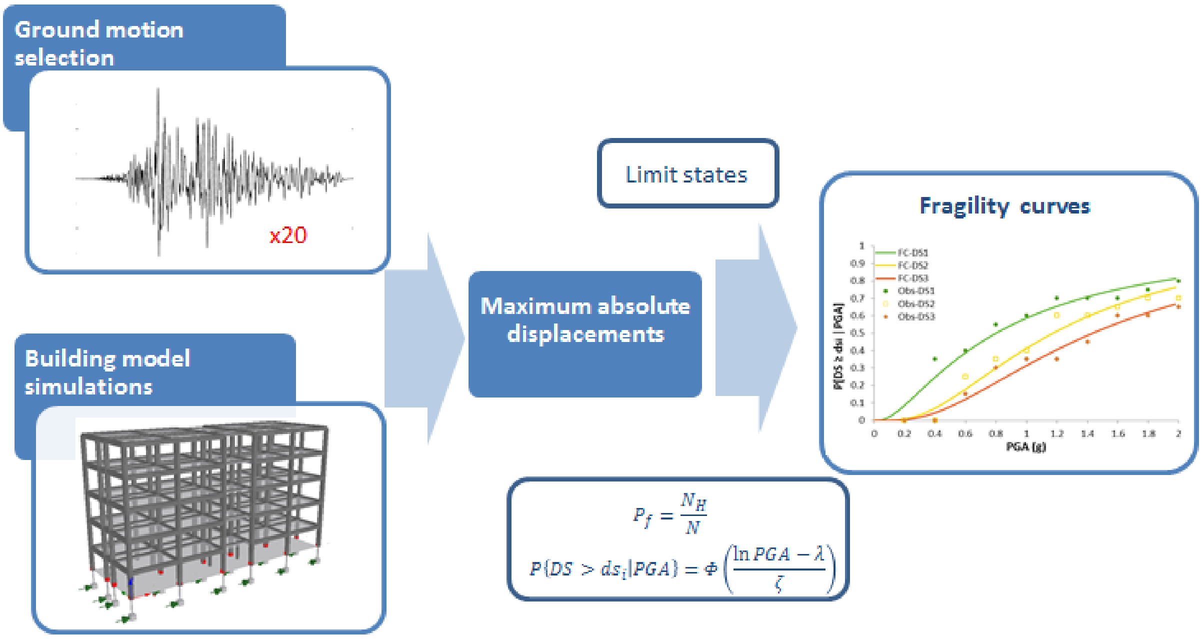

Figure 1.Methodology employed in this study

The building

The structure chosen as a case study to assess the reliability of the elastomeric base isolators is a 5-storey base isolated reinforced concrete moment resisting frame residential building, recently constructed in L'Aquila in Central Italy. The building was built to replace one that was demolished due to severe damages caused by the earthquake that occurred in close proximity to the city of L'Aquila in 2009. The new replacement building is similar to the demolished one, but incorporates base isolation. The normal-faulting earthquake occurred on the 6th of April 2009 and measured a magnitude of 6.3 in the moment magnitude scale (M_w), according to the Italian Instituto Nazionale di Geofisica e Vulcanologia (INGV). Peak ground accelerations (PGA) ranged from 0.3 to 0.65 g, while, according to the Italian Civil Protection, the area is characterized as seismic zone 2. This means that the design peak ground acceleration proposed by the Italian design code is 0.26 g, based on 10% probability of exceedance in 50 years. The low design accelerations were one of the reasons that led to the immense losses in property and life in the city and the surrounding area.

Base isolation system

The base isolation system comprises 24 elastomeric circular-shaped isolators placed on top of a 6 x 4 grid of reinforced concrete columns at basement level (Figure 2). The 1.5 m high supporting columns have rectangular 85 x 85 cm section, but where given a cruciform shape to facilitate the removal or replacement of the isolators by using the free space to adjust hydraulic jacks. They are supported, along with the rest of the structure, by a 60 cm thick raft foundation slab. The designer has allowed a 35cm gap, around the 40cm thick slab separating the superstructure from the isolation system, to account for the lateral movement of the isolators. (Figure 3)

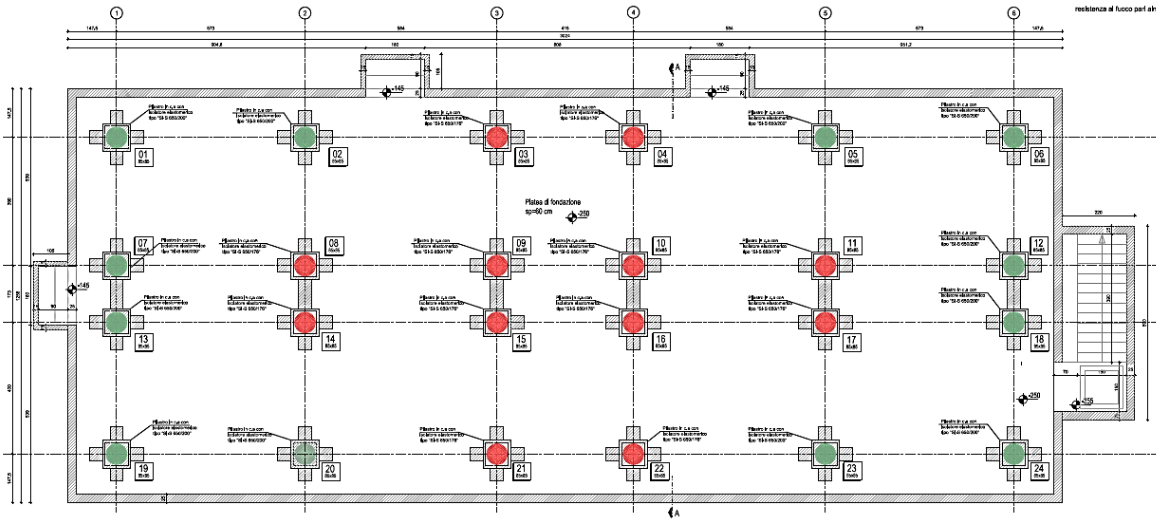

Figure 2.Basement plan and isolators' distribution (StudioDeg, 2011)

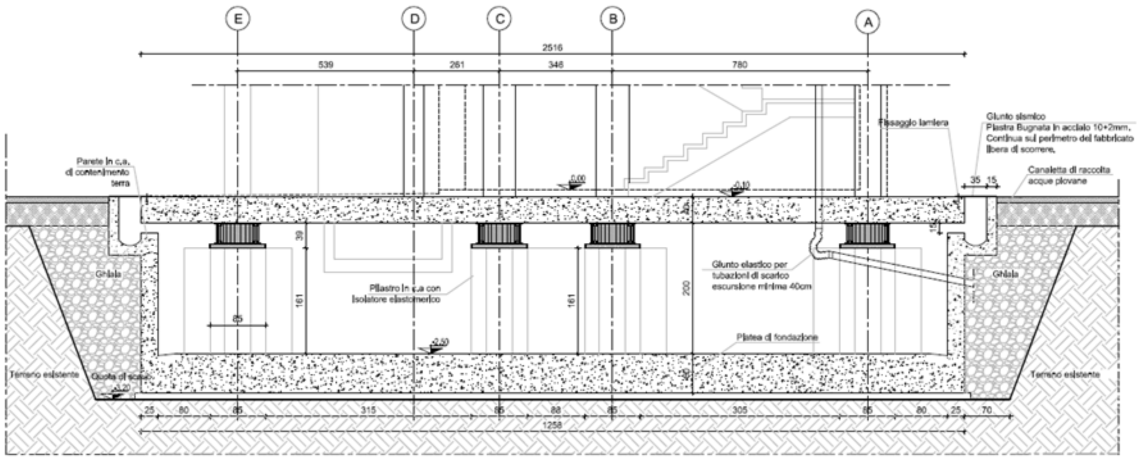

Figure 3.Basement plan and isolators' distribution (StudioDeg, 2011)

The isolation devices are reinforced rubber isolators consisting of alternating layers of neoprene and laminated steel, wrapped with a neoprene jacket. The main properties of the isolators as given by the producer (FIP INDUSTRIALE, 2012) are shown in Table 1.

Table 1. Properties of the elastomeric isolators

Elastomeric Isolator	Equivalent horizontal stiffness k_h (kN/m)	Vertical stiffness k_v (kN/m)	Shear modulus G (MPa)	Isolator diameter (m)	Isolator height (m)	Equivalent vicious damping ξ
SI-S 650/176	750	1017000	0.4	0.65	0.176	15%
SI-S 650/200	660	895000	0.4	0.65	0.2	15%

Building model simulations

SeismoStruct V6.5 was used to create a 3D model of the structure (Figure 4)**Error! Reference source not found.**. All the material needed to model the building realistically were provided by the construction company (StudioDeg, 2011).

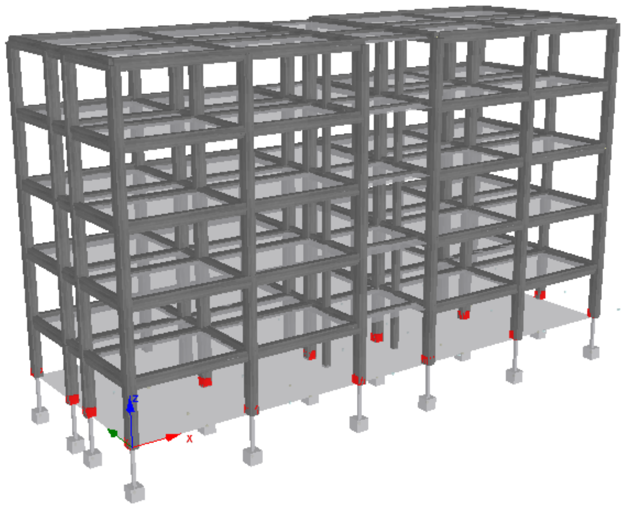

Figure 4.3-dimentional model of the building in SeismoStruct

For simplicity, the reinforced concrete framed structure was modelled using elastic frame elements (elfrm) to represent the beams and columns, so that it remains elastic under the seismic loads. This simplification was made on the ground that the stiffness of the superstructure does not have an important effect on the structure's response to seismic loading, because the seismic response is led by the isolation system. Slabs and the foundation were considered to be rigid, while the roof was considered as additional mass to the beams of the 5th floor.

In SeismoStruct isolators were modelled using 3D link elements, which can be seen with red colour in Figure 4. These elements connect two coincident nodes and require the user to define a force-displacement response curve for all six degrees of freedom. Usually, for high damping rubber bearings, like the ones used in this building, a bilinear force-displacement envelope is used to represent the response of the bearings in shear force.

The main issue in using the bilinear model to simulate the response of a rubber isolator is the choice of the elastic to post-yield stiffness ratio. Naeim and Kelly (1999) pointed out that the maximum value of the effective damping given by the model is dependant of the ratio between the two stiffness values only. Hence, since the values of post-yield stiffness K_2 and characteristic strength Q can be accurately determined, K_1 is either estimated from experimental data, or as a multiple of K_2. The latter is only applicable for lead rubber bearings and friction pendulum bearings, but values from experimental data should still be used, to ensure the correct simulation of the device's properties.
Consequently, choosing the value of elastic stiffness is crucial for the accuracy of the model, and more specifically, for simulating the damping of the isolator. To illustrate this fact, Naeim and Kelly (1999) made a comparison between a system with the same post-yield stiffness and characteristic strength modelled with different values of elastic stiffness. The results are shown in Figure 5.

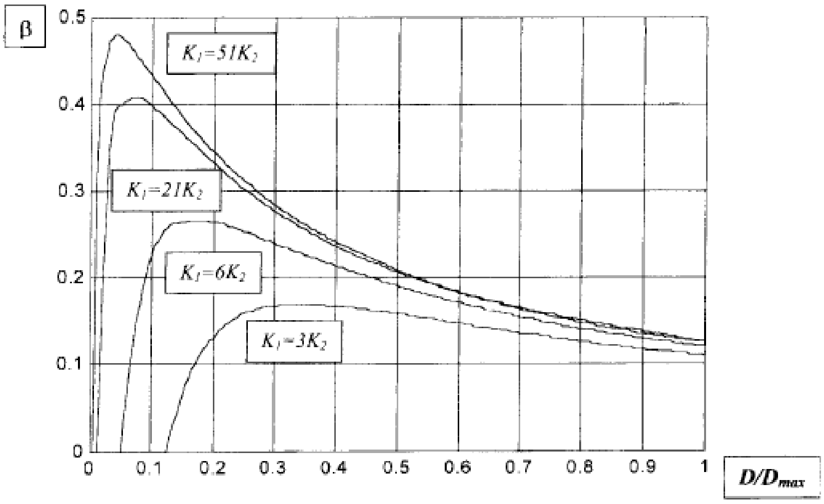

Figure 5. Effective damping as a function for displacement for different choices of K1 (after Naeim & Kelly, 1999)

The nonlinear response of the rubber isolators in this study is based on the results of laboratory tests performed by the contractor, thus, the analytical simulation of the devices can be considered to be reliable.

The calculation of the parameters needed to construct the bilinear curve was done according to the findings of Naeim and Kelly (1999). The post-yield stiffness K_2 is calculated using the following equation:

$$K_{eff} = K_2 + \frac{Q}{D}, \qquad D \geq D_y \tag{1}$$

The displacement at yield D_y is calculated using the expression:

$$\beta_{eff} = \frac{4Q(D - Dy)}{2\pi K_{eff} D^2} \tag{2}$$

For the reasons discussed above it is assumed that $K_1 = 3K_2$. An example of the shear force – horizontal displacement diagram of one of the SI-S 650/200 isolators at 100% shear strain (γ) in comparison to the bilinear model used can be seen in the following figure (Figure 6). The values used in this study are summarized in Table 2.

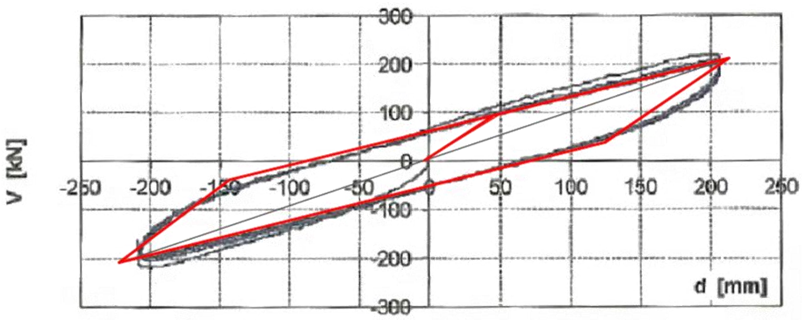

Figure 6.Bilinear curves used to model the isolator's response compared to the experimental response

Table 2.Parameters of the bilinear curve used to model the response of the isolators

Isolator	Linear stiffness (kN/m)	Initial stiffness K_o (kN/m)	Hardening ratio r	Post-yield stiffness $r.K_o$ (kN/m)	Yielding force F_y (kN)	Equivalent damping ratio (%)
650/176	1044	1400	0.5	700	70	15
650/200	910	1220	0.5	610	70	15

Earthquake ground motion data

Since IDA method requires a large number of nonlinear time-history analyses in order to derive the fragility functions, an adequate number of earthquake records needs to be selected for a statistically better prediction of the system response. In this concept, a set of 20 earthquake ground motion records was selected and used to perform the time-history analyses. The ground motions were selected using REXEL v3.5 (Iervolino, et al., 2010), software developed for real earthquake record selection based on code provisions. The software allows searching for spectrum compatible records from 3 different databases (European Strong-motion Database, Italian Accelerometric Archive and SIMBAD). The target spectrum can either be user defined or generated by the software according to Eurocode 8 or the Italian Building Code. In this study, ground motions from the European Strong-motion Database were selected, since it is the largest one, and compatible and site-specific ground motions were found. The Italian Building Code was used for the target spectrum definition, which defines completely site-dependent design spectra based on probabilistic seismic hazard assessment (PSHA) data provided by INGV for every node of a 5km grid covering the whole Italian territory. The sets of records were selected so that their mean spectrum matches the target spectrum in a specific period range.

The input parameters used to generate the target spectrum were the nominal life of the structure (50 years), soil type A, life safety limit state and location coordinates 13.366 longitude and 42.373 latitude. The search was performed for magnitudes ranging from 5.8 to 7.2 and epicentral distance less than 15 km, data based on the disaggregation for PGA. The spectrum matching was done linearly in the range of [0.15s, 4s] and with lower and upper tolerance 10% and 30%, respectively. The proposed range for the spectrum matching by the Italian code for seismically isolated buildings is [0.15s, 1.2Tis]. Even though the equivalent period of the assessed structure is T=2.6s (derived from an Eigenvalue analysis of the model building) and, thus, the proposed range is [0.15s, 3.2s], the range was expanded to account for the whole range of periods that can characterize an isolated building (2 to 4 sec).

Damage States definition

The damage states of the base isolators were described using shear strain as damage index, which has been used to describe the performance of base isolation devices by most authors in theoretical and experimental studies (e.g.(Shahria Alam , et al., 2012; Zhang & Huo, 2009). The limit states were selected based on the literature and calibrated for this case study. Studies have shown that the seismic response of elastomeric bearings can be described by three distinct parts; at low shear strains high stiffness is observed, from low to medium strains the stiffness is smaller but constant and at higher strains the stiffness increases again due to hardening effects. Although, on account of advanced material technology, isolators can experience up to 400% shear strain before failure, it is generally accepted that 250% strain is the collapse limit state of an elastomeric bearing (JRA, 2002). However, for the present case study 200% of shear strain was considered the ultimate limit state, due to the fact that beyond this rate pounding effects are triggered. The construction of the structure allows 35cm of lateral displacement, which accounts for 200% shear strain for the SI-S 650/176 and 175% for the SI-S 650/200 isolators. However, for the definition of extensive damage 200% shear strain was used to account for both isolator sizes. The damage states used to define the damage index of the base isolators is presented in Table 3:

Table 3.Limit states of elastomeric isolator

Shear strain	Damage States		
	Slight (DS1)	Moderate (DS2)	Extensive (DS3)
γ	>100%	>150%	>200%

Derivation of fragility curves

The time-history analyses were performed using SeismoStruct (Seismosoft, 2013). The earthquake load was assigned at the supports of the structure. The load was modelled by acceleration loading curves that can be loaded in the software. Here the IDA tool provided was used, which allows the performance of a series of time-history analyses with increasing intensity (in this case peak ground acceleration) by introducing scale factors. Twenty IDA were performed for the purposes of this study, one for each ground motion record presented before. In each IDA the record was scaled ten times starting from 0.2g and reaching 2g with a step of 0.2g. Thus, 200 nonlinear time-history analyses were performed in total.

The pga-displacement data sets that resulted from the analyses were translated into pga-shear strain data sets and assigned to the 3 damage states defined above. These damage data sets were used to construct a fragility curve by fitting an appropriate statistical model.
The regression model used to define the relationship between the damage and the intensity measure used here is a generalized linear model (GLM). The probability that a ground motion with a certain PGA will cause the response variable to exceed a certain limit state ds_i was expressed by a lognormal cumulative distribution function (CDF), which is the most commonly used regression model in the literature (Shinozuka, et al., 2000; Liel & Lynch, 2009; Ioannou, et al., 2012):

$$P\{DS > ds_i | PGA\} = \Phi\left(\frac{\ln PGA - lnc}{\zeta}\right) = \Phi\left(\frac{\ln PGA - \lambda}{\zeta}\right) \quad (3)$$

where c is the median of the fragility function, ζ is the standard deviation of the lognormal distribution and Φ() is the standard normal cumulative distribution function.
The estimation of the optimum regression parameters of the model selected was done by a probit link function:

$$\Phi^{-1}(P\left(DS \geq ds_i \middle| PGA = x_j\right) = \theta_0 + \theta_1 \ln x_j \quad (4)$$

by maximizing the likelihood function L() given by the equation (Rossetto, et al., 2014):

$$\theta^{opt} = argmax[L(\theta; y, x)] = argmax\left[\prod_{j=1}^{M} f(y_j \mid x_j, \theta)\right] \quad (5)$$

where f() is the probability density distribution of the response variable (equation 1), using an iterative least squares method.
This statistical analysis was performed using R (R Development Core Team, 2008), an environment for statistical computing, based on the guidelines and script provided in the guidelines for empirical vulnerability assessment by Rossetto et al. (2014).

Results and conclusion

The curves that resulted from the analysis show that the elastomeric base isolators exhibit low probability of exceeding the limit states. The general impression from examining Figure 7 is that elastomeric base isolators do not exhibit high fragility under seismic conditions. The increase in probability of exceedance for increasing values of PGA happens at a low rate for all limit states, which proves that isolators are not in danger of sudden poor performance. The probability of exceeding the extensive damage threshold at 1g is 30%, while reaching slight damage does not exceed 60% probability. For smaller values of ground motion intensity, extensive damage is much smaller and tends to zero for peak ground accelerations of under 0.2g.

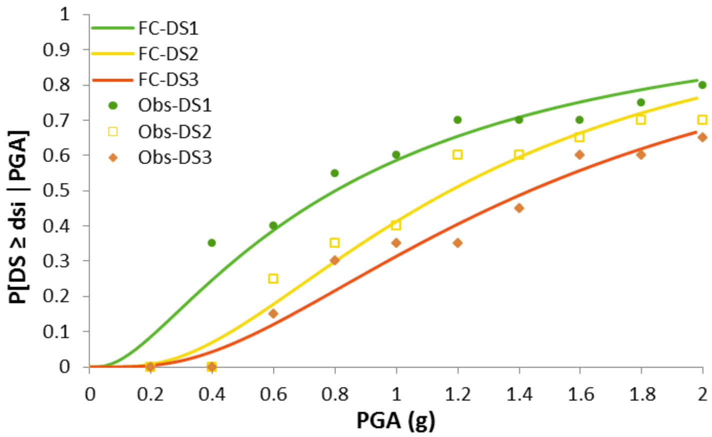

Figure 7.Fragility curves of the elastomeric base isolators

The parameters of the fragility curves, meaning the standard deviation ζ and the logarithm λ of the median of the fragility function c, are presented in Table 4:

Table 4.Parameters of the fragility curve

Regression parameter	Damage States		
	DS1 - Slight	**DS2 - Moderate**	**DS3 – Extensive**
λ	-0.22	0.16	0.36
ζ	1.02	0.73	0.75

Combining the fragility of the structures with the seismic hazard data for the site, the probability of an isolator sustaining extensive damage is limited to 1% for 475 years return period, which indicates high reliability of the device. The probability of slight and moderate damage is also low, but slight damage can be observed even for low levels of peak ground acceleration.

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