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ENGLISH VERSION

Seismic vulnerability in essential buildings through analytical fragility curves

Vulnerabilidad sísmica en edificaciones esenciales mediante curvas de fragilidad analíticas

U. Sáenz *[1], http://orcid.org/0000-0002-6293-0137
R. Santana*, http://orcid.org/0000-0002-6479-3324

* Facultad de Ingeniería Civil, Universidad Nacional del Centro del Perú, PERÚ

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Abstract

This article presents a methodology to assess the seismic vulnerability of essential buildings through analytical fragility curves, applied to the administrative building of the Universidad Nacional del Centro del Perú, for various damage states and different levels of seismic demand according to ATC-40 and SEAOC -VISION 2000. It is shown that the fragility curves through the probability of damage matrices allow us to reasonably estimate the probable state of the building after a seismic event, which in the case of the building under analysis shows that it is more vulnerable in the North-South direction (Y axis).
Keywords: *Seismic vulnerability; fragility curves; damage states; seismic levels; damage probability matrices.*

Resumen

La investigación presenta una metodología para evaluar la vulnerabilidad sísmica de edificaciones esenciales mediante curvas de fragilidad analíticas, aplicada al edificio administrativo de la Universidad Nacional del Centro del Perú para diversos estados de daño y diferentes niveles de demanda sísmica según el ATC-40 y SEAOC-VISIÓN 2000. Se demuestra que las curvas de fragilidad a través de las matrices de probabilidad de daño permiten estimar, de manera razonable, el probable estado del edificio después de un evento sísmico. Para el caso del edificio en análisis, se demuestra que es más vulnerable en la dirección Norte-Sur (eje Y)./
Palabras claves: Vulnerabilidad sísmica, curvas de fragilidad, estados de daño, niveles sísmicos, matrices de probabilidad de daño.

1 Corresponding author:
Facultad de Ingeniería Civil, Universidad Nacional del Centro del Perú,
author: uver.hsa@gmail.com

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1. Introduction

Peru is a highly seismic country, as it is part of the circumpacific belt where more than 80 percent of the world's earthquakes occur. These events have shown that buildings with poor seismic performance are prone to significant damage to their structural elements and consequently collapse, resulting in loss of human and economic life. So it is important to conduct seismic vulnerability studies of essential buildings using methods that consider the uncertainty of structural, seismic and geotechnical factors.

The studied building was projected with peruvian code of sismoresistente design E.030 (1997) in Huancayo city, built between 2000 and 2002. It has an area of 1944,81 square meters and its main use is administrative. The structure has 10 levels, a cellar intended for the parking area and a semisotano, has a glass facade with aluminium frame whose sloping roof has metal frame by the four fronts from the seventh floor and contains fixed partitions only in the hygienic service environments. In the last level of the building is the elevated tank.

The structural settings involves a portic and shear walls of reinforced concrete join by means of solid slabs and lightened. The building is composed of 22 circular columns (1.00 m and 0.70 m in diameter) and four rectangular columns (0.40 m x0.60 m) from the eighth to the tenth level, also has constant section vaulted beams from the basement to the last level, these are: VIG-0.60 m x 0,90 m, VIG-0.40mx 0.90m, VIG-0.40mx0.40m, VIG-0.30m x 0.90m, VIG.CANAL-1.80mx0.90m, VIG. MANDIL-0.40m x 0.90m, VIG. CIRCULAR-0.40mx0.40m. It also has plates that form the elevator box, two plates that support the staircase, two cutting walls located in common bathroom areas and eight symmetrically arranged plates of different thicknesses (e= 0.30 m and e= 0.40 m).

In the present research the seismic vulnerability is determined by fragility curves for various states of damage and the probability matrix of damage of the administrative building of the National University of Central Peru

2. Materials and methods

To determine the seismic vulnerability of the building, the structural data of the building were surveyed, the mechanical model of the typology was proposed, loads were measured, soil mechanics were studied, non-destructive tests on the concrete, definition of seismic demand, thresholds and indicators of structural damage.

2.1. Study of soil mechanics

Over the study area there is a powerful deposit of coarse sub-rounded granular soil, called conglomerate, which corresponds to an ancient alluvial terrace of the Mantaro River. The mechanical behavior of the foundation soil is summarized in the following (Table 1).

***Table 1.** Mechanical parameters of the foundation floor*

Parameter	Value
shear strength	high
cohesion (c)	regulate, among 0.0 and 0.20 kg/cm^2
angle of friction (Φ)	high, between 36 y 38°
Compressibility	low
modulus of elasticity	1000 a 1200 kg/cm^2
bearing capacity	3.5 kg/cm^2

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According to E.030 (2018) the type of foundation soil profile belongs to Intermediate Soil typea la E.030 (2018) el tipo de perfil del suelo de fundación pertenece a Suelo Intermedio tipo " S_2".

2.2. Structural parameters

For the structural evaluation of the building, "in situ tests" were carried out in order to compare the compressive force of concrete f'_c according to (Table 2). For this purpose, the Rebound Hammer Test, Schmidt Hammer or Swiss Hammer was used. (ACI, 1995), developed according to ASTM C 805. 2002.

***Table 2.** Compressive strength of target building concrete*

f'_c (kg/cm^2)	***Structural elements***	***Floor***
184	*Beams, columns and plates*	*fourth floor to tenth floor*
210	*Slabs*	*all*
240	*Beams, columns and plates*	*basement to the third floor*

2.3. Measurements of gravity loads

The purpose of the load measurements was to estimate the loads acting on the structure and to estimate the seismic weight according to (Table 3).

Table 3. Seismic weight of the target building.

Weight	***E.030 (2018)***
$P = CM + 25CV + 0.25CVT$	*11223.66 Ton*

2.4. Structural model of the building

The research project requires a detailed analysis of seismic behavior, so a structural model was defined with the help of Etabs version 19.0.0 software. The structural configuration in the building plan showed a progressive reduction of the constructed area according to (Figure 1).

3. Results and Discussion

3.1. Seismic demand

The deterministic method was used in the estimation of seismic movement, considering more severe conditions. Due to the lack of historical seismic information, alternative seismic records were used, considering primarily the maximum horizontal acceleration of the terrain (PGA), magnitude and those that produce greater spectral accelerations "Sa" in the fundamental period "T0" with a 5% damping.

Therefore, six records of three seismic events were selected as shown in (Table 4), which according to (Aguilar, 2001) belong to the earthquakes of 1966, 1970 and 1974.

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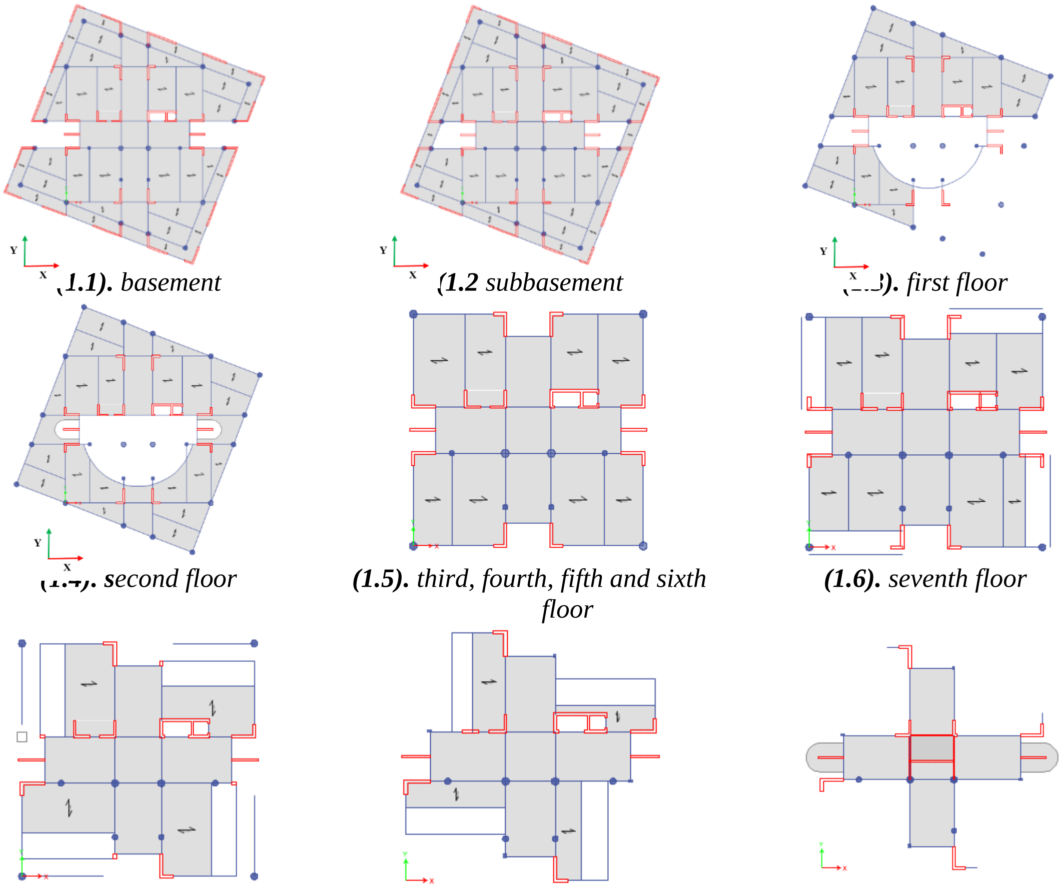


(1.1). *basement* — ***(1.2*** *subbasement* — ***(1.3).*** *first floor*

(1.4). *second floor* — ***(1.5).*** *third, fourth, fifth and sixth floor* — ***(1.6).*** *seventh floor*

(1.7). *eighth floor* — ***(1.8).*** *ninth floor* — ***(1.9).*** *tenth floor*

Figure 1. *Structural configuration of the target building.*

Table 4. *Peruvian seismic records selected for project analysis*

Code	***Date***	***Denomination***	***Component***	***Data***	***PGA***	***PGA (g)***	***M***
7035	*17-oct-1966*	*N82W (Lima)*	*Horizontal*	*3283*	*-180.59*	*0.18*	*7.5*
7036	*17-oct-1966*	*NO8E (Lima)*	*Horizontal*	*3282*	*-269.34*	*0.27*	*7.5*
7038	*31-may-1970*	*Huaraz*	*Horizontal*	*2259*	*-104.82*	*0.11*	*7.7*
7039	*31-may-1970*	*Huaraz*	*Horizontal*	*2259*	*-97.75*	*0.10*	*7.7*
7050	*03-oct-1974*	*1421 GCT NO8E (Lima)*	*Horizontal*	*4899*	*178.95*	*0.18*	*7.5*
7051	*03-oct-1974*	*1421 GCT N82W (Lima)*	*Horizontal*	*4899*	*-192.49*	*0.20*	*7.5*

3.2. Seismic demand levels

In order to develop the elastic spectra of pseudo accelerations, seismic demand levels were used according to the Applied Technology Council TC-40 (1996) according to Table 5 and the California Association of Structural Engineers SEAOC (1995) shown in Table 6.

Table 5. *Acceleration associated with E.030 for earthquake levels (ATC-40, 1996).*

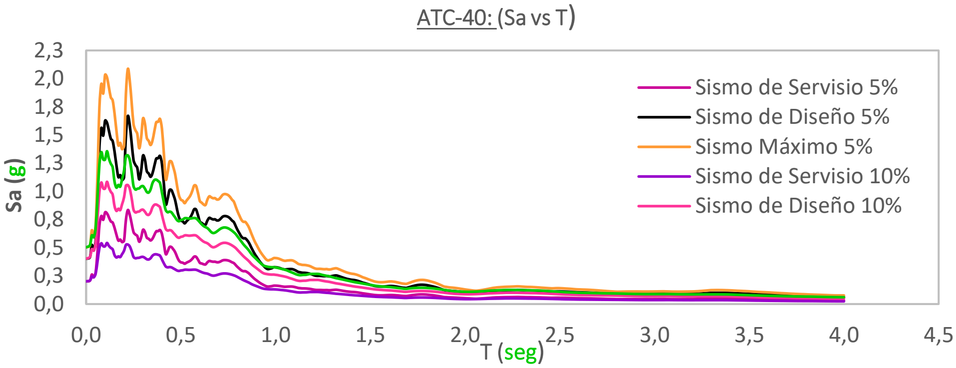
Seismic Levels		***Acceleration: Central Peru Zone Z(g)***
Service earthquake (SS)	*Probability of leave: 50% in 50 years*	*0.175 = (0.5*SD)*
	Return period: 72 years	
Design earthquake (SD)	*Probability of leave: 10% in 50 years*	*0.35*
	Return period: 475 years	
Maximum earthquake (SM)	*Probability of leave: 5% in 50 years*	*0.4375 = (1.25*SD)*
	Return Period: 975 years	

Table 6. *Earthquake design levels for the city of Huancayo - VISION 2000 (SEAOC, 1995)*

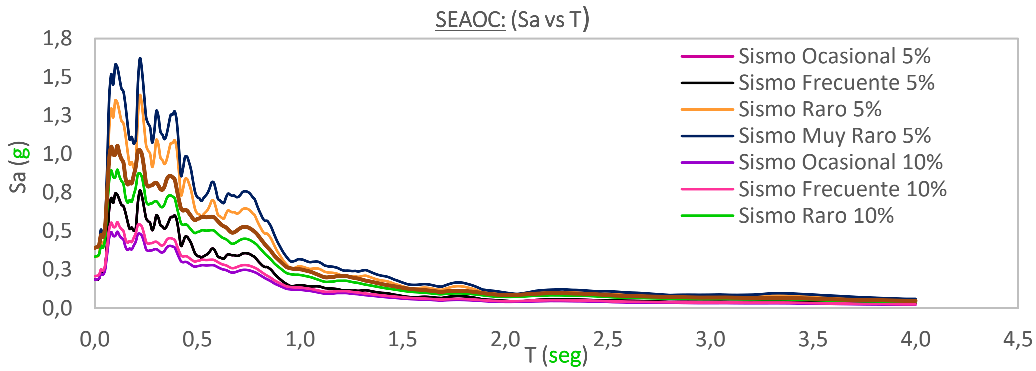
	Levels of earthquake design			
	Frequent	***Occasional***	***Strange***	***Very strange***
	Probability of leave: 50% in 30 years	*Probability of leave: 50% in 50 years*	*Probability of leave: 10% in 50 years*	*Probability of leave: 10% in 100 years*
	Return period: 43 years	*Return period: 72 years*	*Return period: 475 years*	*Return period: 950 years*
Junín-Huancayo LS 12.064 LO: 75.208 Acceleration (g)	*0.16*	*0.18*	*0.29*	*0.34*

3.3. Spectrum of pseudo seismic demand accelerations

The construction of the spectrum of pseudo seismic demand accelerations according to (Figure 2, was made from the pseudo accelerations of each seismic record obtained with the seismosignal program for a damping of 5% and 10%. For this purpose, the geometric mean, the mean plus a standard deviation and the mean plus two standard deviations of the six seismic records were calculated.



(2.1). Seismic levels of ATC-40.



(2.2). SEAOC seismic levels

***Figure 2**. Elastic seismic demand spectrum (Sa vs T)*

3.4. Nonlinear static analysis

The static nonlinear incremental load analysis was performed using the Ebas version 19.0.0 software to estimate the structural response in terms of shear force and displacement at the deck level. For this purpose, the non-linear load-deformation characteristics of the building were considered, subjecting the structure to a monotonic increase of lateral loads

3.5. Non-linearity of materials

The constituent models of the materials sought to define the nonlinear behavior of these. Below are the constituent models of concrete in (Figure 3) and (Table 7) and steel shown in (Figure 4).

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
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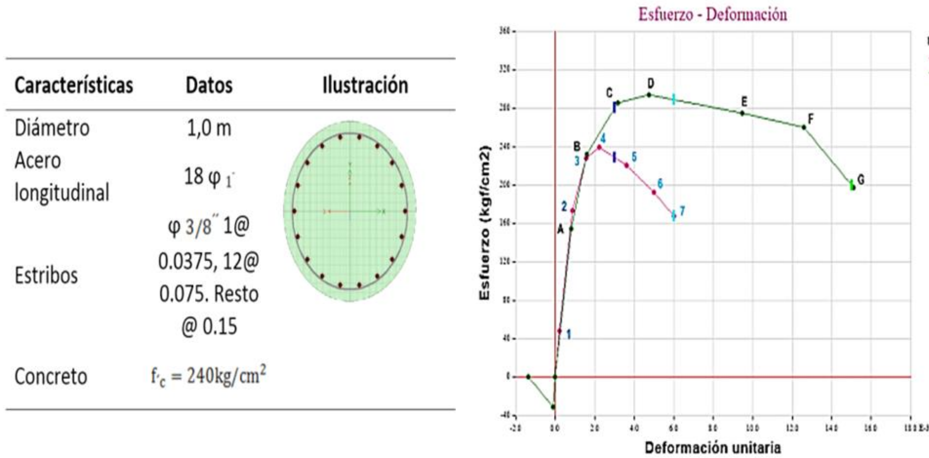
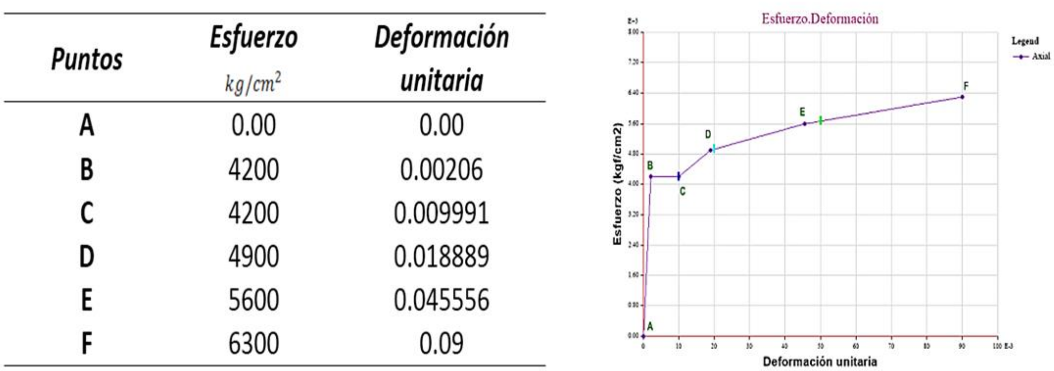


Características	Datos	Ilustración
Diámetro	1,0 m	
Acero longitudinal	18 φ 1¨	
Estribos	φ 3/8¨ 1@ 0.0375, 12@ 0.075. Resto @ 0.15	
Concreto	$f'_c = 240 kg/cm^2$	

Figure 3. *Constituent model of concrete - Mander.*

Table 7. *Stress-deformation values of concrete for the Mander model.*

Confined concrete			***Unconfined concrete***		
Points	*Effort kg/cm^2*	*Deformation*	*Points*	*Effort kg/cm^2*	*Deformation*
A	*0.000789*	*154.33*	***1***	*48.00*	*0.000192*
B	*0.001577*	*232.08*	***2***	*173.47*	*0.000868*
C	*0.003155*	*285.79*	***3***	*228.11*	*0.001543*
D	*0.004732*	*294.36*	***4***	*240.00*	*0.002219*
E	*0.009465*	*275.25*	***5***	*220.58*	*0.003610*
F	*0.012574*	*260.59*	***6***	*192.65*	*0.005000*
G	*0.015089*	*197.69*	***7***	*167.63*	*0.006000*



Puntos	Esfuerzo kg/cm^2	Deformación unitaria
A	0.00	0.00
B	4200	0.00206
C	4200	0.009991
D	4900	0.018889
E	5600	0.045556
F	6300	0.09

Figure 4. *Constitutive model of steel - Parabolic hardening.*

3.6. Capacity curve

The capacity curve of the building under analysis is shown in (Figure 5), obtained by nonlinear static analysis for the two main directions of the building, X and Y. This curve allowed us to assess the behavior of the building when it enters the nonlinear range and determine the maximum response of the structure.

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
DOI: 10.7764/RIC.00072.21

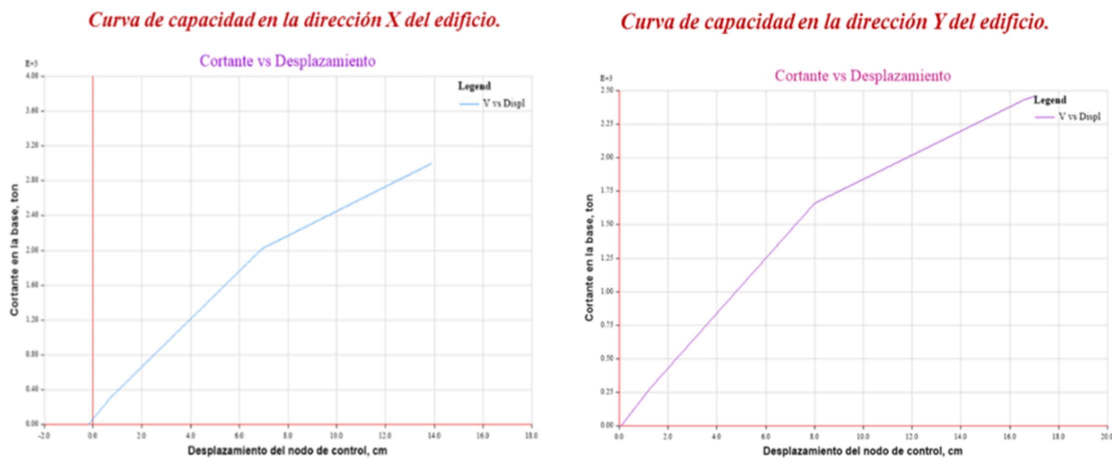


Figure 5. *Pushover curve of target building.*

3.7. Capacity spectrum

To calculate the thresholds and performance point, the capacity spectrum shown in (Figure 6) was generated from the Pushover curve under the criteria of (FEMA 440, 2005), using the following (Equation 1):

$$S_{ai} = \frac{V_i}{W * \alpha_1} \qquad S_{di} = \frac{\Delta_{roof,i}}{PF_1 * \emptyset_{roof,1}} \qquad (1)$$

Where:

S_{ai}*: spectral acceleration,* S_{di}*: Spectral displacement.* PF_1*: Modal participation factor of the first natural mode,* α_1*: Effective mass coefficient for the first natural mode,* $\Delta_{roof,i}$ *: Displacement of ceiling i,* W*: Building deadweight most likely live load,* V *: Base shear*

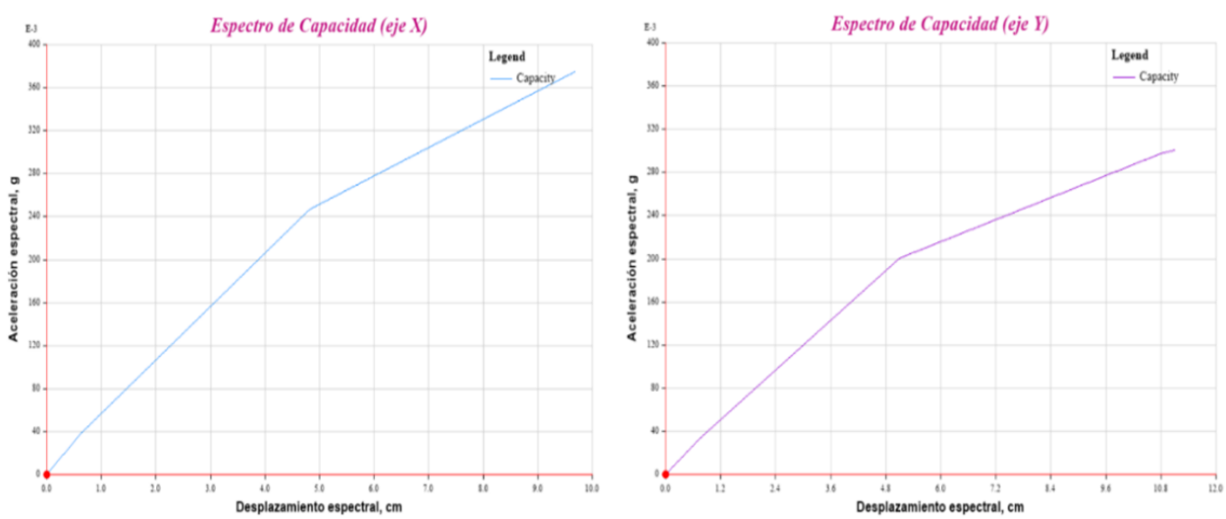


Figure 6. *Target building capacity spectrum.*

3.8. Discrete states of damage

In order to make a qualitative description of the damages produced by earthquake and calculate the fragility curves, discrete damage states according to (Table 8) proposed by (Lagomarsino and Penna, 2003) were used.

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
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Table 8. *Discrete thresholds and damage states for the target building.*

Damage state	***Spectral displacement*** $\overline{Sd}_i\ (i = 1, 2, 3\ y\ 4)$	***Eje X-X***	***Eje Y-Y***
Leve	$\overline{Sd}_1 = 0.70D_y$	$\overline{Sd}_{1x} = 3.37$	$\overline{Sd}_{1y} = 3.57$
Moderate	$\overline{Sd}_2 = D_y$	$\overline{Sd}_{2x} = 4.82$	$\overline{Sd}_{2y} = 5.10$
Severe	$\overline{Sd}_3 = D_y + 0.25(D_u - D_y)$	$\overline{Sd}_{3x} = 6.03$	$\overline{Sd}_{3y}$ =6.60
Complete	$\overline{Sd}_4 = D_u$	$\overline{Sd}_{4x} = 9.67$	$\overline{Sd}_{4y} = 11.09$

3.9 Thresholds for structural damage

The thresholds for each discrete state of damage were calculated from the mezzanine drift shown in (Table 9). For this purpose we record the evolution of these with respect to the global drift of the roof level of the building, by taking data in each increase of lateral load of the nonlinear static analysis.

Table 9. *Spectral displacement of each level for discrete damage states.*

Piso	***Spectral displacement (cm): Eje X***				***Spectral displacement (cm): Eje Y***			
	Leve	*Moderado*	*Severo*	*Completo*	*Leve*	*Moderado*	*Severo*	*Completo*
TECH-10°	*3.02*	*4.33*	*5.47*	*8.64*	*3.68*	*5.28*	*6.78*	*10.42*
TECH-9°	*3.07*	*4.29*	*5.30*	*8.39*	*3.63*	*5.22*	*6.71*	*10.32*
TECH-8°	*3.05*	*4.04*	*4.98*	*7.95*	*3.44*	*4.91*	*6.35*	*9.76*
TECH-7°	*2.49*	*3.64*	*4.54*	*7.18*	*3.14*	*4.45*	*5.74*	*8.83*
TECH.6°	*2.26*	*3.24*	*4.00*	*6.25*	*2.77*	*3.89*	*5.00*	*7.66*
TECH-5°	*1.93*	*2.99*	*3.37*	*5.24*	*2.25*	*3.23*	*4.21*	*6.37*
TECH-4°	*1.51*	*2.13*	*2.67*	*3.49*	*1.79*	*3.17*	*3.27*	*4.98*
TECH-3°	*1.13*	*1.86*	*1.99*	*3.01*	*1.26*	*1.81*	*2.32*	*3.57*
TECH-2°	*0.76*	*1.02*	*1.26*	*1.97*	*0.82*	*1.15*	*1.51*	*2.25*
TECH-1°	*0.44*	*0.58*	*0.70*	*1.08*	*0.47*	*0.61*	*0.73*	*1.11*
TECH. SEM. SOTANO	*0.16*	*0.24*	*0.26*	*0.36*	*0.15*	*0.26*	*0.28*	*0.30*
TECH. SOT	*0.06*	*0.07*	*0.09*	*0.11*	*0.04*	*0.05*	*0.06*	*0.07*
$\overline{S}_{d,ds}$	***1.721***	***2.561***	***3.020***	***4.363***	***2.022***	***3.198***	***3.741***	***5.674***

Where: $\overline{S}_{d,ds}$ *is Median of spectral displacement*

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
www.ricuc.cl
DOI: 10.7764/RIC.00072.21

3.9. Generation of fragility curves

The fragility curves of the administrative building of the National University of Central Peru shown in (Figure 7) were calculated from the spectral floor displacements for each discrete state of damage. Thus obtaining, the probability that the response of the building exceeds a discrete state of damage as a function of the spectral displacement that defines the intensity of the movement of the ground. The following expression of (HAZUS MH 2.1, 2001) was used for this purpose (Equation 2):

$$P(ED \geq EDi \ \| \ Sd = Sd_i) = \Phi[\frac{1}{\beta_{d_s}} ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)] \quad (2)$$

Where:

$\bar{S}_{d,ds}$*: Median of spectral displacement where the building reaches the damage status threshold, ds;* β_{d_s}*: Standard deviation of the natural logarithm of the displacement spectrum by state of damage ds;* Φ*: Standard normal cumulative distribution function.*

To generate the fragility curves, the median of the spectral displacement (median of the damage thresholds) was calculated and the variability of the damage state by the standard deviation of the natural logarithm of the displacement spectrum by damage state shown in (Table 10), by means of the expressions developed in the RISK-EU project that calculated the variability of the damage state β_{d_s} *directly with ultimate ductility* μ.

Table 10. *Standard deviation of the natural logarithm of the displacement spectrum by state of damage.*

Variability	***Eje X***	***Eje Y***
$\beta_{ds1} = 0.25 + 0.07 ln\mu$	*0.299*	*0.303*
$\beta_{ds2} = 0.20 + 0.18 ln\mu$	*0.325*	*0.336*
$\beta_{ds3} = 0.10 + 0.4 ln\mu$	*0.377*	*0.403*
$\beta_{ds4} = 0.15 + 0.5 ln\mu$	*0.497*	*0.528*

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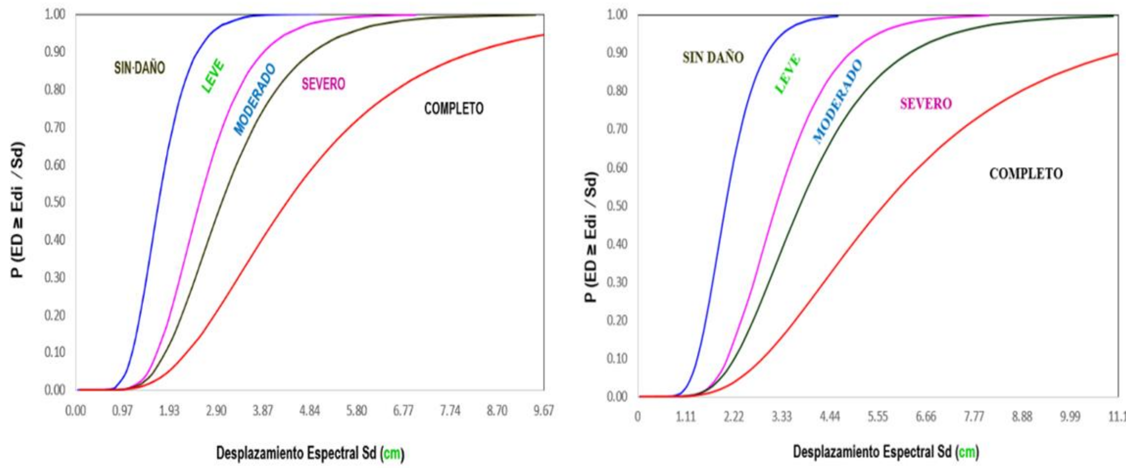

***Figure 7**. Fragility curves of the target building in both directions of analysis. Axis X (left) and Axis Y (right).*

3.10. Calculation of probability of damage matrix

The damage probability matrices were obtained by intersecting the performance points with the fragility curves for each damage state according to (Table 16) and (Table 17), making use of spectral displacement. For this purpose, the following equation expression was used (Equation 3):

$$P(ED = EDi/PISj) = P(ED \geq EDi) - P(ED \geq ED_{i+1}) \quad (3)$$

Where:
EDi, Discrete state of damage; PIS, Parameter of seismic intensity

3.11. Capacity point on demand

The capacity point per demand was determined by intersecting the capacity spectrum with the elastic demand spectrum considering 5% damping when intersecting in the linear range of structural capacity. However, in case the intersection occurs in the inelastic range we use the inelastic demand spectrum with 10% damping. Under these considerations we calculate the maximum capacity point for the seismic demand levels of (ATC-40, 1996) shown in (Table 11) and (SEAOC, 1995) shown in (Table 12).

***Table 11.** Performance points of the building under study: (ATC-40, 1996).*

Seismic levels	***Performance point***	
	Direction X (cm)	***Direction Y (cm)***
Service	*4.565*	*4.057*
Design	*6.919*	*9.728*
Maximum	*9.264*	*Excede*

***Table 12.** Performance points of the building under study: (SEAOC, 1995).*

Seismic levels	***Performance point***	
	Direction X (cm)	***Direction Y (cm)***
Occasional	*4.162*	*3.710*
Frequent	*4.695*	*4.173*

Revista Ingeniería de Construcción RIC
Vol 38 Nº2 2023
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Strange	5.435	6.540
Very strange	6.24	9.107

3.12. Matrix

To illustrate the above, we calculated the probability that the damage in the 12-level building is severe for a spectral displacement of $S_d = 5.435\ cm$ *shown in (Figure 14), which represents the maximum displacement expected for the level of Rare earthquake according to. To do this, the probability of severe and complete damage leave for a spectral displacement of* $S_d = 5.435\ cm$ *, was determined, according to (Figure 8).*

$$P(ED = severe \ / \ Sd = 5.435cm) = P(ED \geq Severo) - P(ED \geq Colapso$$
$$P(ED = severe \ / \ Sd = 5.435cm) = 0.9402 - 0.6709 = 0.2693 = 26.93\%$$

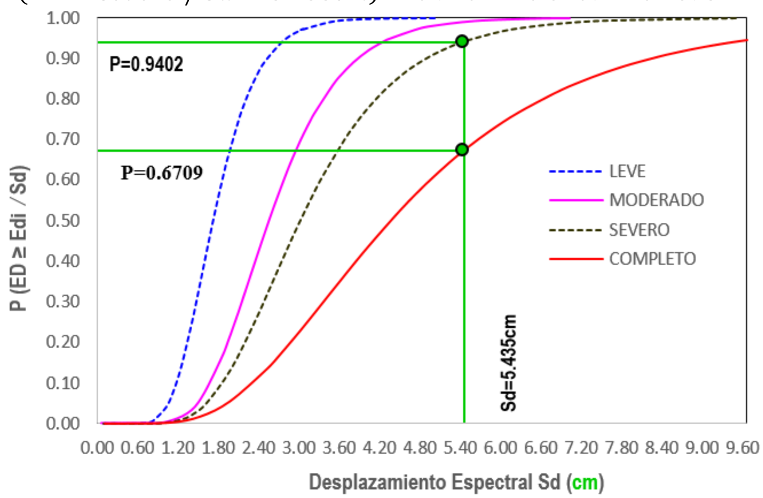

Figure 8. *Calculation of probability of damage matrices, Axis X*

Interpretation: *The probability of the 12-level building reaching a severe damage level for a Rare seismic level is 26.93%.*

Table 13. *Probability matrix of damage of the building under study, axis X*

Seismic levels		***Probability of damage matrix***			
		Leve	***Moderate***	***Severe***	***Complete***
ATC - 40	*Service*	*3.70%*	*9.93%*	*32.68%*	*53.64%*
	Design	***0.11%***	***1.29%***	***16.26%***	***82.34%***
	Maximum	*0.00%*	*0.15%*	*6.33%*	*93.52%*
SEAOC VISIÓN 2000	*Frequent*	*6.59%*	*13.03%*	*34.00%*	*46.22%*
	Occasional	*3.06%*	*9.02%*	*32.01%*	*55.87%*
	Strange	***1.02%***	***4.95%***	***26.94%***	***67.09%***

Seismic levels		*Probability of damage matrix*			
		Leve	***Moderate***	***Severe***	***Complete***
	Very strange	*0.30%*	*2.42%*	*20.84%*	*76.43%*

Table 14. *Probability matrix of damage of the building in study, axis Y.*

Seismic levels		***Probability of Damage Matrix***			
		Leve	***Moderate***	***Severe***	***Complete***
ATC - 40	*Service*	*22.87%*	*18.07%*	*31.71%*	*26.27%*
	Design	***0.05%***	***0.83%***	***14.50%***	***84.62%***
	Maximum	*100%*	*100%*	*100%*	*100%*
SEAOC VISIÓN 2000	*Frequen*	*30.67%*	*17.90%*	*28.11%*	*21.06%*
	Occasional	*20.59%*	*17.88%*	*32.65%*	*28.04%*
	Strange	***1.66%***	***6.60%***	***31.14%***	***60.59%***
	Very strange	*0.09%*	*1.26%*	*17.17%*	*81.47%*

3.13 Analysis of results

The probability of occurrence of a state of mild, moderate, severe or complete damage is determined from the fragility curves and capacity point by demand, because the seismic behavior of the building can be quantified by the point of performance. The maximum expected displacement of the building for the seismic levels of the ATC-40 and SEAOC Vision 2000 are obtained by superimposing the spectrum of capacity and demand spectrum, by the method of the capacity diagram - seismic solicitation, proposed by (Chopra and Goel, 1999). For the North-South direction (Y axis), according to (ATC-40, 1996) and with a seismic level of design, it has a probability of 84.62% that the damage is complete, 14.50% that is severe; while according to (SEAOC, 1995), for the seismic level "Rare" equivalent, has a 60.59% chance of damage being complete, 31.14% severe.

4. Conclusions

Fragility curves obtained for states of mild, moderate, severe damage and collapse show that the administrative building of the National University of Central Peru is more vulnerable in the North-South direction (axis Y) than the East-West direction (axis X) and allow a reasonable estimate of the likely condition of the building after a seismic event.

The contribution of the damage probability matrix is significant, because it allows to predict the level of damage that will reach the building when it suffers earthquake of different levels. Thus, for the East-West direction (X axis) according to the SEAOC and with a seismic level of design, it has a probability of 82.34% that the damage is complete, 16.26% that it is severe; while according to SEAOC for the rare seismic level has a probability of 67.09% that the damage is complete, 26.94% that it is severe of the administrative building of the UNCP

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