Performance evaluation of high-rise apartment building using pushover analysis

Masrilayanti[1*], *Yuni Aulia* Hasibuan[2], *Ruddy* Kurniawan[1], *Jati* Sunaryati[1], and *Ridho* Aidil Fitrah[1]

[1]Civil Engineering Department, Universitas Andalas, Padang, Indonesia
[2]Postgraduate Program of Civil Engineering, Universitas Andalas, Jakarta, Indonesia

Abstract. Indonesia is a developing country that is experiencing rapid development growth. According to the Central Statistics Agency, in 2020 the population of Indonesia will be 270.20 million people. The increase in population from year-to-year results in increasingly narrow lands for development. Therefore, developers and businesspeople make the best use of this opportunity in the world of construction by carrying out developments, including high-rise apartments. As an earthquake-prone area, the planning process for buildings, especially tall buildings in Indonesia, must be carried out very carefully by considering the strength of the structure against high-intensity earthquake loads. Risk reduction strategies can be implemented through building vulnerability assessment by checking structural performance using pushover analysis. In this study, the performance of a 32-storey apartment building was examined using the pushover analysis method. The resulting calculation is that the performance of the structure is 0.0023 for the lateral direction and 0.0113 for the transverse direction. Through the ATC 40 method it is known that the result of structural performance is Damage Control, where after an earthquake the building is still habitable.

1 Introduction

The main principle of earthquake resistant buildings is that the building will be permittable damaged during a strong earthquake occurs but will not collapse immediately. Thus, the safety of the occupants become the main design criteria consideration. According to Priestley et al in their publication, the resistant earthquake structure is having some phenomena as below [1]:

- When a small earthquake occurs, all structural elements of the building are designed to be undamaged.
- In a moderate earthquake, the structural elements of the building may suffer damage that can be repaired.
- When a strong earthquake occurs, the building is designed not to experience a fatal collapse, even though the structural components are damaged.

Indonesia is a developing country that is experiencing rapid development growth. This is due to the increasing population in Indonesia. Indonesia itself is ranked fourth in the world with the largest population, namely 270.20 million people in 2020 according to data from the Central Statistics Agency. The increase in population results in increasingly narrow land for development. Therefore, developers and businesspeople make the best use of this opportunity in of construction by carrying out developments of apartments.

Earthquakes can be categorized into two types: volcanic earthquakes and tectonic earthquakes. Volcanic earthquakes occur due to volcanic activity that spews hot lava from the volcano. Tectonic earthquakes occur due to the movement of the earth's crust plates or the presence of fault lines in the earth. Some of the world's famous crustal plates and faults that can cause tectonic earthquakes are the Eurasian plate, the Indo-Australian plate, the Pacific plate and the San Andreas fault. Earthquakes that are closely related to building and non-building structures are tectonic earthquakes. Indonesia itself is crossed by the Eurasian plate and the Indo-Australian plate so that earthquakes can occur at any time, therefore buildings and non-buildings in Indonesia must be designed to withstand large earthquake forces. For this reason, it is necessary to have extensive knowledge about seismicity and earthquake technology [2].

Reinforced concrete is one of the most common building materials used to build high-rise buildings for decades. Different building shapes are possible using advanced mouldings. Shear walls are used in reinforced concrete buildings to increase their resistance to all types of gravity and lateral loads (including seismic loads). Placement of shear walls in optimal positions in buildings is very important to achieve sustainable and resilient building performance under both daily and extreme load [3-4].

Earthquake disasters can claim many lives. History records that the most powerful earthquake in the last 50 years occurred in Bio-Bio Chile in 1960 with an earthquake magnitude of 9.5 Magnitude called the Valvidia earthquake, while the most powerful earthquake in 50 years in Indonesia was recorded as

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

occurring in Aceh in 2004 which resulted in a tsunami with an earthquake magnitude of 9.1 magnitude [5].

The fragility of a structure (or component) is defined by "capacity". Capacity is defined as the earthquake load limit before failure occurs. Therefore, if a peak ground acceleration PGA has been chosen to characterize the degree of seismic ground motion, then the capacity is also expressed in PGA. To simplify notation, it can be considered that the PGA was chosen to characterize seismic ground motions. Structural capacities, in general, should be log-normally distributed [6].

1.1 Performance based design and analysis

Performance-based design is an approach to structural engineering that aims to ensure that structures perform well under extreme loading conditions such as earthquakes, high winds, or floods. Rather than relying solely on prescriptive codes and standards, performance-based design considers the actual performance of the structure under specific loading conditions, considering factors such as the intended use of the structure, its location, and its expected lifespan.

Performance-based design (PBD) has its roots in the seismic design of buildings and structures, and its development can be traced back to the 1970s. At that time, engineers realized that traditional prescriptive design methods were not sufficient to ensure that structures would perform adequately under strong seismic forces [1, 7-8]. Structures that are designed as an earthquake resistant structure typically incorporate specific design features to achieve this objective, such as ductility, redundancy, and seismic isolation.

Ductility is the ability of a structure to deform without breaking. Structures that are designed to be ductile are better able to absorb and dissipate seismic energy, reducing the risk of collapse and limiting the extent of damage. Redundancy involves designing a structure with multiple load paths, so that if one load path fails, the structure can still support the loads. Redundancy can help to prevent progressive collapse and limit the extent of damage to a structure. Seismic isolation involves isolating a structure from the ground using isolation bearings or other devices. This can help to reduce the seismic forces on the structure and limit the extent of damage [9].

In the early 1980s, a group of researchers at the University of California, Berkeley, led by Vitelmo Bertero, began developing the Capacity Spectrum Method, which allowed engineers to analyze the seismic performance of structures more accurately and reliably.

In the 1990s, the Federal Emergency Management Agency (FEMA) began developing guidelines and standards for PBD, including the Multi-Hazard Mitigation Council's "Planning and Designing for Earthquakes: A Manual for Architects and Engineers," which was first published in 1994. These guidelines and standards provided a framework for incorporating performance-based design principles into building codes and standards [10].

Since then, PBD has continued to evolve and expand, with new developments in modelling, analysis techniques, and performance objectives for other hazards such as wind and floods. Today, PBD is widely used in structural engineering for designing and evaluating buildings and other structures, and it has become an essential tool for ensuring the safety and resilience of the built environment.

The process of performance-based design typically involves several steps, including hazard assessment, performance objectives definition, performance criteria development, and performance evaluation. In hazard assessment, the potential hazards that a structure may face are identified and analyzed. Performance objectives definition involves setting goals for how the structure should perform under those hazards, such as limiting damage, protecting life safety, or minimizing downtime.

Performance criteria are then developed, which are quantitative measures of how well the structure must perform to achieve the performance objectives. These criteria can include factors such as maximum deformation, maximum acceleration, or maximum drift.

HAZUS (Hazard US) defines the performance criteria becomes slight, moderate, extensive, and complete damage as can be seen in Fig. 1.

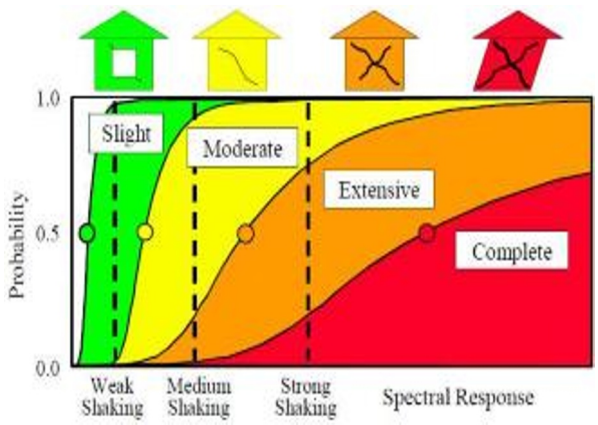

Fig. 1. Performance level of structure based on HAZUS standard [11].

Finally, the structure is evaluated using advanced analytical methods such as nonlinear time history analysis or nonlinear static pushover analysis to ensure that it meets the performance criteria. Performance-based design can result in more resilient and cost-effective structures, as well as reduced risk to life safety and property damage.

1.2 Pushover analysis

Pushover analysis is a widely used nonlinear static analysis method in structural engineering to evaluate the seismic performance of buildings and other structures. The method involves applying a series of lateral loads to a structure and analyzing its response at each load level to determine the ultimate capacity and potential failure modes.

The performance level of pushover analysis depends on various factors such as the accuracy of the structural model, the selection of ground motion records, the consideration of nonlinear behavior of the structure, and the experience and expertise of the analyst. When conducted properly with a suitable level of detail,

pushover analysis can provide a useful estimate of the seismic performance of a structure.

However, it's important to note that pushover analysis is not a substitute for more sophisticated dynamic analysis methods such as time-history analysis or response spectrum analysis, which take into account the actual ground motion and the dynamic behavior of the structure in more detail. Pushover analysis can be a valuable tool for preliminary design and rapid evaluation of structures, but its results should be interpreted with caution and verified using more rigorous analysis methods if necessary.

2 Methodology

Pushover analysis is the main methodology of this study. A method for the nonlinear static analysis of the building is presented, suitable for seismic assessment procedures based on pushover analyses. The method is based on an equivalent frame idealization of the structure, and on simplified constitutive laws for the structural elements.

Performance levels are a way of categorizing the seismic performance of structures based on their ability to meet specific performance objectives under different levels of ground shaking.

The four commonly recognized performance levels in seismic design are:

A. Immediate Occupancy: This performance level is intended for structures that need to remain functional after a moderate earthquake, with no damage to the structural system that would require repair or replacement.

B. Life Safety: This performance level is intended for structures that must remain functional after a design-level earthquake and provide a safe means of egress for occupants but may sustain some damage that requires repair.

C. Damage Control: This performance level is intended for structures that are not required to remain functional after a design-level earthquake but must not collapse, with damage that can be repaired at a reasonable cost.

D. Collapse Prevention: This performance level is intended for structures that are required to prevent collapse under a design-level earthquake, with no consideration of repair costs.

Each performance level has specific requirements for structural design and detailing, based on the expected ground motion and the importance of the structure. The higher the performance level, the more stringent the design requirements, and results in the greater the level of seismic protection provided to occupants and the structure itself.

A pre-determined lateral load pattern is applied onto the structure and steadily increased to identify yielding and plastic hinge formations and the load at which failure of the various structural components occurs.

Analyses have been performed using ETABS, which is a structural analysis program used for static and dynamic analyses of building structures. A 32 floors apartment building is analysed using the software. The data of the building is considered as below:

a.	Location	: Jakarta City
b.	Function of the building	: Apartment
c.	Type of the structure	: Reinforced concrete
d.	Total height	: 100,85 m
e.	Amount of the floors	: 32
f.	Height per floors	: 3.05 m
g.	Length of the building	: 31.5 m
h.	Width of the building	: 14 m
i.	Strength of the concrete	: 40 MPa – 50 MPa
j.	Strength of the steel	: fy 400 MPa.
k.	Soil type	: Medium

The response spectrum of Jakarta City for medium soil type is as can be seen in Fig. 2.

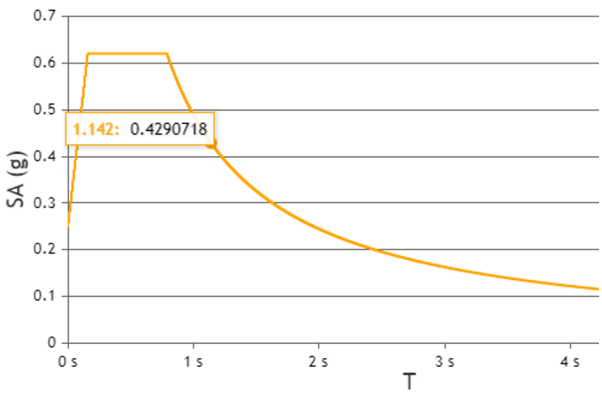

Fig. 2. Response spectrum of Jakarta for medium soil type.

A response spectrum graph is a graphical representation of the maximum response of a structure to an earthquake ground motion. It is a plot of the maximum acceleration, velocity, or displacement of the structure as a function of frequency. The response spectrum graph is typically used in response spectrum analysis, which is a method of seismic analysis used in structural engineering.

The response spectrum graph is generated by calculating the maximum response of a structure to a set of ground motions with varying frequencies. The ground motions are usually selected to represent the range of seismic hazards that the structure may experience at its location. The response spectrum graph is then used to determine the design forces and displacements that the structure must be able to withstand to meet specific performance objectives.

The response spectrum graph typically has a smooth curve with peaks and valleys that correspond to the natural frequencies of the structure. The height of the curve at each frequency represents the maximum response of the structure to ground motion at that frequency. The shape of the response spectrum curve depends on the characteristics of the ground motion and the damping ratio of the structure [12].

The response spectrum graph is an important tool for seismic design, as it allows engineers to determine the seismic demands that a structure may experience and to design the structure to meet specific performance objectives.

The response spectrum graph is used in pushover analysis to determine the distribution of the seismic forces and displacements throughout the structure. It provides a simplified representation of the ground motion that is used to determine the distribution of forces and displacements throughout the structure, and to determine the load pattern for the pushover analysis.

The response spectrum graph is typically used in pushover analysis to determine the capacity of the structure to resist seismic forces at different levels of deformation. The graph can be used to identify critical locations in the structure where plastic hinges may form, and to determine the load pattern that will result in the most efficient use of the structural capacity.

Overall, the response spectrum graph is an important tool in pushover analysis, as it provides a basis for selecting the load pattern and for assessing the capacity of the structure to resist seismic forces.

For the model of the building is as in Fig. 3.

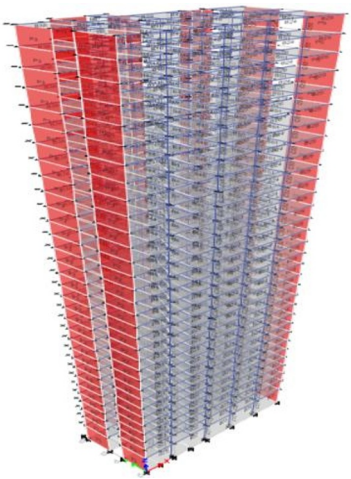

Fig. 3. Model of the structure.

When applying lateral loads to this system, the largest moments are expected at the joints. Therefore, plastic hinges are defined at the start and end of each beam. The structural system and the position of the plastic hinges represent a strong-column / weak-beam frame building where a beam-sway plastic mechanism is expected.

3 Results and discussion

After the analysis is done, plastic hinge only occurs in beam elements. The most plastic hinges appear in the pushover step 7, as can be seen from Fig. 4. Therefore, it is concluded that the building meets the criteria for strong column and weak beam mechanisms.

To obtain the performance point, we need a spectrum response curve that has been converted into ADRS format and get a performance point after getting the intersection point of the capacity spectrum curve with the spectrum response curve.

From the results of the pushover analysis with the ETABS assistance program in terms of FEMA 440, the results for each direction of building X and Y are as follows as can be seen in Fig. 5-6.

Capacity curve or pushover curve represents the nonlinear behaviour of the structure and is a load-deformation curve of the base shear force versus the horizontal roof displacement of the building. The capacity curve provides valuable information about the structure's strength and ductility, which is essential for evaluating its seismic performance.

The capacity curve typically has force or base shear on the horizontal axis and displacement on the vertical axis. The force or base shear represents the applied load, while displacement measures the corresponding deformation or drift of the structure.

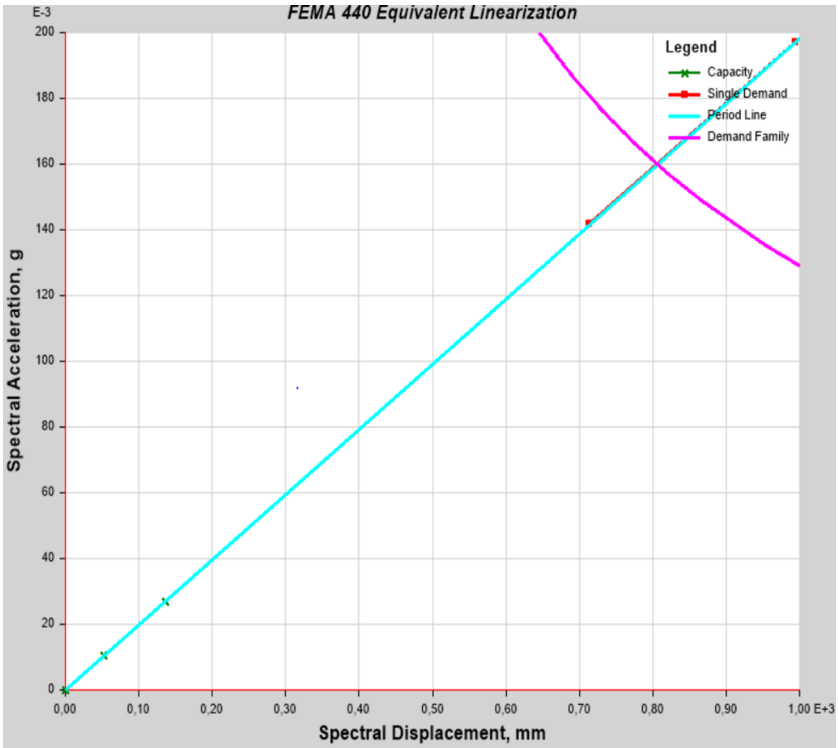

Fig. 5. Performance point in longitudinal (X) direction.

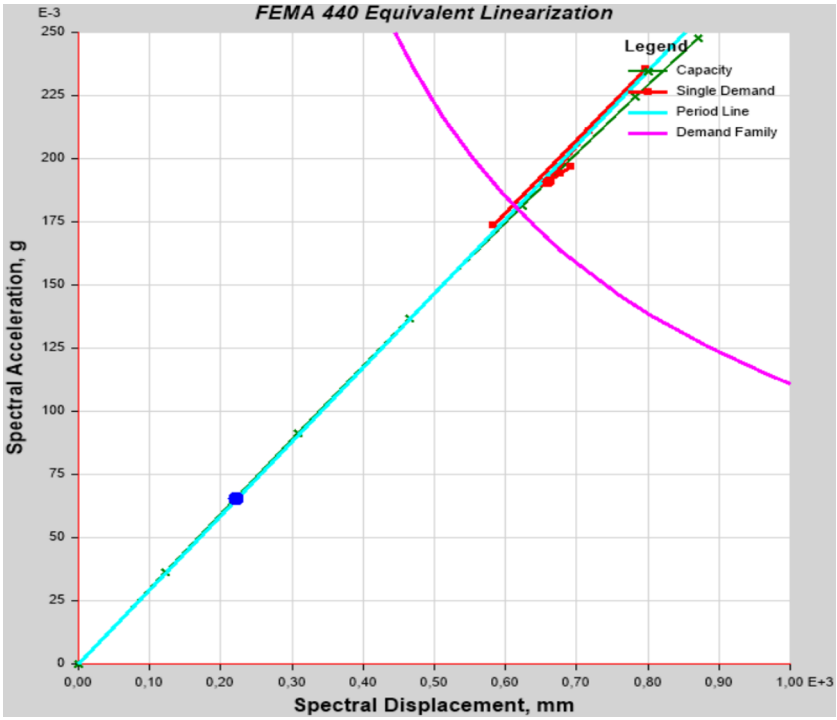

Fig. 6. Performance pointin transversal (Y) direction.

To determine the performance level of the structure, it is necessary define the ratio of the drift by dividing the performance point value of the structure to the total height of the structure.

Tables 1 and 2 describe the value of displacement versus base force in X and Y direction, respectively. The tables show the maximum values of each direction (bold), which are used to define the ratio of limitation to obtain the performance level of the structure. The formula used to carry out the ratio is stated by Equation 1.

Table 1. Displacement vs base force in X direction.

Step	Monitored displacement (mm)	Base Force (kN)
0	0	0
1	79,526	1287,6366
2	**206,687**	3338,0399

Table 2. Displacement vs base force in Y direction.

Step	Monitored Displacement (mm)	Base Force (kN)
0	0	0
1	159,23	4022,4829
2	404,336	10181,5478
3	610,14	15257,0406
4	818,856	20181,185
5	1027,432	24978,4063
6	**1142,755**	27587,5845

$$Ratio = \frac{Maximum\ drift\ value}{Total\ building\ height} \quad (1)$$

$$Ratio\ X = \frac{206.687}{100000.85}$$

$$Ratio\ Y = \frac{1142,755}{100000.85}$$

The limitation ratio for X direction (longitudinal) is 0.0021, meanwhile for Y direction is 0.0114.

The results then are compared to the drift requirements of ATC 40 standard, as can be seen in Table 3. The ATC-40 guidelines provide specific recommandations for the maximum allowable damage control drift for different building types and seismic hazard levels. The guidelines also provide recommendations for retrofit measures that can be used to improve the seismic performance of existing buildings and meet the desired performance objectives.

Results show that in this building, the maximum total drift of the longitudinal direction is smaller compared to transversal direction, that is 0.0021 and 0,0114, respectively. This is a logic results, since the stiffness of the structure is larger in longitudinal direction compared to the other one.

Based on the Table 3, it can be obtained that the performance level of the structure is damage control. In structural engineering, a structure that is defined as "damage control" is a structure that is designed to limit the extent of damage that occurs during a seismic event, while still maintaining its structural integrity and functionality.

Table 3. The requirements of performance level of ATC 40 [13].

Parameter	Perfomance Level			
	IO (Immeddiate Occupancy)	Damage Control	LS (Life Safety)	Structural Stability
Maksimum total drift	0,01	**0,01-0,02**	0,02	0,33 (Vi/Pi)
Maksimum inelastic drift	0,005	0,005-0,015	No limit	No limit

Based on the Table 3, it can be obtained that the performance level of the structure is damage control. In structural engineering, a structure that is defined as "damage control" is a structure that is designed to limit the extent of damage that occurs during a seismic event, while still maintaining its structural integrity and functionality.

The concept of damage control is based on the idea that it may not be possible or cost-effective to design a structure to resist all levels of seismic forces, especially in regions with high seismic hazard. Therefore, structures are designed with a certain level of seismic resilience, which is based on the expected seismic hazard and the desired performance objectives.

A structure that is defined as "damage control" is typically designed to meet the damage control performance objective, which is one of the three performance objectives defined in the ATC-40 guidelines, as mentioned in my previous response. The damage control performance objective is intended to limit the extent of damage that occurs during a seismic event and to ensure that the repair costs are manageable.

Overall, a structure that is designed as damage control is intended to provide a certain level of seismic resilience and limit the extent of damage that occurs during a seismic event. The concept of damage control in structural engineering is a design philosophy that aims to balance the level of seismic resilience of a structure with the expected seismic hazard and the desired performance objectives.

In general, designing a structure for damage control is a reasonable approach in regions with moderate to high seismic hazard, where it may not be practical or cost-effective to design a structure to resist all levels of seismic forces. Instead, a damage control approach focuses on limiting the extent of damage that occurs during a seismic event, while still maintaining the structural integrity and functionality of the building.

A structure designed for damage control is still designed to meet certain performance objectives, such as the life safety objective, which ensures that the building remains stable during a seismic event and that occupants can safely evacuate the building without injury.

4 Conclusion

This study is conducted to obtain the level performance of a high building in Jakarta which is used as an apartment. Jakarta is known as a high risk of earthquake, therefore it is very essential to prepare the society relating to the disaster. If the performance of the building is not appropriate enough to withstand the earthquake, it needs to do some other works such as retrofitting to ensure that the building is safe for being occupied by the people.

From this study, by conducting pushover analysis, the value of ratio of drift limitation is below 0.02, those are 0.0021 for longitudinal direction, and 0.0114 for transversal direction. Therefore, it can be concluded that the structure of this high rise building and functioned as an apartment in Jakarta, has a level of performance as damage control.

This level assumes that the building can withstand the earthquake predicted occurs in Jakarta for medium soil type. The building remains stable when the earthquake happens.

References

1. M.J.N. Priestley, Bulletin of the New Zealand Society for Earthquake Engineering **33**(3), 325-346 (2000) https://doi.org/10.5459/bnzsee.33.3.325-346
2. U. Wijaya, Desain rekayasa gempa berbasis kinerja (ANDI, 2018)
3. S. Mentari, R. Nursani, JTSP **23**(2), 167-176 (2021) https://doi.org/10.15294/jtsp.v23i2.32009
4. S. Molina-Palacios, RUA (2007) http://hdl.handle.net/10045/2626
5. R. Aryanti, M. Masrilayanti, E3S Web Conf. **331**, 07013 (2021) https://doi.org/10.1051/e3sconf/202133107013
6. I. Zentner, A. Nadjarin, N. Humbert, E. Viallet, *Numerical calculation of fragility curves for probabilistic seismic risk assessment*, in The 14th World Conference on Earthquake Engineering, 12-17 Oct 2008, Beijing, China (2008)
7. Masrilayanti, R. Kurniawan, A.L. Budi, S.H. Sourkan, IOP Conf. Ser.: Mater. Sci. Eng. **1041**, 012003 (2021) DOI 10.1088/1757-899X/1041/1/012003
8. J. Su, B. Liu, G. Xing, Y. Ma, J. Huang, Mathematical Problems in Engineering **2019**, 6438450 (2019) https://doi.org/10.1155/2019/6438450
9. G. Sachdeva, S. Chakraborty, S. Ray-Chaudhuri, Engineering Structures **159**, 1-13 (2018) https://doi.org/10.1016/j.engstruct.2017.12.033
10. G.R. Searer, S.A. Freeman, T.F. Paret, *Does it make sense from engineering and economic perspectives to design for a 2475-year earthquake?* in Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues, Seth Stein, Stéphane Mazzotti (2007) https://doi.org/10.1130/2007.2425(23)
11. M. Nastev, N. Todorov, Canadian Water Resources Journal **38**(3), 223-231 (2013) https://doi.org/10.1080/07011784.2013.801599
12. G. Carvalho, R. Bento, C. Bhatt, Earthquakes and Structures **4**(5), 451–470 (2013) http://dx.doi.org/10.12989/eas.2013.4.5.451
13. Applied Technology Council, Seismic evaluation and retrofit of concrete buildings Vol. 1 (ATC-40, 1996)