Fragility curves for low-to-mid-rise concrete frame building retrofitted by shear wall-frame system

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Abstract. The need for an earthquake-resistant building must be fulfilled, especially for areas with high levels of earthquake vulnerability, such Indonesia. Installing a shear wall-frame system is one of the strengthening strategies to withstand the lateral forces caused by the earthquake and to achieve satisfactory global seismic behavior of the concrete frame structure. This ongoing research aims to demonstrate the seismic performance of a low to mid-rise concrete frame building equipped with a shear wall-frame system in several configurations. The response of the structure is analyzed through a nonlinear static procedure. Using Seismostruct, FE package, the capacity curve was obtained as structural response subjected to incremental static loading up to collapse load. The output shows that the structure of a shear wall-frame system has a maximum base value of 19.7x10³ kN, which is greater than the base sliding value in the non-retrofitted building structure, which is 15.2x10³ kN. The obtained fragility curve shows a comparison of the probability of damage to the structures of retrofitted and non-retrofitted shear wall-frame system buildings.

1. Introduction
The need for an earthquake-resistant building must be satisfied, especially for areas with a high level of earthquake vulnerability like Indonesia. From what has happened, the collapse of the building due to the earthquakes took many lives. Therefore, a building must be planned to be able to provide a minimum performance of life safety. It means that the building is allowed to have damage but not collapse. Thus, the potential loss of life can be minimized.

Earthquakes are one of the large dynamic loads that their directions change over time. This causes the response to its building to also change with time. One of the consequences of these dynamic loads is that the building will experience horizontal displacement. If this horizontal displacement exceeds the safety requirements set by existing regulations, the building will collapse.

One of the solutions used to improve the performance of high-rise building structures in overcoming horizontal displacement is by retrofitting in the form of shear wall installation [1]. A shear wall is a reinforced concrete slab installed vertically on the side of a particular building which serves to increase the rigidity of the structure and absorb large shear forces due to seismic load [2]. The function of shear wall in a multi-story structure is also vital to support the floor in the structure and ensure it does not collapse when lateral forces occur due to earthquakes [3]. When shear walls are placed in specific suitable and strategic locations, they can be used economically to provide the required horizontal load resistance.

This study evaluates the seismic performance of retrofitted concrete building structures for low-to-medium building types by determining the seismic fragility before and after using the retrofitting of the shear wall-frame system. Fragility function may be expressed as fragility curve which describe the
conditional probability that structural response exceed prescribed limit state (damage state) as a function of earthquake intensity during structure’s service life. Having fragility function the of strategy can then be assessed rationally.

2. Methodology
2.1 Building Models
The research was conducted using the model of the existing building structure, a namely residential building for low-income apartment type (rusunawa) at Cilacap, Central Java. The structure of the building model has four irregular floors so that it is categorized as a low to medium-rise building, as shown in Figure 1 and Figure 2 [4].

![Figure 1](image1.png)

**Figure 1** The building with non retrofitted model (2D)

![Figure 2](image2.png)

**Figure 2** The building with non retrofitted model (3D)

The location of the building structure model, which was under review, had earthquake characteristics with Spectral Response Acceleration of 0.987 for a short time and 0.389 for the long term [5]. Therefore, it was categorized in relatively high seismicity. To reduce the deviation caused by the acceleration of the occurred earthquake, retrofitting was carried out in the form of installing shear walls on the model of the building structure. Material properties of shear walls have a concrete
compressive strength of 28 MPa and a steel tensile strength of 440 MPa. The location of the first shear wall placement is in the left corner of the outer front of the building, while the second position is in the right corner of the outer rear of the building as shown in Figure 3, Figure 4 and Figure 5.

Figure 3 The building with a retrofitted shear-wall model (2D)

Figure 4 The building with a retrofitted shear-wall model : type I (3D)

Figure 5 The building with a retrofitted shear-wall model : type II (3D)

2.2 Seismic Performance Evaluation

2.2.1 Nonlinear Static (Pushover) Analysis. Pushover analysis simulates the earthquake loads planning on the building model by providing a static horizontal force at the center of mass of each floor of the building whose size was gradually increasing [6]. This analysis was assisted by the Seismostruct software program with finite element analysis. This analysis was done by increasing the loads until the building experienced the first yield and would be continued until the building reached its inelastic deformation limit. As long as the load was applied, the base shear and horizontal deformations were recorded at the control point (center of mass on the roof floor of the building). This recording was then presented in the form of a curve with the y-axis showing the magnitude of the working base shear and the x-axis showing the horizontal deformation on the roof floor of the building[3]. This curve is known as the capacity curve. In broad terms, this curve showed the ability or capacity of the inelastic deformation of the structure before it collapsed.
2.2.2 Fragility Curve.
Seismic performance assessment can be defined as an estimation of potential damage and loss due to earthquake loads. The primacy of this assessment allows us to predict how much damage or loss we will experience when a building structure receives earthquake loads [3], [4], [5]. By knowing the existing potential, planners can design buildings to be stronger to withstand earthquake loads.

The fragility curve is a curve that shows the probability of damage to a structure as a result of receiving earthquake loads at a certain level. The fragility curve has a beneficial function when we evaluate the seismic performance because it displays the level of seismic fragility as the possibility of damage based on earthquake loads that exceed the design load on the performance of a particular structure. So that we can predict how much damage or loss we will have when a building structure receives earthquake loads.

3. Results and Discussion
3.1 Capacity Curve
The capacity curve is a curve that projects a structural response because of pushover loading where the curve forms a relationship between the base shear and the displacement. The capacity curve of the studied building was obtained using the analysis of the Seismostruct software program with the criteria for the performance limit of the structure referring to EUROCODE 8 [4]. Figure 6 shows a comparison of the two capacity curves between a building without retrofitting and a building using shear wall retrofitting.

The building with structural shear wall retrofitting obtained a primary shear value of 19.7x10^3 kN. In contrast, a building without structural retrofitting only obtained a primary shear value of 15.2x10^3 kN at the top of the curve, which could be seen in the figure below. With the comparison of the maximum base shear value, the behavior of the building structure with shear wall retrofitting was increased by 29.6% compared to the behavior of the unretrofitted building structure, which was influenced by the strength and stiffness of the shear wall-frame system. In buildings that are added to the retrofitting of the shear wall-frame system, it will increase the stiffness value of a building [3].

3.2 Spectrum Capacity
The spectrum capacity method was obtained from converting the capacity curve into a capacity spectrum in ADRS (acceleration displacement response spectrum) [7]. The capacity spectrum is a curve of the relationship between the spectral displacement (sd) and the spectral acceleration (sa). Figure 7 shows the comparison of the curve of capacity spectrum using Idealization conversion
method and Per-step conversion method. For information, the idealization conversion method is a capacity spectrum whose displacement occurs at the center of the weak axis of the 4th floor, while per step conversion is a capacity spectrum whose displacement occurs at the center of the weak axis from the 1st floor to the 4th floor [5].

![Figure 7 Spectrum Capacity Comparison Using Per-step Conversion Method and Idealisation Conversion Method](image)

3.3 Fragility Curve

This Fragile Curve showed the probability of an occurred condition linked with spectral displacement (Sd) based on a predetermined damage state, which is formulated in equation 1 [8].

\[
P[ds|S_d] = \Phi \left[ \frac{1}{\beta_{ds}} \ln \left( \frac{S_d}{S_{d,ds}} \right) \right]
\]

(1)

With uncertainty in each damaged condition, it could be calculated using the standard deviation formula shown in equation 2. The meaning (βds) is the total standard deviation for ambiguity in each damaged condition [9].

\[
(\beta_{ds}) = \sqrt{[(CONV[\beta_C, \beta_d])]^2 + [\beta_{M(ds)}]^2}
\]

(2)

To determine the limits of damage to the performance of the structure in this study, two methods were used, namely the HAZUS MH-MR5 method [8] and Silva et al method [10]. The HAZUS MH-MR5 method classifies the damage limits as slight, moderate, extensive, and complete. The parameters of the fragility analysis of the HAZUS MH-MR5 method are the spectra displacement and the damage limits shown in Table 1. While the silva et al method classifies the damage limit consisting of limit state 1 (LS1), limit state 2 (LS2), and limits state 3 (LS3) in terms of maximum base shear. The parameters of the fragility analysis of the Silva et al. method are the spectra displacement and the damage limits shown in Table 2.

| Damage Levels  | Non Retrofitted | Retrofitted Shearwall |
|----------------|-----------------|-----------------------|
| Slight         | 0.01848         | 0.01789               |
| Moderate       | 0.03696         | 0.03577               |
| Extensive      | 0.09240         | 0.08943               |
| Damage Levels | Sd (m) | Non Retrofitted | | Retrofitted Shearwall |
|---------------|--------|-----------------|-----------------|
| Complete      |        | 0.21560         | 0.20867         |

Table 2 Damage Criteria (Silva et al.)

| Damage Levels          | Non Retrofitted | | Retrofitted Shearwall |
|------------------------|-----------------|-----------------|------------------------|
|                        | Δ    | Sd   | Δ    | Sd                        |
| Limit State 1 (LS1)    | 0.030 | 0.022000 | 0.033 | 0.023422                  |
| Limit State 2 (LS2)    | 0.078 | 0.057201 | 0.120 | 0.085221                  |
| Limit State 3 (LS3)    | 0.162 | 0.118798 | 0.299 | 0.212915                  |

The fragility curve in this study describes the probability of the buildings with the unretrofitted and retrofitted shear wall-frame systems to the performance limits according to the HAZUS MH-MR5 method, as shown in Figure 8. While in Figure 9 shows the fragility curve that describes the probability of the buildings with the unretrofitted and retrofitted shear wall-frame systems to the performance limits according to the method of Silva et al. The fragility curve with damage state using maximum base shear (limit state 2 and limit state 3) shows that the building model with shear wall retrofitting is very effective in reducing the impact of earthquake damage.

Figure 8 Fragility Curve (FEMA)
4. Conclusion
The building structure with the retrofitting of a shear wall-frame system affects the seismic performance of the building. The capacity curve in the building structure with the shear wall-frame system was increased compared to the building without retrofitting. The building structure in this study experienced an increase in the peak base shear value of 29.6% due to the effect of installing a shear wall-frame system which increased the strength and stiffness of the building structure.

The building structure that receives various acceleration of ground vibration will reach a certain level of damage with a conditional probability as illustrated on the fragile curve. The benefit of the fragility curve itself was to assess the seismic performance of the building structure rationally. In this study, it was obtained a comparison of the fragility curve for the building with and without retrofitting of the shear wall-frame system. The probability of the building with the retrofitting of shear wall-frame structure using a predetermined level of damage and acceleration of ground vibration is very minimal compared to a building structure without retrofitting.

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