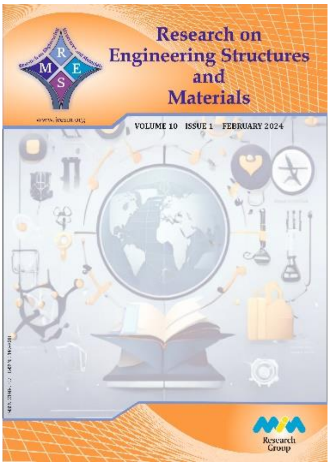
Research on Engineering Structures & Materials

Research Group

www.jresm.org



Integrating push-over analysis and FEMA guidelines for building vulnerability assessment

Jojok Widodo Soetjipto, Ida Elif Nurmaliab, Krisnamurti

Online Publication Date: 01 October 2023

URL: http://www.jresm.org/archive/resm2023.45ma0803rs.html

DOI: http://dx.doi.org/10.17515/resm2023.45ma0803rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Soetjipto JW, Nurmaliab IE, Krisnamurti. Integrating push-over analysis and FEMA guidelines for building vulnerability assessment. *Res. Eng. Struct. Mater.*, 2024; 10(2): 691-709.

Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Research Article

Integrating push-over analysis and FEMA guidelines for building vulnerability assessment

Jojok Widodo Soetjipto*[,a], Ida Elif Nurmalia[b], Krisnamurti[c]

Department of Civil Engineering, Universitas Jember, Indonesia

Article Info

Article history:

Received 24 Oct 2023
Accepted 25 Nov 2023

Keywords:

Rapid visual screening; Structural response; Integrating push-over; Integrating FEMA

Abstract

An earthquake has impacted the existing buildings around the area where the earthquake occurred. To maintain the safety of building occupants, it is necessary to evaluate the building's vulnerability. The most frequently used assessment methods are the Rapid Visual Screening (RVS) from FEMA and the push-over. FEMA can assess the exposure of a building quickly through visual observation but cannot provide a structural response. The push-over can explain the structural response seismic capacity and performance, collapse identification, and building strengthening strategies. However, the push-over has weaknesses; the analysis depends on modelling and structural analysis. This study aims to integrate push-over with FEMA to obtain the most appropriate assessment of buildings in earthquake vulnerability. Both assessment models have been applied to mid-rise buildings of flats after the earthquake. The building received a final score of 2.3 in the FEMA screening evaluation, indicating that it is secure. The push-over analysis shows the damage to the structure is Immediate Occupancy, which means only slight damage occurs. Overall, both methods give the same results and can be integrated to develop RVS and push-over assessments mutually when new modes of building failure are identified and as tools to assess fast, precise and accurate structural failure.

1. Introduction

The Indo-Australian plate, the Eurasian plate, and the Pacific plate all converge in Indonesia [1]. An earthquake has impacted buildings near the earthquake area [2]. Therefore, the main structural components of the building must be designed very carefully at the beam-column connections to withstand cyclic loads caused by earthquakes [3]. If an earthquake hits a building, it causes casualties. Therefore, evaluating the structure is necessary [4]. It is crucial to minimize losses and avoid fatalities.

The factors that influence building damage due to earthquakes are the strength, depth and duration of earthquake vibrations, as well as the condition of the soil and buildings. Guidelines for evaluating the vulnerability of buildings to earthquakes are needed to assess the condition of a building for earthquake vulnerability. Rapid Visual Screening (RVS) is a method for evaluating a building's susceptibility to earthquakes. [5]. The use of RVS has been widely developed through several applications: (i) Using Android-based rapid visual screening (RVS) (using FEMA 154 - 2002) to map the earthquake risk of buildings [6]-[7]; (ii) the application of soft computing techniques for RVS [8]; and (iii) Automated Rapid Vulnerability Assessment of Existing RC Buildings using hybrid ANN-GA model [9].

*Corresponding author: jojok.teknik@unej.ac.id
[a] orcid.org/0000-0003-0026-8296; [b] orcid.org/0000-0002-0928-6178; [c] orcid.org/0000-0002-7858-8073
DOI: http://dx.doi.org/10.17515/resm2023.56st1024rs

Lumajang Regency has a 5-story flat building consisting of 2 buildings with around 191 residents. A five-floor building requires an excellent structure to withstand disasters, including earthquakes. In 2005, the government built these buildings. The construction of flat buildings is an effort to address the problem of slums and meet housing needs in urban areas, especially for low-income people.

Based on USGS data, on April 10 2021, in Lumajang Regency, there was an earthquake magnitude 6.7. The earthquake caused damage to buildings, with a total of 1081 buildings, with details of 441 lightly damaged, 328 moderately damaged, and 328 heavily damaged. Based on this data, an evaluation of existing buildings in Lumajang district is needed.

RVS was previously used in research to quickly assess the initial seismic risk evaluation of flat buildings in Cilacap Regency [10]. RVS, based on FEMA 154 (Federal Emergency Management Agency), was developed in the United States to evaluate the building quickly. The screening process at Rusunawa Cilacap received a final score of 0.7. A final score of 0.7 means there is a 1 in $10^{0.7}$ or 1 in 5 chance the building collapses if an earthquake occurs. Evaluating building vulnerability to earthquakes using the rapid visual screening method on education building [11]. For the moment frame concrete building category (C1), the final score was 3.6, while for the concrete frame building category with unreinforced brick walls (C3), it was 1.4.

The findings of the study demonstrate that this 6-story structure is susceptible to earthquakes, with a high likelihood of level 3 damage and a very high likelihood of level 2 damage. Rapid Visual Screening (RVS) method is used to assess the earthquake-vulnerability of hospital buildings that have been hit by an earthquake [12]. The Hospital Building is classified as safe and not prone to earthquakes, with a potential vulnerability percentage of 0.0126%, according to the RVS method evaluation results. The building does not need to be specially prepared to withstand earthquakes, but regular maintenance is necessary to ensure occupant safety and extend the life of a building. Research on building vulnerability to earthquakes in high-story education buildings in Yogyakata [13]. The form used is the high seismicity type, which means the level of seismicity at the research location has a high earthquake distribution. The research results found that the final score value was 2.3, with the percentage of vulnerability of the building to collapse being 0.5%, making it safe against earthquakes.

Based on the previous studies above, building reliability evaluations using Rapid Visual Screening of Buildings can only be used to determine Building Performance Levels. RVS is used as a guide to assess the vulnerability of a building, which is recommended for all buildings [5]. Several components that be used as evaluation material in FEMA P-154 are location seismicity, population size, type and type of soil, structural elements that are dangerous for falling, kind or type of building, number of building floors, vertical irregularity, plan irregularity, regulations used when building and scoring. In the meantime, it is necessary to assess the damage and performance of the previously designed and analyzed structures using linear static analysis for seismic loads and the implementation of reinforced concrete moment-resisting frame buildings in order to determine the dependability of facilities that experience earthquake loads. One of the analytical methods that has been developed is using push-over analysis.

Performance-based design (PBD) processes have grown to be one of the cornerstones of earthquake engineering over the last few decades. The push-over procedure consists of two steps. The first type of force applies to the structure while estimating the total amount of energy present. The second is the displacement of the structure, which was built to evaluate whether the top would fall off under planned earthquake excitation. The building is then subjected to a push-over analysis until the peak displacement equals the target displacement. The framework is vulnerable to increased vertical irregularity, according to an analysis of previous research findings. If the vertical irregularity increases, more plastic hinges will cross the boundary. This analysis shows that model 2 has better behavior [14]. The accuracy of Push-over is highly reliant on the form, complexity, and analysis of structural use in the Adaptive Capacity Spectrum Method for Seismic Assessment of Planned Asymmetric Buildings [15], [16]. In accordance with Indian codes, push-over analysis is also used to assess the performance of structures that have been designed and studied using linear static analysis for seismic loads [17]. Push-overs are also used to rotate the effects of lateral connections in the moment-bearing frames of low, medium and high-rise RC structures [18]. Through the development of better methods for assessing seismic performance in reinforced concrete moment-resisting frame structures, push-over accuracy has been developed [19]. By directly accounting for the cyclic degradation of actual MDOF systems while retaining the SDOF systems' ease of use and computational efficiency for the evaluation of displacement requirements, Push-over has also been created to assess the structure of multiple earthquakes, making them appealing for use in real-world scenarios [20], [21].

Deviations in Reinforced Concrete Multi-Storey Buildings based on Push-over Analysis using the ATC-40 Method [22]. According to the research findings, the building structure can exhibit nonlinear behavior, as was demonstrated in the preliminary stage, and the majority of plastic joints are found in the beam elements, followed by the column elements. If the building's structural performance level satisfies operational standards, there is only minor structural damage, and it can resume use right away. The seismic performance of concrete structures using push-over analysis has also been evaluated using the SAP 2000 program [23]. From the results of the research carried out, it was found that the effective shear force was 428,206 tons, less than the planned base shear force of 747,132 tons, with the peak acceleration of the bedrock of 0.012 g, less than the peak acceleration of the base rock in the plan for earthquake area 3, namely 0.15 g. As demonstrated in the initial phase, the building structure can exhibit nonlinear behavior, and the majority of plastic joints are found first in the beam elements and then the column elements. Since there is only minor structural damage, the building can be used again right away because its structural performance level meets the requirements for immediate occupancy. However, obtaining this assessment necessitates a thorough structural analysis that is time-consuming and complex.

Based on this background, research is needed on evaluating building vulnerability using the Rapid Visual Screening (RVS) method integrated with push-over analysis to assess building vulnerability quickly, efficiently and accurately. This integration is necessary because RVS can speed up the evaluation process while push-over can increase the accuracy of the analysis and known structure behavior results obtained from RVS. This study was carried out by determining building vulnerability using RVS and push-over analysis. Then, the RVS results will be developed and validated based on push-over analysis so that the behavior of the structure and its failure pattern can be known. In this way, RVS, which initially only gets values and estimates of failure after being integrated with push-over analysis, can produce more accurate vulnerability estimates and improve procedures if new potential failure modes exist.

2. Methodology

The research method was developed to evaluate the result of RVS analysis using the push-over method and enhance the result assessment of both methods based on structure behavior.

2.1. RVS Method

Using the FEMA P-154 approach to establish a seismic RVS method, the RVS method was used to assess the seismic risk of the apartment building in Lumajang. Accordingly, the fundamental score modifiers are suggested, taking building characteristics into account. The building capacity demand and fragility parameters, which were computed based on the exposure conditions and performance levels of the buildings, are the basis for the methods described to derive the basic scores and score modifiers in FEMA P-154 [24]. Figure 1 depicts the RVS method's flow diagram.

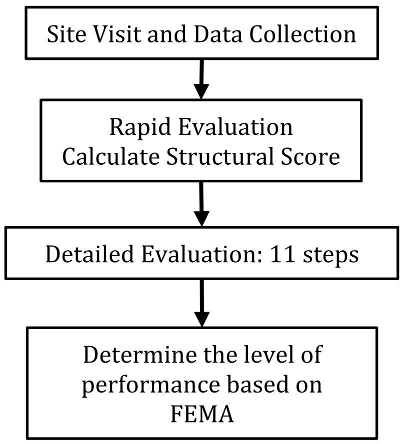


Fig. 1. Evaluation procedure

2.1.1. Site Visit and Data Collection

The screener sketched the building's plan and noted its characteristics (such as regularity, structural components, visual appeal, etc.) while walking around the building and through its interior to determine the type of building based on FEMA 154. Using the provided high seismicity data collection form, they gathered information about the structure, including pre-field data such as the address, the number of stories, the year of construction, and soil data.

2.1.2. Rapid Evaluation Calculate Structural Score

A two-stage seismic risk assessment technique developed by RVS method can be used to evaluate RC buildings. A straightforward screening process for reinforced concrete buildings was suggested in FEMA-154. The number of stories, apparent building quality, soft story irregularity, substantial overhangs, short column effect, pounding effect, topographic properties, seismic hazard, and local soil conditions are all determined using this method at the evaluation stage of the buildings. The number of stories and seismic hazard zones (earthquake zones) are used to calculate a basic score.

2.1.3. Detailed Evaluation

A computation of the FEMA Building Basic Score is shown in this section [5] as follows:

Step 1: Development of the capacity curve

The yield capacity and ultimate capacity points (Dy, Ay) and (Du, Au) are what the capacity curve is made of:

$$Ay = CS \frac{\gamma}{\alpha_1} \tag{1}$$

$$Dy = 9.8\, Ay\, Te2 \tag{2}$$

$$Au = \lambda\, Ay \tag{3}$$

$$Du = \lambda\, \mu\, Dy \tag{4}$$

The values for the variables C_S, γ, α_1, T_e, λ, and μ are taken from the FEMA Handbook.

When the spectral displacement is smaller than the yield displacement, the building capacity curve is considered to be linear, and it is taken for granted that it will continue to be plastic after the ultimate point. It is expected that the capacity curve's transition from the yield point to the ultimate point will take the following shape:

$$\frac{(D - Du)^2}{a^2} + \frac{(A - k)^2}{b^2} = 1 \tag{5}$$

where a, b, and k are from Equations:

$$a = \sqrt{\frac{Dy}{Ay} b^2 \frac{(Du - Dy)}{(Ay - k)}} \tag{6}$$

$$b = Au - k \tag{7}$$

$$k = \frac{Au^2 - Ay^2 + \frac{Ay^2}{Dy}(Dy - Du)}{2\,(Au - Ay) + \frac{Ay}{Dy}(Dy - Du)} \tag{8}$$

Step 2: Values for the input spectral acceleration response are determined

The building's position affects the median one-second period spectral acceleration response, S_1, as well as the median short-period spectral acceleration response, S_S.

Step 3: Calculation of the S_{MS} and S_{M1} values for the adjusted input spectral acceleration response

Site coefficients are used to account for soil when adjusting S_S and S_1 values..

Step 4: 5%-damped demand response spectrum development

The following equations, which are taken from HAZUS TM, are used to produce the demand response spectrum, formatted with spectral displacement response as the X-axis and spectral acceleration response as the Y-axis:

$$\textit{At short periods (acceleration domain), } 0 < T < TS\text{: } S_A(T) = \frac{S_{MS}}{R_A} \tag{9}$$

$$\textit{At long periods (velocity domain), } TS < T < TVD\text{: } S_A(T) = \frac{\frac{S_{M1}}{T}}{R_v}\,; S_A\,(T) = 9.8\, S_A\, T^2 \tag{10}$$

where: Ts is the transition time between the constant acceleration and constant velocity sections of the response spectrum; $S_A(T)$ is the spectral acceleration response in g at period T; $S_D(T)$ is the spectral displacement response in inches at period T.

$$T_s = (SM1/SMS) \times (RA/RV) \tag{11}$$

$$R_A = \text{reduction factor in acceleration domain} = 2.12/(3.21 - 0.68\ln(\beta_{eff})) \tag{12}$$

$$R_V = \text{reduction factor in velocity domain} = 1.65/(2.31 - 0.41\ln(\beta_{eff})) \tag{13}$$

β_{eff} = effective damping, This is the result of adding the hysteretic damping, β_H, and the elastic damping, β_E;

β_H = hysteretic damping, which depends on the magnitude of the response and is based on the region contained by the hysteresis loop, takes into account the possibility of the structure's ability to absorb energy degrading during cyclic earthquake loading.

Step 5: The creation of a damped response spectrum

A 5% dampening assumption is made in the demand spectrum created in the preceding stage. The region beneath the hysteresis loop expands as the building's spectral displacement does, raising β_H and β_{eff} in the process. The demand curve flattens out as eff rises (due to the reduction factors R_A and R_V).

The peak response so determines how the demand spectrum will behave. The peak response, or the point at which the capacity and demand curves connect, must thus be calculated using an iterative process. There are several ways to carry out this computation.

In order to determine the peak response, an " β_{eff}-damped locus demand spectrum" is developed. The period and effective damping for each conceivable displacement, D, are calculated, and the spectral displacement against spectral acceleration are shown for each value of D.

Step 6: Peak response measurement

The peak response is defined as the point where the demand spectrum and the capacity curve converge. based on the overlap of the demand spectrum and capacity curve.

Step 7: Creation of a fragility curve

$$S_{d,C} = \Delta_C \; H_R \left(\frac{\propto_2}{\propto_3}\right) \tag{14}$$

The entire (C) structural damage state's median value is:

Step 8: Estimating the likelihood of total destruction

For a one-story S2 structure in the seismic zone, the likelihood of total destruction is:

$$P_{[Complete\ Demage]} = \varphi \left(\frac{1}{\beta_{C,P}} \; ln \frac{D}{S_{d,C}}\right) \tag{15}$$

Step 9: Calculating the likelihood of a collapse

The likelihood of collapse of in seismicity is

$$P(Collapse) = P_{[Collapse\ rate]} \; x \; P_{[Complete\ Demage]} \tag{16}$$

Step 10: Interact collapse uncertainty to a matched score

The one-story S2 with High seismicity's relating score is

$$S = -log10(P(Collapse)) \tag{17}$$

Step 11: Recognize the basic score.

The outcome of taking the building's basic score in the seismic region.

2.1.4. Determine the Level of Performance Based On FEMA

The performance levels, according to FEMA, are as follows: (i) Operational Performance Level; (ii) Immediate Occupancy Level; (iii) Life Savety Level; and (iv) Collapse Prevention Level.

- 1. Operational level (1-A): The building has no significant damage to structures and non-structures at this level. The building still functions well even though minor damage is not significant, such as damage to the electrical installation, water network and several other utilities. Figure 2 (a) shows the building performance level's condition.
- 2. Immediate Occupancy Level (1-B): The building experiences structural damage at this level, but the damage is insignificant. The condition of non-structural components is still functioning and is or is available in place. The building can still be used without being disturbed by the problem of repairing damage to the building. The risk of casualties occurring at this level of performance is minimal. Figure 2 (b) shows the building performance level's condition and the yield capacity point.
- 3. Life safety level (3-C): At this level, the building experiences structural damage and reduced stiffness but still has sufficient ability to collapse. Non-structural components are damaged and no longer function. Buildings can be reused if repairs have been made to damaged parts of the structure, but this also needs to be considered from an economic perspective. Figure 2 (c) shows the building's condition at this level and the ultimate capacity point.
- 4. Structural Stability/Collapse Prevention (4-D): At this point, both structural and non-structural elements of the structure sustain quite serious damage. The building is on the verge of collapsing due to the strength of the structure, and its rigidity is significantly reduced due to damage or collapse of materials. Casualties may occur, and the building will suffer significant economic losses. Figure 2 (d) displays the state of this building's performance level and its maximum capacity point.

The explanation of each level of building performance due to earthquake loads and structural drift can be illustrated in Figure 2.

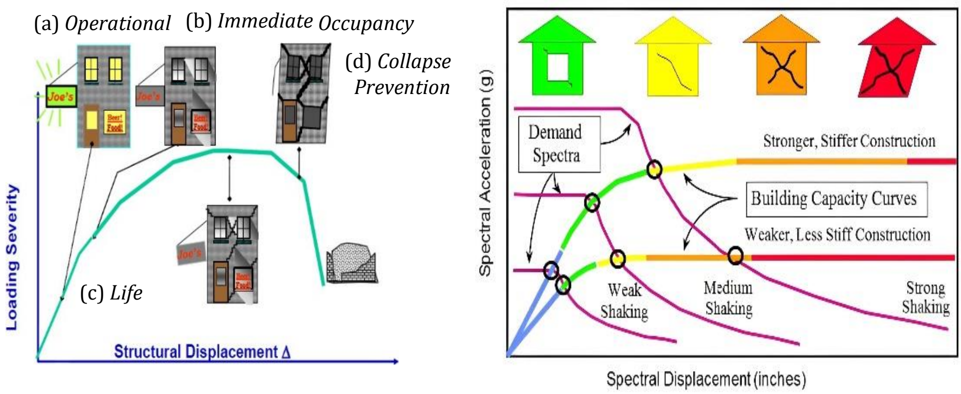


Fig. 2. The level of building performance and building capacity curve and control points [5]

The building performance level requirement for flats is Immediate Occupancy. Performance analysis can be done by comparing structure capacity and demand. Demand represents ground movement due to an earthquake, so the parameter used is structural displacement. In contrast, structural capacity means the structure's ability to withstand seismic demand.

2.2. Push-over Method

Push-over analysis is needed to analyze structures with monotonically increasing lateral load patterns. The inertial force that the structure will experience when exposed to ground movement. Numerous structural components can consecutively fail under stresses that increase gradually. As a result, the structure becomes less rigid throughout each occurrence. Non-linear static push-over analysis may be used to derive a typical non-linear force-displacement relationship. Initially, gravity loads are applied to a three-dimensional model that includes tri-linear load deformation diagrams for every lateral force-resisting component.

Then, a lateral load pattern that is dispersed along the building's height is applied. Increased lateral pressures cause certain members to give way. The lateral forces are raised further until the new part yields, and the structural model is changed to account for the lower stiffness of the yielding member. Until the controlled displacement at the top of the building deforms to a specific degree or the structure becomes unstable, this procedure is repeated.

2.2.1. Types of Push-over Analysis

Analyses of push-over are used for force or displacement control. Full loads are combined under force control (such as gravity loading). Additionally, due to the evolution of the mechanism and the P-delta effect, the target displacement in the force-controlled push-over study may be connected to very tiny amounts of positive or even negative lateral stiffness, which has an impact on the correctness of the results.

Push-over analysis is often carried out as a controlled displacement. When the size of the applied load is unknown in advance, specific displacement/drift controls are needed (as in seismic loading). As necessary, the load combination's significance is altered until the control displacement achieves the desired value. The roof displacement at the mass center of the structure is often used as the control displacement. Calculated internal forces and deformations at target displacements determine inelastic pressures and deformation demands that must be contrasted with the capacity available for performance assessments.

2.2.2. Performance Levels of Building

The maximum base shear that the structure can bear is outlined by push-over analysis. The building performance level combines the performance level of structures and non-structural components. It describes the limited damage conditions to a particular building with a specific ground movement. Performance levels as per FEMA are:

Immediate Occupancy (IO): The structure retains the majority of its initial stiffness despite suffering relatively less damage. The likelihood of a fatal injury from structural damage is low, and while some minor structural repairs could be necessary before reuse, they are often not.

Life Safety Level (LS): The structure has sustained severe damage and may have lost a sizeable portion of its initial stiffness. Before failure comes, however, there is still a sizable amount of opportunity for more lateral distortion. Although this may not be feasible due to financial constraints, the building must be repairable. Although there is no immediate risk of collapse due to a broken system, it would be prudent to perform structural repairs or construct temporary supports before resuming operation.

Collapse Prevention (CP): If lateral displacement continues at this stage, the structure may become unstable and collapse. At this point, the building has suffered serious damage. Because aftershock activity might result in failure, the system might be dangerous to reoccupy and impractical to repair.

2.2.3. Push-over Curve

At different phases of the investigation, we may utilize a push-over curve to determine structural performance points and hinge placements (see Figure 3). In this curve, the instantaneous occupancy range is B to IO, the life safety range is IO to LS, and the collapse prevention range is LS to CP.

A hinge must start releasing the load when it reaches point C on the forced displacement curve. The load will be reduced until the base shear or pushing force at point C equals the force at point D. All elements release the load when the force is reduced, reducing their displacement. The amount of the compressive force is once again reinforced once the yielding hinge contacts the force level point D, and the removal starts to rise once more. If every hinge is within the specified CP limits, the construction is deemed safe. However, depending on the significance of the building, hinges after the IO span might also need to be restored.

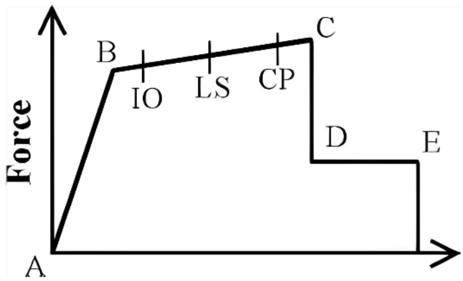


Fig. 3. Typical Push-over Curve and Performance Levels [17]

2.2.4. Key Elements of Push-over Analysis

Definition of Plastic Hinges: In structural analysis, it is presumed that concentrated plastic hinges would exhibit non-linear behavior in frame components. Unpaired moment, unpaired axial, unpaired sliding, paired axial force, and biaxial bending moment hinges are examples of common kinds.

Control nodes are defined as nodes that are used to regulate a structure's displacement. The capacity (push-over) curve of the structure is defined as displacement versus base shear. In developing the push-over curve, the predicted inertial force distribution was taken into account for force-displacement. The severity of earthquake loads may be modeled using various force distributions.

Shift Demand Estimation: When employing push-over analysis, this phase is crucial. The control node is driven to achieve a demand displacement that represents the greatest displacement anticipated as a result of the magnitude of the earthquake being taken into account.

Evaluation of Performance Levels: Performance-based design is the goal of performance evaluation. If a component or activity satisfies the required performance, it is regarded as satisfactory. Demand response in comparison to capacity is the main result of push-over study. If the demand curve crosses the capacity envelope close to the elastic range, the structure is robust. Assume that the capacity reserve has low strength and deforms when the demand curve crosses it. In that instance, it may be deduced that the building would respond improperly during seismic excitation and that it has to be altered to prevent serious damage or collapse in the future.

2.2.5. Evaluation Procedures

Different building evaluation methods are used, but the fundamental ideas remain the same. The evaluation methods in accordance with FEMA 356 are listed below. Method of Displacement Coefficient (DCM): The displacement coefficient approach, which was adopted by FEMA 356, estimates maximum displacement using push-over analysis and a modified precise displacement estimate. Based on a statistical examination of the outcomes from the time history analysis of various types of SDOF oscillators, DCM is a method for analyzing data. According to the findings of several research, the capacity spectrum approach significantly underestimates the response of structures that are in the inelastic region. The displacement coefficient approach, however, typically yields numbers that are appropriate.

3. Results and Discussion

In this section, this study discusses the analysis results of both methods of evaluating building vulnerability due to earthquakes. Detailed results of the discussion can be explained in the following sub-section.

3.1. Result and Analysis

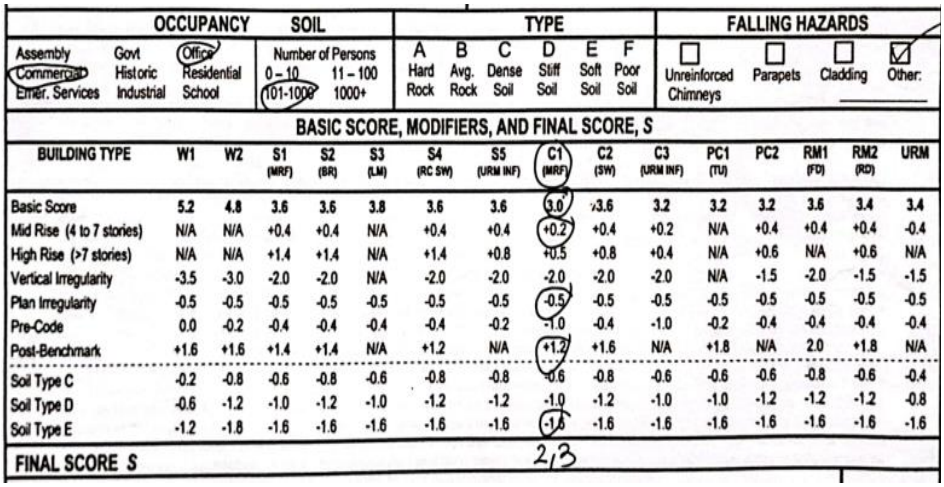
3.1.1 Result of RVS Analysis

The results of the walking around survey of the building and through the interior of the building to identify building type based on FEMA 154 showed that the building, including a commercial building, was located on soft soil with no architectural components that could easily fall (see Figure 4). Based on this data, a basic score of 3.0 was obtained with the characteristics of a middle-rise building (5 stories), without vertical irregularities but with plan irregularities, and determining seismicity based on bench-marks and soil type. From the calculation analysis above, the final RVS score was 2.3 (see Figure 5). This score has a value greater than 2, which is the limit score for buildings according to FEMA 154. Rapid Visual Screening findings indicate that no more analysis is required, indicating that the building has a little chance of collapsing in the event of an earthquake.

Based on the screening data on the RVS, FEMA can construct a capacity curve using equations (1) – (8). This curve shows the relationship between spectral acceleration (g) and spectral displacement. Based on spectral acceleration, this capacity curve can estimate the magnitude of shear force and displacement in buildings due to earthquake loads. Figure 6 (a) shows more details of this curve. Meanwhile, a damped demand spectrum is a method of capacity and demand curves in a response spectrum. A 5% submerged pseudo-elastic single degree of freedom (SDOF) is used in this curve. This curve was prepared from FEMA interpretation data using equations (9) - (13) (see Figure 6 (b)). The performance point, which depicts the seismic behavior of various structures, is generated from the intersection of the two curves between the inelastic demand spectrum and the capacity spectrum (Figure 6(c)).

The cumulative probability curve of damage in the lognormal distribution on the vertical axis and the spectral displacement on the horizontal axis may be used to calculate the chance of damage with the specified spectral displacement of the performance point. Determination of cumulative probability is calculated using equations (14) – (17). Then, the discrete probability (Figure 6 (d)) in each condition of building damage. From the FEMA 154 analysis results, it was obtained that the performance level is Operational Performance Level with a probability of collapse of 0.5%. This result follows the RVS assessment, namely that the building has no potential for collapse during an earthquake.

Fig. 4. The building as case study

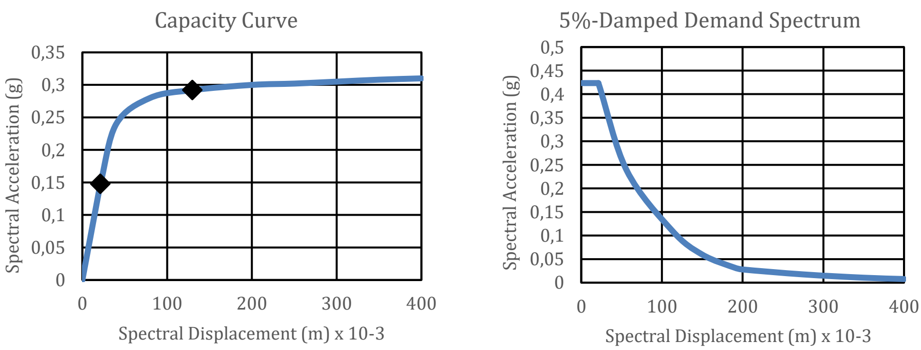


OCCUPANCY			SOIL		TYPE						FALLING HAZARDS			
Assembly	Govt	Office	Number of Persons		A Hard Rock	B Avg. Rock	C Dense Soil	D Stiff Soil	E Soft Soil	F Poor Soil	Unreinforced Chimneys	Parapets	Cladding	Other:
Commercial	Historic	Residential	0 – 10	11 – 100										
Emer. Services	Industrial	School	101-1000	1000+										

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

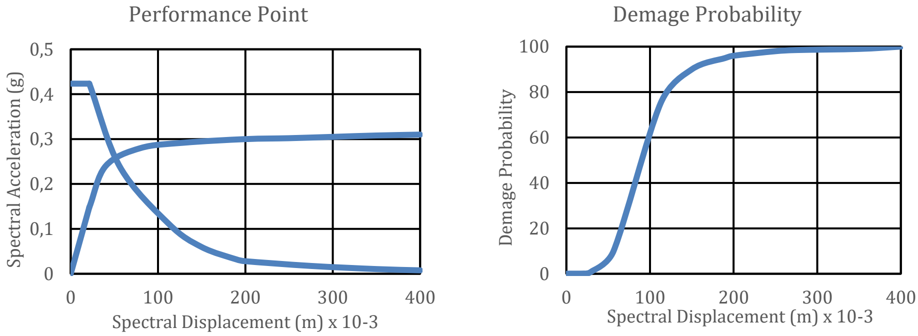
BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	5.2	4.8	3.6	3.6	3.8	3.6	3.6	3.0	3.6	3.2	3.2	3.2	3.6	3.4	3.4
Mid Rise (4 to 7 stories)	N/A	N/A	+0.4	+0.4	N/A	+0.4	+0.4	+0.2	+0.4	+0.2	N/A	+0.4	+0.4	+0.4	-0.4
High Rise (>7 stories)	N/A	N/A	+1.4	+1.4	N/A	+1.4	+0.8	+0.5	+0.8	+0.4	N/A	+0.6	N/A	+0.6	N/A
Vertical Irregularity	-3.5	-3.0	-2.0	-2.0	N/A	-2.0	-2.0	-2.0	-2.0	-2.0	N/A	-1.5	-2.0	-1.5	-1.5
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	-1.0	-0.4	-1.0	-0.2	-0.4	-0.4	-0.4	-0.4
Post-Benchmark	+1.6	+1.6	+1.4	+1.4	N/A	+1.2	N/A	+1.2	+1.6	N/A	+1.8	N/A	2.0	+1.8	N/A
Soil Type C	-0.2	-0.8	-0.6	-0.8	-0.6	-0.8	-0.8	-0.6	-0.8	-0.6	-0.6	-0.6	-0.8	-0.6	-0.4
Soil Type D	-0.6	-1.2	-1.0	-1.2	-1.0	-1.2	-1.2	-1.0	-1.2	-1.0	-1.0	-1.2	-1.2	-1.2	-0.8
Soil Type E	-1.2	-1.8	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6
FINAL SCORE S								2,3							

Fig. 5. Manual Form of RVS Method in accordance with FEMA 154



(a) The capacity curve

(b) 5%-damped demand spectrum



(c) Performance point (d) Probability

Fig. 6. The demand spectrum for a high seismicity zone and its capacity curve, with 5% damping

3.1.2 Result of Push-over Analysis

This flat building is designed to be a multi-storey reinforced concrete building which has been designed for non-linear earthquake static analysis. Linear static analysis was carried out using a structural analysis program with Push-over Analysis to assess potential damage to buildings due to earthquakes. The analysis process is carried out through several stages:

The structure modeling:

Table 1 and Figure 7 both list the number of members, nodes, and supports that make up constructing frames. Table 2 lists the structural components' material characteristics.

Table 1. Material properties considered for analysis

Member	Size (mm x mm)
Beams	200 x 300
Sloof	150 x 250
Ring Balk	150 x 250
Column 1	300 x 500
Column 2	250 x 350

Table 2. Material properties of structure

Material	Modulus of elasticity (KN/m³)	Poisson ration	Density (KN/m³)	Coefficient of thermal expansion	F_{ek}/f_y (KN/m²)
Concrete Properties					
K250	2.18E+09	0.2	23.045	9.90E-06	30
K 300	2.39E+09	0.2	23.045	9.90E-06	30
Reinforcing bar (rebar) Properties					
BJTP 30	2.04E+10	0.3	76.97	1.17E-05	415
BJTS 40	2.04E+10	0.3		1.17E-05	415

Analysis Results of Seismic Load Case:

The structural analysis support program analyses the structural modelling and material properties above. This structure application tool, a finite element analysis package used for structural analysis, proposes hinges for columns and beams in accordance with FEMA-356 and offers default hinge properties. A non-linear push-over study was done to determine the structure's seismic response after designing and specifying the reinforced concrete frame construction mentioned above.

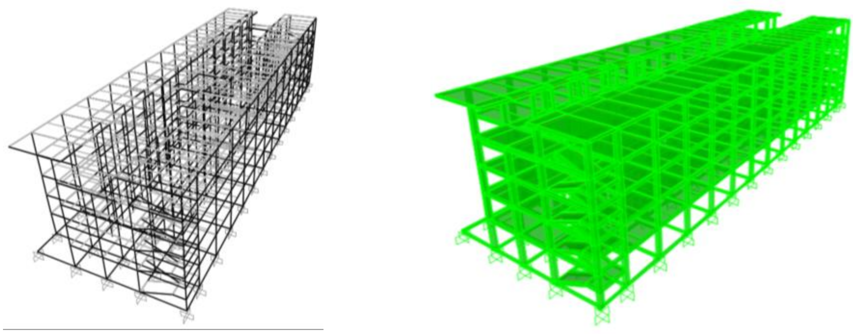


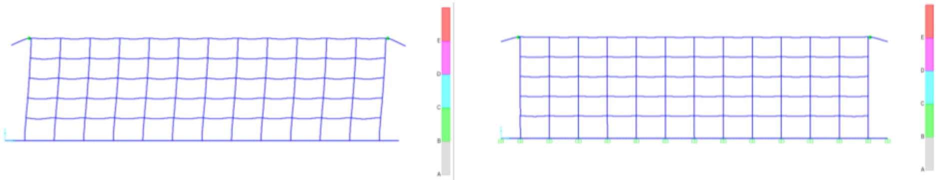
Fig. 7. Frame with support, framing and node

This structure application tool, a finite element analysis package used for structural analysis, proposes hinges for columns and beams in accordance with FEMA-356 and offers default hinge properties. A non-linear push-over study was done to determine the structure's seismic response after designing and specifying the reinforced concrete frame construction mentioned above. When the load is increased further, it undergoes significant elastoplastic deformation and eventually approaches the point of collapse. In a step-by-step process, lateral loads are applied monotonically in nonlinear analysis. In place of the force the structure would feel as a result of ground movement, lateral loads are assumed to be acceleration in each direction. Element yielding is possible under monotonous loading. As a result, the structure's stiffness changes as a result of damage at each level. This analysis requires nine steps until the push-over iteration is stopped. The analysis results are displayed in Table 3, and the graph in Figure 8.

Table 3. Base shear vs displacement

Step Unitless	Displace-ment (m)	Base Force Kgf	AtoB Unitless	BtoB Unitless	CtoD Unitless	CtoE Unitless	BeyondE Unitless	AtoIO Unitless	IOtoLS Unitless	LStoCP Unitless	BeyondCP Unitless	Total Unitless
0	0.003384	0	2750	2	0	0	0	2752	0	0	0	2752
1	0.005073	48254.54	2748	4	0	0	0	2752	0	0	0	2752
2	45869	243493.54	2542	210	0	0	0	2752	0	0	0	2752
3	0.086877	407066.59	2430	322	0	0	0	2734	16	0	2	2752
4	0.127012	545240.32	2315	437	0	0	0	2688	48	0	16	2752
5	0.185919	700972.71	2183	553	16	0	0	2569	149	14	20	2752
6	0.225919	791648.93	2133	598	21	0	0	2507	204	12	29	2752
7	0.265919	870318.03	2077	646	29	0	0	2436	261	15	40	2752
8	0.330919	990455.32	1997	686	69	0	0	2353	308	36	55	2752
9	0.396616	1106329.37	1908	733	103	0	0	2301	274	105	72	2752

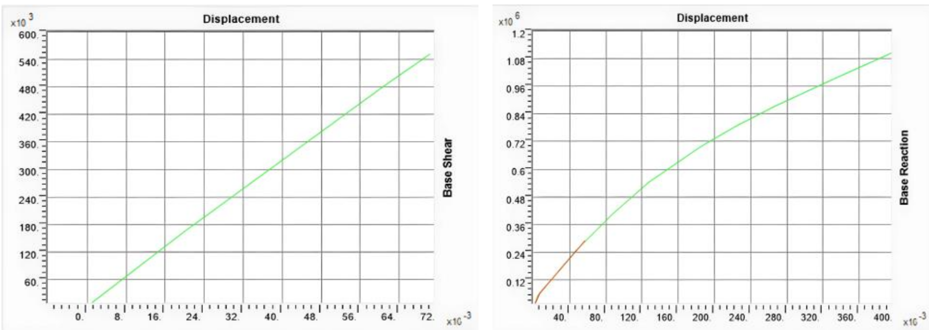
In the analysis of the push-over process, one plastic joint reaches the yield condition first, followed by the yield condition in the other plastic joints. The analysis continues until the deviation at the top of the structure finally reaches the target deviation or enters an unstable state. The push-over process can be carried out with a load-controlled or displacement-controlled procedure. Load-controlled procedures are used if the applied load has a known value. For example, gravity loads can be applied in load-controlled push-overs. Displacement-controlled methods are usually used if the load that a structure can withstand is not known with certainty. So, until the structure reaches the desired deviation value, the load is raised.



X-Direction Y-Direction

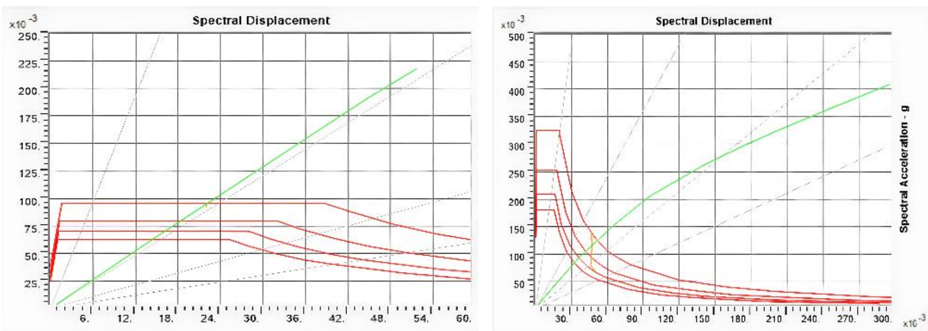
Fig. 8. Distribution of Plastic Joints

The relationship between the base shear force as a result of push-over analysis and the lateral displacement of the top floor/roof is known as the capacity curve. The results of the capacity curve between displacement and base shear can be seen in Figure 9. The inelastic conditions of the structure are plotted in ADRS (Acceleration Displacement Response Spectrum) format. This method is specifically built in the SAP program; converting push-over and reduced spectrum response curves in ADRS format is done automatically. The results of the capacity spectrum curve can be seen in Figure 10.



X-Direction Y-Direction

Fig. 9. Push-over Capacity Curve (Resultant Base Shear vs Monitored Displacement)



X-Direction Y-Direction

Fig. 10. Capacity Spectrum Curve

A performance point is used to gauge a building's capability. Based on the intersection of the spectrum response curve and the capacity curve obtained after performing push-over analysis, the point determination is made. Tables 4 and 5 provide the outcomes for the performance points. The capacity spectrum method graphically presents three graphs: the capacity, response, and demand spectrum in ADRS format. To determine the behavior of the structure under consideration for a given earthquake intensity, the capacity curve is then compared with the performance demand in the form of a spectrum response of various earthquake intensities (return periods). The figure below shows the transfer objective that was determined by the point where the capacity spectrum and the demand spectrum met.

Table 4. Performance point FEMA 356 direction-Y

Performance Point	Value
V (KN)	462428.2
D (m)	0.103
Sa	0.115
Sd	0.047
Teff	1.274
Beff	0.051

Table 5. Performance point FEMA 356 direction-X

Performance Point	Value
V (KN)	1106329.4
D (m)	0.542
Sa	0.115
Sd	0.047
Teff	1.274
Beff	0.051

Evaluation Procedures:

This building underwent evaluation and a push-over examination, and as a consequence, it was put into the Immediate Occupancy (IO) category. With very little damage, the structure nevertheless maintains the majority of its initial stiffness. Although some minor structural repairs could be required, these are often not essential before reuse since the danger of a life-threatening injury from structural deterioration is low.

If alternative modeling techniques and assumptions were employed in the numerical model, the outcomes of this study may be different in various ways [25][19]. Furthermore, this study solely considers the design-level evaluation of the seismic requirements for plan-symmetric special moment-resisting frame structures. The accuracy and effectiveness of the advanced push-over technique in calculating seismic needs in structures with a greater level of seismic danger, buildings with varied lateral load resisting systems, buildings with masonry infill walls, plan asymmetric buildings, in-plan buildings, and irregular building verticals, must therefore be further investigated. The push-over analysis provides more accurate information so that the behavior of each component can be known and efforts to prevent collapse can be carried out earlier.

3.2. Observation and Discussion

In this research, in order to determine the likelihood of damage, it is suggested to analyze damage and examine the performance of structures built to withstand earthquake loads. The evaluation design produced in this research is an analysis using RVS, which was developed with push-over structural analysis so that the research results will provide speedy and valid information and can determine the behavior of the structure's performance in withstanding earthquake loads. RVS was developed using FEAM 154, modified with the latest rules and validated using push-over structural analysis to determine detailed structural behavior.

A rapid evaluation design can use RVS FEMA 154, modified according to the latest regulations, to obtain more detailed results. The output of FEMA 154 not only determines the basic score and the possibility of collapse but also produces a capacity curve and damping demand spectrum so that it is possible to establish the structure's performance point. The structural performance results based on FMA 154 were obtained at a spectral acceleration of 0.238 with a spectral displacement of 56,388 cm. while the detailed structural behavior resulting from the push-over analysis shows that the performance point occurs at a placement of 54.2 cm with Sa=0.115 and Sd=0.047 (X direction). These two methods provide almost the same point performance values so that the RVS FEMA 154 output can be used as a reference with accurate results even though the results are slightly more significant than the push-over analysis predictions.

From the interpretation of the results, both methods also provide the same recommendation: according to FEMA's RVS, the structure's condition is still at the operation level (1-A). According to the results of the push-over analysis, the structure is in Immediate Occupancy (IO) condition. According to FEMA 154, operational level (1-A) indicates that the building experienced minor damage with little impact on structural and non-structural elements so that the building can operate with minor repairs. Meanwhile, the Immediate Occupancy (IO) level is the level where the structure experiences minimal damage and is still able to maintain most of its structural rigidity so that no retrofitting and repairs are needed to reuse the building.

The advantage of integrating RVS FEMA 154 with push-over analysis is that the RVS method can be the most suitable screening method because it can provide reasonably accurate results from previous research [24]. However, FEMA 154 depends on the screener's assumptions and experience; therefore, in this study, FEMA can be evaluated and recalibrated through this push-over outcome. This study can be used to re-evaluate when new potential failure modes are identified so that these failure modes must be added to the FEMA procedure and control plan. Meanwhile, additional dynamic analysis needs to be considered in the push-over study to model in more detail the material, boundary frame and coupling beam when damaged [26].

The weakness of this research is that the evaluation results generally require more detailed studies because the performance assessment procedure is very dependent on the data assumptions used [24], so many case studies are needed to improve the calibration of the interpretation results of this model. Push-over analysis as a calibration still needs to be developed using a double lateral force-resisting system that combines a particular moment frame with concentric bracing, especially in buildings that have poor performance due to earthquakes [27]. The output of this research still needs to be developed using multi-criteria decision-making (MCDM) using the resulting index values as criteria that need to be considered [28]. Apart from that, FEMA prioritizes failure modes, so it has yet to design efforts to prevent building collapse. Therefore, wireless deformation sensors based on radio frequency identification (RFID) can be developed as deformation threshold detectors calibrated with FEMA RVS 154 and push-over analysis to improve the output—model of this study [29]. In addition, using machine learning to classify building damage data can predict damage categories better than conventional RVS and is useful in planning and decision-making for emergency response and post-earthquake recovery [30].

4. Conclusions

The final score from learning using the RVS form is 2.3. It has a vulnerability percentage of 0.5%, which is still considered minimal in terms of vulnerability, so this building has a small potential for damage or failure in the event of an earthquake. From the results of this assessment, the building is included in the Operational Performance Level category. It is declared secure but requires further validation to ensure the building's behavior with push-over analysis because this RVS assessment depends on the screener's assumptions and experience. In this study, the push-over analysis can evaluate and recalibrate FEMA outcomes. This follows the results of previous research, in which the push-over analysis produced an assessment correlated with building condition categories. Beyond, this research has succeeded in developing an integration method between RVS and push-over analysis so that the resulting integrated RVS-push-over has been validated and developed based on push-over analysis.

The evaluation results using push-over analysis obtained an immediate level of building flats' structural performance, which means that if an earthquake occurs, the damage to the structure will only be minimal. The characteristics and capacity of the vertical and lateral force-resisting system on the structure are still the same as before an earthquake, so the building is safe and can be used immediately. However, the push-over analysis method applied in this study is still superficial; it does not include lateral bracing components/supports, shear retaining walls and other similar construction forms. Several studies recommend further research into push-over analysis considering these elements. Therefore, the push-over method still needs to be developed using a lateral force-resisting system that combines a particular moment frame with concentric bracing, especially in buildings with poor performance due to earthquakes. The research results show that both methods produce the same assessment conditions; the building is declared secure without any structural repair treatment. The performance value of the two analysis points has similarities with the spectral and displacement, respectively, FEMA and push-over methods of 0.238, 56.388 and 0.115, 0.047, 54.2. The analysis results show that FEMA produces higher deterioration probability and displacement values than Push-over. This indicates that FEMA has more conservative effects than Push-Over. FEMA is prudent in providing assessments because it only uses visual data, while push-over uses more detailed data and structural analysis. Integrating the FEMA 154 RVS method with push-over analysis results in more precise FEMA method analysis development procedures and tools based on structural behaviour, mainly when new potential failure modes exist.

In addition, this research can potentially be used as a fast, precise and accurate assessment of structural failure if this behaviour is measured with sensors developed with analysis using artificial intelligence technology and machine learning. It provides benefits as a guide in making decisions when rehabilitating and repairing building structures. It can be an early warning for building managers when an earthquake pre- or post-hit a building.

Acknowledgement

The authors acknowledge that this study is supported by data from the Public Works Department of Lumajang Regency.

References

[1] Kurniawandy A, Hendri A, Firdaus R. Evaluation of Building Vulnerability to Earthquakes Using Rapid Visual Screening (RVS) based on FEMA 154. Annu Civ Eng Semin. 2015;2:338-45.
[2] Adeswastoto H, Djauhari Z, Suryanita R. Evaluation of the Vulnerability of Buildings to Earthquakes Based on ASCE 41-13. SIKLUS J Tek Sipil. 2017;3(2):86-99. https://doi.org/10.31849/siklus.v3i2.383
[3] Araby Z, Samsul Rizal, Abdullah, Mochammad Afifuddin. The Analysis of Beam-Column Joint Reinforced with Cross Bars according to SK SNI T-15-1991-03 on Cyclic Loads. J Civ Eng Forum. 2022;8(1):1-10. https://doi.org/10.22146/jcef.3601

[4] Pangestu IMS., Wibowo A, Wijaya M. Non-Linear Pushover Static Analysis on Optimizing the Design of the FKUB Education Building with Varying Steel Bracing Configurations. Civil Engineering Department. Universitas Brawijaya; 2017.
[5] Michael Mahoney; Mai Tong; Erin Walsh; John Gillengerten. Rapid Visual Screening of Buildings for Potential Seismic Hazards : Supporting Documentation. Federal Emergency Management Agency. Washington, D.C.; 2015.
[6] Irnawan I. Mapping Building Risk from Earthquakes Using Android-Based Rapid Visual Screening (RVS) (Using Fema 154 - 2002). Angew Chemie Int Ed 6(11), 951-952. 2016;325.
[7] Nanda RP, Damarla R, Nayak KA. Android application of rapid visual screening for buildings in indian context. Structures. 2022;46(November):1823-36. https://doi.org/10.1016/j.istruc.2022.10.140
[8] Harirchian E, Hossein SEA, Jadhav K, Kumari V, Rasulzade S, Işık E, et al. A review on application of soft computing techniques for the rapid visual safety evaluation and damage classification of existing buildings. J Build Eng. 2021;43(102536). https://doi.org/10.1016/j.jobe.2021.102536
[9] Bülbül MA, Harirchian E, Işık MF, Aghakouchaki Hosseini SE, Işık E. A Hybrid ANN-GA Model for an Automated Rapid Vulnerability Assessment of Existing RC Buildings. Appl Sci. 2022;12(10). https://doi.org/10.3390/app12105138
[10] Astuti ND, Sangadji S, Rahmadi AP. Initial Evaluation of Seismic Risk of Flat Buildings. Pros Semnastek. 2016;(November):1-9.
[11] V.A.R.Barao, R.C.Coata, J.A.Shibli, M.Bertolini, J.G.S.Souza. Evaluation Of Building Vulnerability To Earthquakes Using Rapid Visual Screening Method (Case Study: Febi Building UIN Prof. Kh. Saifuddin Zuhri). Braz Dent J. 2022;33(1):1-12.
[12] Dwi Pratama AR, Soetjipto JW, Krisnamurti K. Evaluation of Building Vulnerability to Earthquake Using Rapid Visual Screening (RVS) Method. J Tek Sipil dan Perenc. 2021;23(2):114-24. https://doi.org/10.15294/jtsp.v23i2.31399
[13] Zulfiar MH, Zai MII. Assessment of Building Vulnerability to Earthquakes in High-Rise Education Buildings in Yogyakarta. Bull Civ Eng. 2021;1(2):73-80. https://doi.org/10.18196/bce.v1i2.11075
[14] Hasibuan SARS, Ma'arif F, Praja BA. Non-Linear Behavior of Reinforced Concrete Frame Structure with Vertical Irregularities. Int J Innov Res Comput Sci Technol. 2023;11(1):45-51. https://doi.org/10.55524/ijircst.2023.11.1.10
[15] Bhatt C, Bento R. The extended adaptive capacity spectrum method for the seismic assessment of plan-asymmetric buildings. Earthq Spectra. 2014;30(2):683-703. https://doi.org/10.1193/022112EQS048M
[16] Erlicher S, Lherminier O, Huguet M. The E-DVA method: A new approach for multi-modal pushover analysis under multi-component earthquakes. Soil Dyn Earthq Eng. 2020;132:1-27. https://doi.org/10.1016/j.soildyn.2020.106069
[17] Kumar GVAP, Babu RH. Damage Assessment of Multistoried Structures. Int J Eng Res Technol. 2014;3(10):99-110.
[18] Mahorkar, Rohit Ravindra; Kalurkar L. The Effect of Lateral Connection in Moment Carrying Capacity Frames of Low-Rise , Mid-Rise and High-Rise RC Structures by Perfoming Pushover Analysis. Int J Eng Res Technol. 2021;10(01):17-23.
[19] Daei A, Poursha M. On the accuracy of enhanced pushover procedures for seismic performance evaluation of code-conforming RC moment-resisting frame buildings subjected to pulse-like and non-pulse-like excitations. Structures. 2021;32:929-45. https://doi.org/10.1016/j.istruc.2021.03.035
[20] Kagermanov A, Gee R. Cyclic pushover method for seismic assessment under multiple earthquakes. Earthq Spectra. 2019;35(4):1541-58. https://doi.org/10.1193/010518EQS001M

[21] Nafeh AMB, O'Reilly GJ. Simplified pushover-based seismic risk assessment methodology for existing infilled frame structures. Bull Earthq Eng [Internet]. 2023;21(4):2337-68. https://doi.org/10.1007/s10518-022-01600-y

[22] Atc- M, Zebua D, Setia L, Wibowo B, Cahyono MSD. Evaluation of Deviations in Reinforced Concrete Multi-Storey Buildings Based on Pushover Analysis with the ATC-40 Method. 2020;03(September):53-7. https://doi.org/10.25139/jprs.v3i2.2475

[23] Nur Rachmad Afandi. Pushover Analysis Using The SAP 2000 Program. Universitas Sebelas Maret; 2010.

[24] Doğan TP, Kızılkula T, Mohammadi M, Erkan H, Tekeli Kabaş H, Arslan MH. A comparative study on the rapid seismic evaluation methods of reinforced concrete buildings. Int J Disaster Risk Reduct. 2021;56(December 2020). https://doi.org/10.1016/j.ijdrr.2021.102143

[25] Khorami M, Khorami M, Motahar H, Alvansazyazdi M, Shariati M, Jalali A, et al. Evaluation of the seismic performance of special moment frames using incremental nonlinear dynamic analysis. Struct Eng Mech. 2017;63(2):259-68.

[26] Ma Y, Yan Z, Berman JW, Taoum A, Tian W. Seismic Performance of Coupled Steel Plate Shear Walls with Different Degrees of Coupling. J Struct Eng. 2022 Sep;148(9):148(9). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003386

[27] Maleki EBHAAS. Evaluation of seismic performance factors for dual steel SMF-SCBF systems using FEMA P695 methodology. Soil Dyn Earthq Eng. 2022;163(107506). https://doi.org/10.1016/j.soildyn.2022.107506

[28] Es-haghi MS, Barkhordari MS, Huang Z, Ye J. Multicriteria Decision-Making Methods in Selecting Seismic Upgrading Strategy of High-Rise RC Wall Buildings. J Struct Eng. 2022 Apr;148(4):389. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003304

[29] You T, Wang W, Fang C, Chen Y. Rapid probabilistic loss assessment of buildings based on post-earthquake structural deformation conditions. J Build Eng. 2022;45(103629). https://doi.org/10.1016/j.jobe.2021.103629

[30] Bhatta S. Machine Learning-Based Classification for Rapid Seismic Damage Assessment of Buildings at a Regional Scale. J Earthq Eng [Internet]. 2023;1-31. https://doi.org/10.1080/13632469.2023.2252521