

Seismic vulnerability analysis of irregular and regular structures using fragility curve

Setiati Rehni¹, Masrilayanti^{1*}, Kurniawan Ruddy¹, Ainy Asri Luthfi¹, and Sulleyman Sourkan²

¹Civil Engineering Department, Faculty of Engineering, Universitas Andalas, Padang, Indonesia

²Petroleum and Energy Engineering Department, Sulaimani Polytechnic University, Sulaymaniyah, Iraq

Abstract. The demand for innovative and visually appealing building designs according to specific desires or needs has led to many structures being built with irregularities. High-rise buildings with structural irregularities are at a higher risk of collapse during an earthquake if they are not designed and constructed properly according to existing regulations. Some buildings have non-uniform floor heights, which can lead to uneven distribution of stiffness throughout the structure vertically. Excessive height of one floor compared to the floor above it can potentially create an excessive soft story. Evaluating and assessing seismic vulnerability of structures is a major issue in earthquake-resistant design. This study discusses an analytical model for developing fragility curves by evaluating the seismic performance of a structure. The objective of this research is to determine and compare the estimated fragility levels of structures subjected to seismic loads between irregular structures with soft story irregularities and regular structures. Based on the results and discussion, it can be concluded that irregular structures (with soft story irregularities) have higher fragility levels compared to regular structures in both the x and y directions.

1 Introduction

Earthquakes are considered one of the most challenging hazards affecting structures, especially high-rise buildings [1]. This study selects Padang City as the site for the research. Padang City is a highly tectonically active region, caused by the interaction between two tectonic plates: the Indo-Australian Plate and the Eurasian Plate. The dynamic interaction between these plates creates a subduction zone or a zone of plate convergence. As a result of this pressure, Padang City and its surroundings are highly susceptible to earthquakes and tsunamis. Earthquakes in this area can be very strong and destructive, such as the 2009 Padang earthquake with a magnitude of 7.6 on the Richter scale, which resulted in thousands of fatalities [1-3].

During one example of a reinforced concrete (RC) building that suffered significant damage, both structural and non-structural, due to the 2009 Padang earthquake is a building with an asymmetrical floor plan [3]. The demand for innovative and visually appealing building designs according to specific desires or needs has led to many structures being built with irregularities [4]. Some buildings have floors with non-uniform heights, leading to an uneven distribution of stiffness vertically throughout the building. Excessive height in one floor compared to the floor above can potentially create a soft story [4-6].

High-rise buildings with structural irregularities are at a higher risk of collapse during an earthquake if not designed and constructed properly according to existing regulations [6]. The performance of a structure can be

assessed based on its vulnerability to loads. Performance can be developed in the form of fragility curves [7-9]. From the obtained fragility curves, the damage level due to lateral loads can be identified and categorized into four levels: slight, moderate, extensive, and collapse. This damage classification refers to HAZUS (Hazards United States). The results of the seismic fragility evaluation of the two structures will reveal which type of building demonstrates higher fragility, providing insights for future structural design [10].

2 Methodology

2.1 Building model and material properties

The study discusses an analytical model for constructing fragility curves by evaluating the seismic performance of a structure. The structural variations to be discussed are irregular structures with excessive soft story irregularities and regular structures. The building models selected are:

- **Model 1 regular structure** - The structure in question is an existing 12-story building with a special moment-resisting frame system (SMRF) that was previously designed by researchers.

- **Model 2 irregular structure** - the regular structure is redesigned to achieve structural irregularity. The plan, building height, and dimensions of the columns, beams, slabs, and reinforcement are the same as those of the regular structure, but the floor height on the first floor is increased to 10.5 meters.

* Corresponding author: masrilayanti@eng.unand.ac.id

The modification and addition of floor height in this irregular structure are based on the phenomenon of structural collapse with soft story irregularities due to earthquakes, which often occurs on the first floor [11, 12]. This is because high-rise buildings, such as office buildings and apartments, are designed to have lobbies with floor heights usually greater than the typical floors

above. Architects typically desire this to make the lobby appear larger, more spacious, and grander. Due to the need for more space, the use of brick walls on the lobby floor is relatively less compared to the floors above, which require partition walls between rooms. The layout of the regular and irregular structures is shown in Fig. 1, and the structural variations shown in Fig. 2.

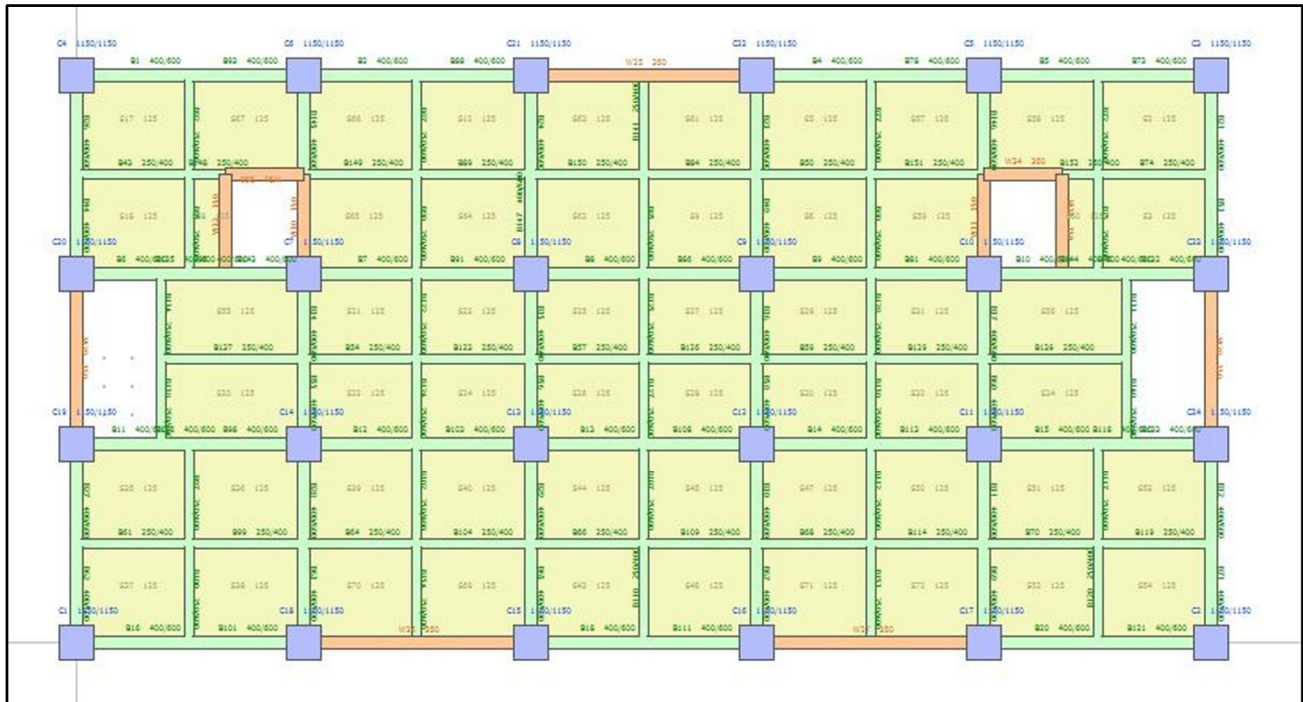


Fig. 1. Typical building plans for regular structures and irregular structures.

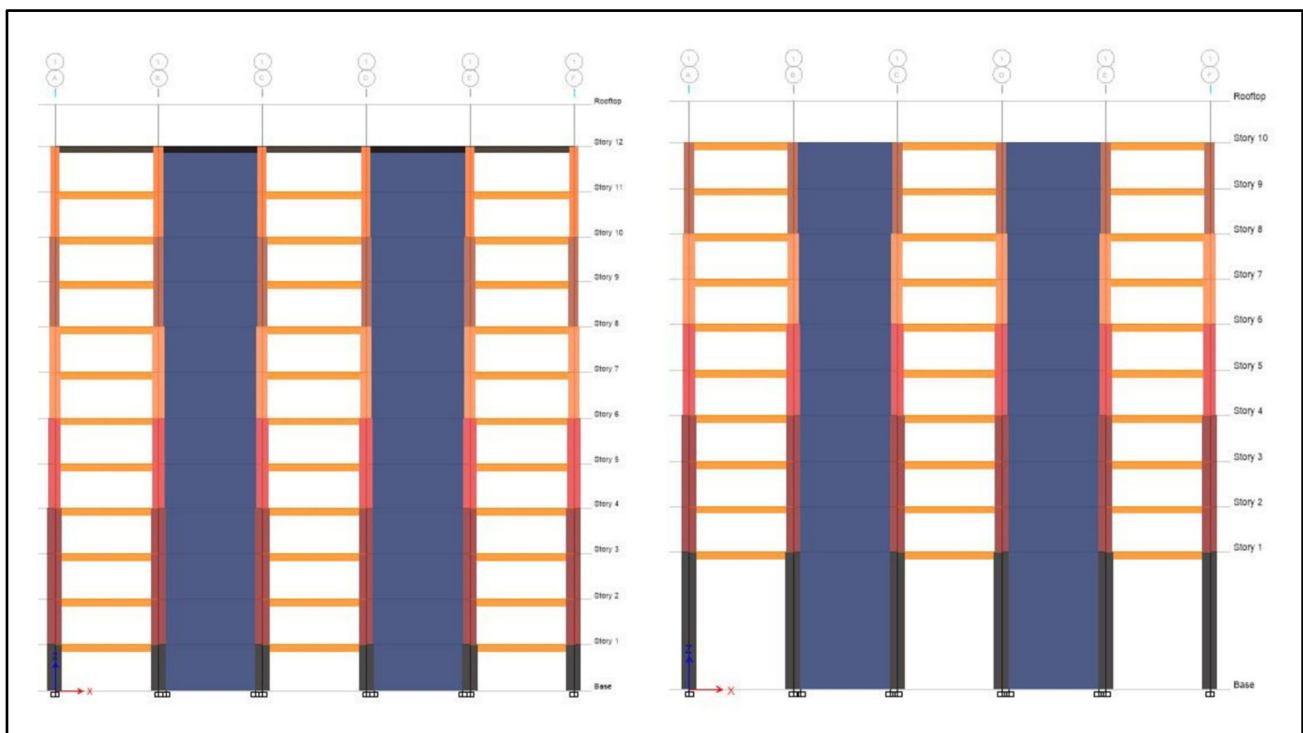


Fig. 2. Modelling: (a) regular structure, (b) irregular structure.

Vertical irregularity check of the structure was first conducted based on Table 14 of SNI 1726-2019. The results indicated that the irregular structure exhibited excessive soft story stiffness irregularity on the first floor, as shown in Table 1. The structure is categorized as having excessive soft story stiffness irregularity if there is a story where the lateral stiffness is less than 60% of the lateral stiffness of the story above or less than 70% of the average lateral stiffness of the three stories above. According to Table 14 of SNI 1726-2019, certain consequences must be met if the structure has excessive soft story stiffness irregularity, as referred to in Section 7.3.3.1 and Table 16 of SNI 1726-2019. However, in this study, the structure was intentionally designed to have soft story stiffness irregularity to understand the effects of this irregularity by comparing it with a regular structure without irregularity.

Table 1. Results of the soft story stiffness irregularity check for the irregular structure.

Story	X direction Stiffness (kN/m)	Check	Y direction Stiffness (kN/m)	Check
Roof	65029.669	OK	52059.072	OK
10	321981.044	OK	251263.956	OK
9	499414.525	OK	376724.199	OK
8	604849.631	OK	443426.425	OK
7	667470.694	OK	475926.756	OK
6	716742.444	OK	499933.312	OK
5	766919.971	OK	524174.189	OK
4	833268.758	OK	559392.226	OK
3	926285.714	OK	610104.802	OK
2	1144926.091	OK	692519.152	OK
1	647464.936	V.1b	417323.532	V.1a

2.2 Pushover analysis

From the results of the static pushover analysis run on SeismoStruct software, a capacity curve (base shear-displacement) is obtained. The resulting pushover curve must then be converted into a bilinear form as shown in Fig. 3. From the pushover curve obtained, the first value taken is the roof displacement at yield (Δ_y), and the second value is the roof displacement at ultimate (Δ_u), taken at 80% of the peak condition. The capability of a

structure will be directly related to the capacity of the structure to accommodate the needs. In other words, the structure has the capacity to withstand the design earthquake force requirements so that the structure's performance is in accordance with the design objectives. The inelastic (post-elastic) behavior of the structure is represented by the presence of plastic joints formed at the foot of the columns and beams.

2.3 Fragility curves

Fragility curve is a lognormal function that correlates the probability of occurrence of a certain level of structural damage due to earthquake intensity. HAZUS (Hazard United States) defines a fragility curve as the relationship between the probability of occurrence of a damage state (Damage State/DS) in a structure and a given earthquake intensity (Intensity Measure/IM). Therefore, fragility curves are highly beneficial for determining the damage state of a structure based on a damage measure. The damage states defined by HAZUS include: slight damage, moderate damage, extensive damage, and complete damage (collapse) [11].

To develop the fragility function, the first step is to define the damage states and to set their threshold limits. A relatively simpler criterion for the definition of damage state thresholds has been proposed by Barbet al., which is presented in Table 2.

Table 2. Damage state definitions as Barbet [10].

Damage state	Damage state thresholds
Slight damage	$Sd_{ds1} = 0,7 \times D_y$
Moderate damage	$Sd_{ds2} = D_y$
Extensive damage	$Sd_{ds3} = D_y + 0,25(D_u - D_y)$
Collapse damage	$Sd_{ds3} = D_u$

In this study, spectral displacement S_d is taken as the intensity measure. The fragility curves can be developed using log-normal functions represented by two variables, the mean value of displacement, and the standard deviation. the fragility curve using the following equation:

$$P(DS/S_d) = \Phi \frac{\ln(S_d) - \ln(\lambda)}{\beta} \quad (1)$$

Description:

$P(DS/S_d)$ = Probability Function (damage state)

Φ = Cumulative normal distribution

S_d = spectral displacement

λ = median value

β = Standard deviation

3 Results and discussion

From the results of the static pushover analysis run on SeismoStruct v.18 software, a capacity curve (base shear

- displacement) is obtained. The resulting pushover curve must then be converted into a bilinear form as shown in Figs. 3 and 4. The capacity curve of the regular structure shows a higher base shear value compared to the irregular structure. This is because the regular structure has a uniform story height on each floor, leading to an even

distribution of stiffness throughout the building vertically. The capacity curve also shows that as stiffness increases, ductility decreases. The capacity curves for regular and irregular structures in the x-direction can be seen in Fig. 3, and for the y-direction in Fig. 4.

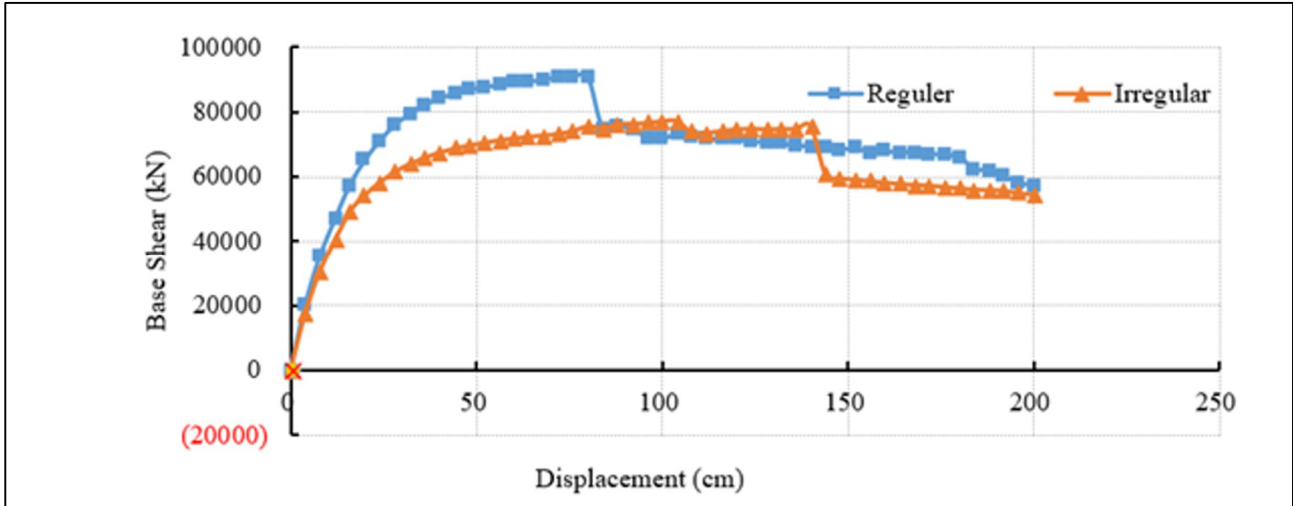


Fig. 3. The capacity curve resulting from the pushover in the x-direction.

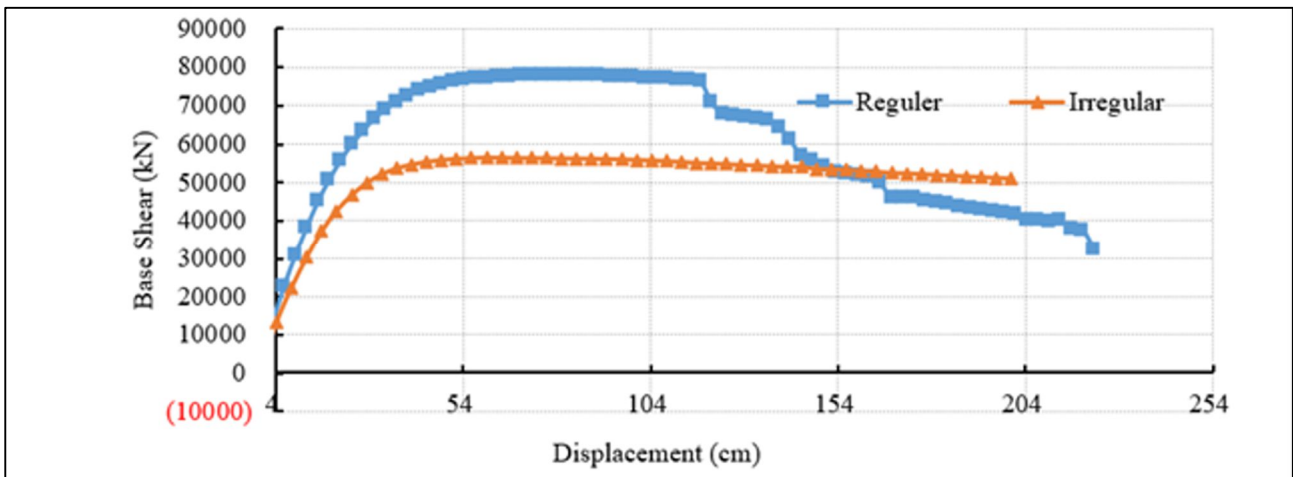


Fig. 4. The capacity curve resulting from the pushover in the y-direction.

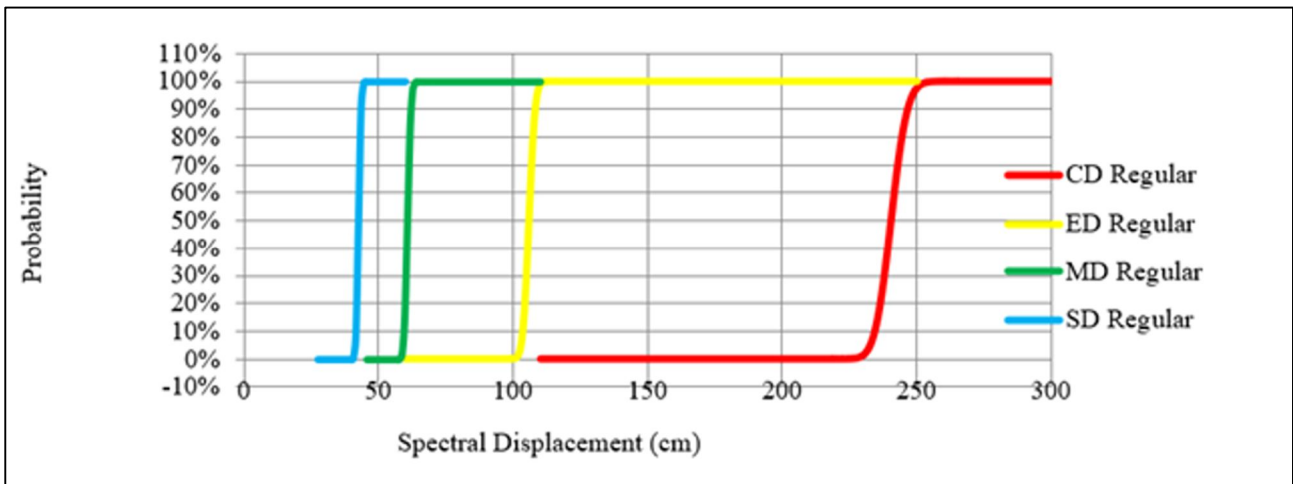


Fig. 5. Fragility curve of the regular structure in the x-direction.

The fragility curve results for the regular structure in the x-direction are shown in Fig. 5, and for the y-direction in Fig. 6. The fragility curves for the irregular structure in the x-direction can be seen in Fig. 7, and in the y-direction in Fig. 8. From the fragility curve of the regular structure in the x-direction, it can be observed that at an ultimate

displacement of 80 cm, the fragility level indicates a 100% probability of experiencing moderate damage, which includes shear cracks and medium cracks in the columns (the columns remain structurally sound), with joints also experiencing cracking.

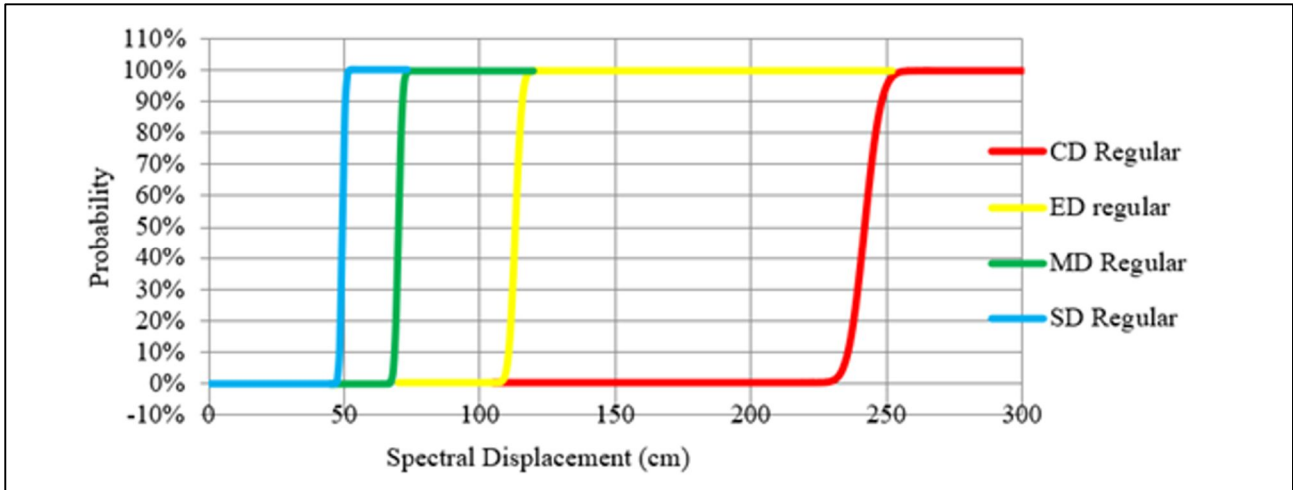


Fig. 6. Fragility curve of the regular structure in the y-direction.

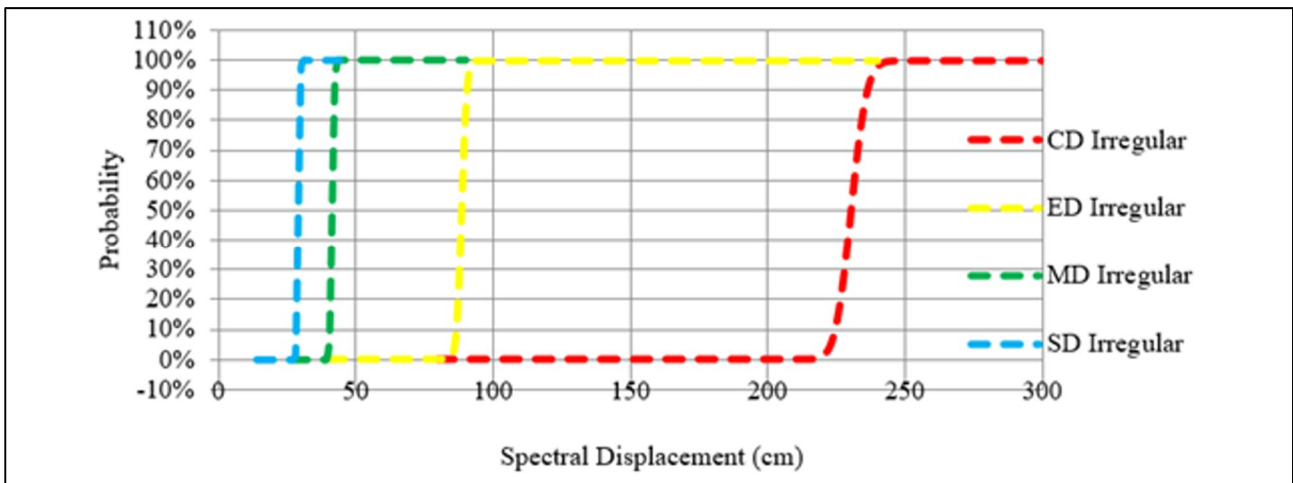


Fig. 7. Fragility curve of the irregular structure in the x-direction.

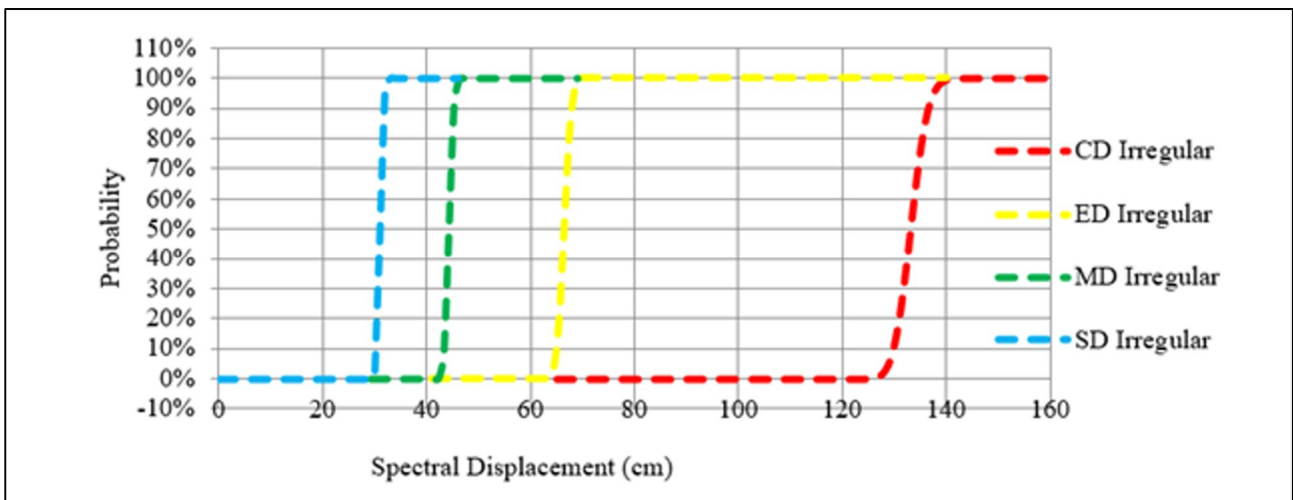


Fig. 8. Fragility curve of the irregular structure in the y-direction.

From the fragility curve of the regular structure in the y-direction, it can be observed that at an ultimate displacement of 70 cm, the fragility level indicates a 100% probability of experiencing moderate damage, which includes shear cracks and medium cracks in the columns (the columns remain structurally sound), with joints also experiencing cracking.

Use From the fragility curve of the irregular structure in the x-direction, it can be observed that at an ultimate displacement of 104 cm, the structure has a 100% probability of experiencing extensive damage. This includes a reduction in strength without collapse in the columns, shear failure (columns are structurally unsafe), and significant residual displacement in the joints.

From the fragility curve of the irregular structure in the y-direction, it can be observed that at an ultimate displacement of 60 cm, the structure has a 100% probability of experiencing moderate damage. This includes shear cracks and medium cracks in the columns (the columns remain structurally sound), with joints also experiencing cracking.

4 Conclusion

Based on the results and discussion for both buildings, namely the regular structure and the irregular structure, it can be concluded that the irregular structure (excessive soft story irregularity) has a higher fragility level compared to the regular structure in both the x and y directions. For the regular structure, the building experiences moderate damage at a drift of 2% as per SNI 1726-2019. In contrast, the irregular structure (excessive soft story irregularity) exhibits extensive damage in both the x and y directions.

References

1. F. D. Shubandrio, A. M. El-Maissi, M. M. Kassem, M. Masrilayanti, S. R. Rahmat, and F. Mohamed Nazri, Evaluating the Interdependencies of Infrastructure Critical Systems during Earthquake Event: A Case Study for Padang City. *Sustainability*, **14**(23), (2022). <https://doi.org/10.3390/su142315926>.
2. R. Aryanti and M. Masrilayanti, State of the art of seismic risk and loss assessment in structures, *E3S Web of Conferences*, **331**, 07013, (2021), <https://doi.org/10.1051/e3sconf/202133107013>.
3. R. Masrilayanti, J. Kurniawan, Tanjung, and M. Yunus, Displacement Performance of 8 Storys Hotel Building Using Nonlinear Time History Analysis Method. **389**, (2024). https://doi.org/10.1007/978-981-99-6368-3_28.
4. P. Fajfar, H. Krawinkler, *Nonlinear Seismic Analysis and Design Buildings* (CRC Press, London, 2005).
5. C. Scawthorn, A Brief History of Seismic Risk Assessment, in *Risk Assessment, Modelling and Decision Support*, S. F. Gottlieb, Ann Bostrom, Ed., Springer, ch. **2**(5–81), (2006). <https://doi.org/10.1525/9780520954731-004>.
6. B. Belletti, C. Damoni, and A. Gasperi, Modeling approaches suitable for pushover analyses of RC structural wall buildings. *Eng Struct*, **57**, 327–338, (2013). <https://doi.org/10.1016/j.engstruct.2013.09.023>
7. M. Masrilayanti, A. P. Nasution, R. Kurniawan, J. Tanjung, and S. Sarmayenti, Fragility Curve Analysis of Medium Cable Stayed Bridge, *Civil and Environmental Engineering*. **17**, 209–218, (2021), <https://doi.org/10.2478/cee-2021-0022>.
8. F. Hosseinpour and A. E. Abdelnaby, Fragility curves for RC frames under multiple earthquakes, *Soil Dynamics and Earthquake Engineering*. (2017). <https://doi.org/10.1016/j.soildyn.2017.04.013>.
9. Masrilayanti, Fragility curves as a tool for disaster mitigation (state of the art), in *Proceedings of AIP Conference*, American Institute of Physics, May (2024). <https://doi.org/10.1063/5.0202953>.
10. C. A. Kircher, R. V. Whitman, and W. T. Holmes, HAZUS Earthquake Loss Estimation Methods, *Nat Hazards Rev*, (2006). [https://doi.org/10.1061/\(asce\)1527-6988\(2006\)7:2\(45\)](https://doi.org/10.1061/(asce)1527-6988(2006)7:2(45)).
11. Z. Guo, *Seismic Resistance. Principles of Reinforced Concrete*. 411–436, (2014), <https://doi.org/10.1016/B978-0-12-800859-1.00016-5>.
12. M. J. N. Priestley, *Performance based seismic design*, *Bulletin of the New Zealand Society for Earthquake Engineering*, (2000). <https://doi.org/10.5459/bnzsee.33.3.325-346>