International Journal on
Advanced Science
Engineering
Information Technology

Vol.15 (2025) No. 1
ISSN: 2088-5334

Evaluation of Damage Assessment of the High-Rise Building with Brace

Siti Nur Rahmah Anwar [a,*], Feryan Ernanda [a], Mohammad Sulton [a], Siti Aminah Anwar [b]

[a] *Department of Civil Engineering and Planning, Universitas Negeri Malang, Malang, Indonesia*
[b] *Department of Economics, Universitas Islam Malang, Malang, Indonesia*
*Corresponding author: *rahmahsnra@gmail.com*

Abstract—**A bracing system is a component within a structure that counters horizontal forces such as wind, seismic activity, and other loads that may lead to the building swaying or falling. A properly designed bracing system can enhance a building's capacity to endure these forces and reduce harm to both the structure and those inside. The outcome of this research is to investigate the dynamic performance on the structural damage of high-rise building with various brace types. The methodology in this research is combined between experimental and numerical modeling of structures. The materials data of concrete and steel as the braces materials is defined from experimental results. The structures analysis is modeled using SAP2000 software, based on the existing materials data from experimental tests. The outputs reviewed are stiffness, vibration period of structure, displacement, drift, stiffness and ductility. The structural damage potential is connected to dynamic response of the building with braces as well. The dynamic parameters of natural frequency, and vibration period for the V brace shape, inverted-V brace shaped (Λ), and X shape (in two floors) are 0.806 Hz; 1.24 s, 0.893 Hz; 1.12 s, and 0.862 Hz; 1.16 s. The ductility of structures with V brace, inverted V brace and X brace (in two floors) are 2.58, 2.95, and 2.85. The result showed that inverted V-shaped bracing has the best dynamic performance than others shapes. Based on modeling results, the building is safe condition under the actual spectra-response that is vibrated the building model.**

Keywords— **Bracing; numerical modeling; dynamic response; structural stability; high rise building; restrain system.**

Manuscript received 12 Jul. 2024; revised 25 Dec. 2024; accepted 18 Jan. 2025. Date of publication 28 Feb. 2025.

I. INTRODUCTION

Earthquakes occur due to the phenomenon of vibrations with a shock to the earth's crust which can cause damage to buildings [1], [2], [3], [4], [5], [6], [7], [8]. Solutions to overcome this lateral load are inserting of diagonal structural elements such braces, shear walls, or by changing the relationship between structural elements [9], [10]. Some investigations have been studied in Indonesia regarding the earthquake effects [11], [12] to find the solution for damage rehabilitation; [13], [14]. Diagonal stiffeners (braces) are an alternative stiffener for building structures that function to increase building rigidity, withstand lateral loads, increase ductility, strength and is able to reduce energy caused by vibrations [15], [16], [17], [18]. Usually, tall buildings react to seismic movement in a distinct way compared to buildings with fewer floors. The level of inertia forces generated during an earthquake is influenced by the building mass, the ground acceleration, foundation type, and structural dynamic characteristics. Many researchers also studied the reaction of steel frames to seismic forces with various bracing systems [19], [20], [21] using numerical analysis by [22], [23], [24], [25], [26].

Braces have various shapes and locations; their use is adjusted to the existing planning and the impact of the braces regarding the actions of the structure due to the loads acting on tall buildings. Several past studies have combined the behavior of the bracings and dampers to decrease the earthquake effects, [27].

Lateral loads vibrations (earthquake, wind) cause the structural damages in buildings. That vibration induces the foundation oscillation as well. A building has the inertia to remain the stable condition. Indonesia is surrounded by volcanoes so it is vulnerable to earthquakes hazard. The investigation of the dynamic response of the building to the structural damage potential is very important. The several code standards of the structure are considered in the structure design in the seismic area [28],[29],[30]. Some investigations have been studied in Indonesia regarding the earthquake effects; [31], [32]. Bracing shapes include V, inverted V (Λ) or even two floors) against earthquake loads applied to the

Faculty of Sports Science Building, State University of Malang. To enhance the rigidity of the braces, the braces are added in number and placed on the outside of the building. This is because the further the reinforcement is located from the building's point of balance, the greater the stiffness. In this research, researchers want to know changes in structural performance, stiffness, vibration period, natural frequency, lateral displacement, and drift that occur in reinforced concrete braces which have the same shape but differ in their placement. Researchers want to know whether these braces can be used as an alternative for reinforcement in tall buildings.

This research examined the performance of the structure using braces V, inverted V (Λ) and X (on two floors) against earthquake loads applied to e construction of the Faculty of Sport Sciences, Malang's State University. To increase the stiffness of the braces so that they are equivalent to the stiffness of the braces is added and placed on the outer part of the building. Researchers want to know the comparison of the performance of the structure is stiffness, period of vibration, natural frequency, lateral displacement, and drift caused by the use of reinforced concrete braces and whether the braces can be used as an alternative reinforcement in tall buildings.

II. MATERIALS AND METHOD

In this paper, the investigation looks into specific eight-story rectangular office buildings with a plan layout and size 78.00 m × 28.00 m. The story heights are: 3.50 m for basement; 5.50 m for first floor; 4.00 m for fourth, fifth, and sixth floors; 5.00 m for seventh floor. Fig. 2.1 displays the site layout of the existing building of Sport Centre Faculty, State University of Malang, Indonesia.

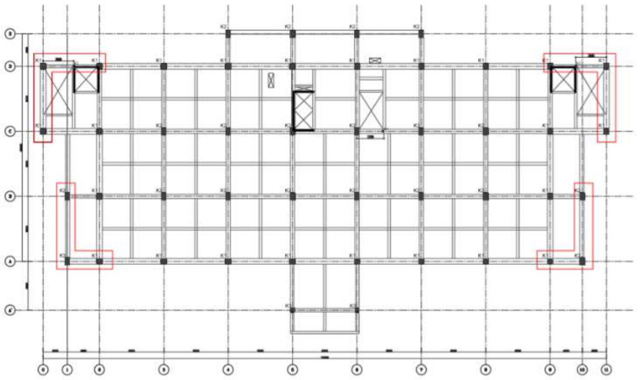

Fig. 1 Site plan of building

A. Materials

Input data materials on modeling structures are taken from laboratory testing results. Several mechanical characteristics of materials used in this paper are determined from the laboratory test, described in Table 1.

TABLE I
MECHANICAL CHARACTERISTICS OF THE MATERIALS

Properties	Concrete	Steel
Compressive strength, (f_c)	30 MPa	-
Yield Strength, (f_y)	-	250 MPa
Ultimate Strength, (f_u)	-	410 MPa
Elasticity modulus, (E)	25742.96 MPa	21000000 MPa

B. Structure Analysis

The structural analysis method using design analysis of existing buildings. Designing columns and beams to fit the current dimensions. Then determining the dimensions of the earthquake reinforcement by using reinforced concrete braces (40 cm x 75 cm). Calculation of structural loading, for example dead, live, rain, wind and earthquake loads. Then the structural modeling is carried out to clarify the research carried out using bracing structures on 8 story building of Faculty of Sport Science Building, State University of Malang, Indonesia. Then comparing the results of the analysis that has been conducted using SAP 2000 v.20. The results of the analysis used are structural stiffness, period of structural vibration, natural frequency of the building, lateral displacement and deviation between story (drift). The procedures of structures analysis is defined in Fig. 2.

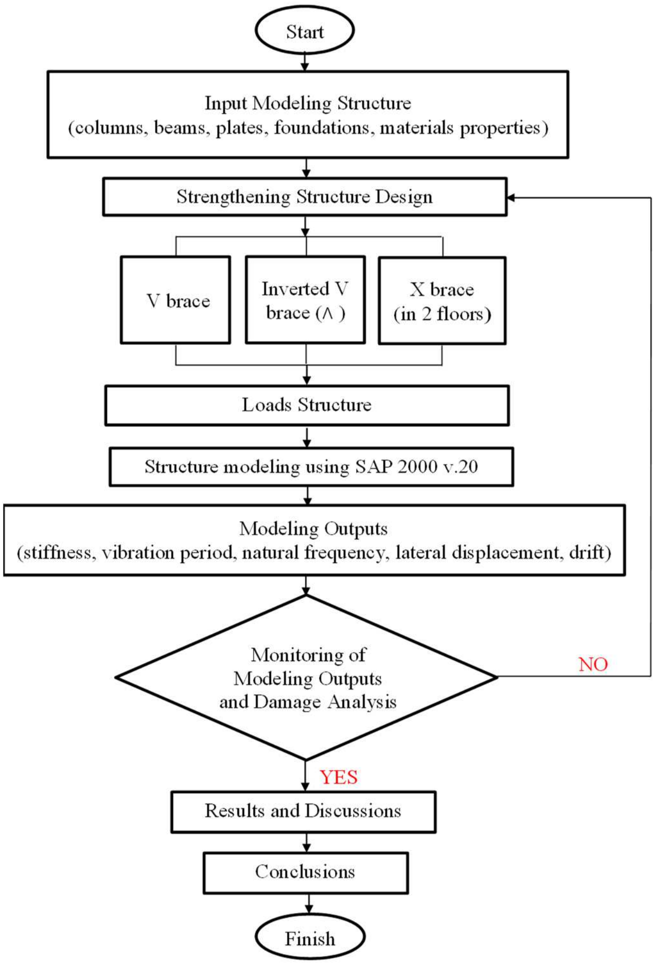

Fig. 2 Research flow diagram of research

1) Loading on Tall Buildings:

When planning a tall building, a consultant design must pay attention to the loads that will occur on the building. To determine the load used, it can be estimated using established regulations. The loads that occur can come from loads from the building (vertical loads) and loads that do not originate from the building (horizontal loads). The design of the structure should ensure that its strength either matches or surpasses the impact of loaded combinations [31], [32]:

$$1{,}2\ D. + 1{,}6.\ (Lr\ or\ R)\ +\ (L\ or\ 0{,}5\ W) \quad (1\text{-a})$$

$$1{,}2\ D. + 1{,}0\ W. + 0{,}5\ (Lr\ or\ R) \quad (1\text{-b})$$

$$1{,}2\ D. + 1{,}0\ E. + L \quad (1\text{-c})$$

$$0{,}9\ D. + 1{,}0\ W. \quad (1\text{-d})$$

$$0{,}9\ D. + 1{,}0\ E. \quad (1\text{-e})$$

where:

D-dead load, L- live load, $L_{r.}$-temporary load, R-rainwater load, W-wind load, and, E-earthquake load.

The building's dimensions and weight influence the size of the vertical load. Vertical loads consist of the dead load and the live load. Horizontal loads are loading that act horizontally on the building. This load has a significant influence on the collapse of the building. In the design of tall buildings, attention must be paid to the load design for horizontal loads such as earthquakes and wind loads.

Earthquake load is caused by earthquakes or movement in tectonic plates. Like wind loads, the building's location and height affect earthquake forces on tall buildings. If the building is large, the deviation that occurs when exposed to earthquake loads will also be more significant. A building designer must consider the earthquake as the earthquake resistance of construction. Even though the building will collapse, there is still time for building users to save themselves. Calculating earthquake loading based on Indonesia's Building and Non-Building Structures Earthquake Resistance Design Code [28]. A wind load is a horizontal load caused by wind pressure. The amount of gust is caused by wind speed, air density, location, surface behavior of the structure, geometric shape, and construction dimensions.

2) *Drift Story:*

Drift is a deviation measured from floor x to floor x-1. The difference between design levels (Δ) must be determined by subtracting the deviation at the mass center higher up the designated level from the deviation below it. When design allowable stresses are employed, (Δ) should be determined using the designated design seismic forces without any reduction for design permissible stresses. The allowable deviation between levels should not exceed the drift value (Δ_a). Drift can be formulated as:

$$\Delta x\ =\ (\delta ex\ -\ \delta ex - 1)\ Cd/Ie \quad (2)$$

where:

Δ_x- displacement deviation between floors, Δ_{ex}-displacement at a location on floor x, δ_{ex-1} -displacement at the location on floor x-1, C_d-amplification factor of displacement, and I_e-earthquake priority factor.

3) *Stiffness:*

The static stiffness of a structure (K) is related to the application of load to the structure, while he stiffness of a point (k) is influenced by the location and orientation of the load on the structure, causing the stiffness value to change with different positions and directions. The connection between the load, stiffness, and displacement of a structure is demonstrated in the following equation:

$$[K]\{U\} = \{P\} \quad (3)$$

where[K]-stiffness matrix by considering the influence of boundary conditions, $U\}$-displacement vector, and $\{P\}$- load vector.

Stiffness is also one of the dynamic characteristics of structures besides mass. Self-characteristics refer to the special connection between a structure's mass and stiffness when experiencing dynamic loads. The unique relationship determines the angular frequency and vibration period of the construction. Each mass (m), damping (c), stiffness (k), and external force (P) are considered to be concentrated on a single fission element and are expressed:

$$m_i\ddot{u}_i + c_i\dot{u}_i + k_i u_i = P_i(t) \quad (4)$$

where:

m -total mass, $u^{\cdot\cdot}$ -acceleration of movement, $u^{\cdot}$-speed of movement, u -displacement of movement, k –stiffness, and P -load.

4) *Ductility*

Ductility refers to a structure's capability to experience significant deformations at high amplitudes within the inelastic range without losing considerable strength. Ductile constructions can typically absorb substantial energy during deformation. The ductility factor of $1R$ is the proportion of the biggest displacement to the yield displacement (δ_{max}/δ_y) or ultimate drift to the yield drift (θ_{max}/θ_y). This shows that a R value close to 1 results in an elastic response, while a R value far from 1 results in an inelastic response.

$$R = \frac{\delta_{max}}{\delta_y} = \frac{\theta_{\max}}{\theta_y} \quad (5)$$

C. *Dynamic Response Earthquake Load Analysis*

Analyzing the structural dynamic on a building in Malang city by utilizing seismic data record from the Ministry of Public Works and Human Settlements website in Indonesia in 2021, including various values of S_s = 0.621 g dan S_1. = 0.390 g. The building is in Malang City, East Java and is on medium soil.

1) *Equivalent static analysis:*

According to procedures for earthquake resistance of structures, both building and non-building, the nominal static equivalent base shear load occurs at the base level. At the same time, the horizontal force, F_x, resulting from earthquakes at each story of building is:

$$F_x = C_{vc}V \quad (6)$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \quad (7)$$

where:

C_{vx}-factor for vertical distribution, V-the base combined horizontal forces, w_i -building weight at level I, w_x-building weight at level x, h_i - the measurement of the distance from the base to level i, h_x -distance from the base to level x, k-the exponent associated in T.

2) *Spectrum Response Analysis:*

The spectrum response graphically displays the correlation of the vibration period (T) and the maximum responses considering the damping ratio and specific earthquakes, as shown in Fig. 3.

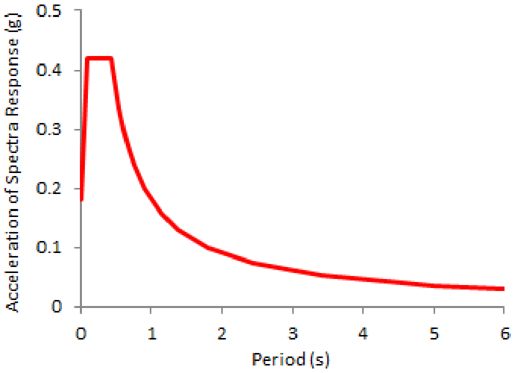

Fig. 3 Design of earthquake response spectrum

1. For periods smaller than T_0, the design acceleration response spectrum, S_a, should be taken from the equation);

$$S_a = S_{DS}\left(0.4 + 0.6\frac{T}{T_0}\right) \tag{8}$$

2. For a period greater than or equal to a T_0 and less than or equal to a T_s, the design acceleration response spectra, the S_a, is the same as the S_{DS};
3. For periods greater than a T_s but less than or equal to a T_L, then a design acceleration spectral response, the S_a, is taken based on the formula:

$$S_a = \frac{S_{D1}}{T} \tag{9}$$

4. For a period greater than a T_L, the formula for calculating the design acceleration spectral response, the S_a, is utilized:

$$S_a = \frac{D_{D1}T_L}{T^2} \tag{10}$$

Where are S_{DS}-design acceleration of spectrum response at the short periods, S_{D1}-design acceleration of spectrum response at first period, and T-period of the fundamental vibrations of a structure.

Vibration Periods

The time of completing one full vibration cycle, denoted as T, is taken in the first mode (fundamental period) which has an inverse relationship with the natural frequency. It is a natural property of structures that depend on mass and stiffness to vibrate freely without any external forces.

A fundamental period of the building, T, in the considered direction must be obtained using the characteristics of structure and deformation on the supporting elements in the tested calculations. The T cannot exceed the result of multiplying the factor for the upper limit on the calculated period (C_u) from Table 17 of SNI 1726-2019. The building approach period, T_a, represents the a fundamental-period of approach in seconds, according to SNI 1726 of [28] as an equation:

$$T_a = C_t h_n^x \tag{11}$$

where h_n-calculated from a base foundation to a top-level of the structure, C_t -showed from Table 18 SNI 1726-2019, and, x - determined from Table 18 SNI 1726, 2019

The maximum fundamental period ($T_{a,max}$) in seconds, formulated by the equation:

$$T_{a,max} = C_u T_a \tag{12}$$

where C_u is the seismic response coefficient.

Vibration period analysis determine two periods T_a from manual analysis, and T_c. The fundamental period (T) value should be used for structural analysis after comparing the following:

$T_c > T_a C_u$ is used T=Ta.Cu (13)

$T_c < T_c < T_a C_u$ is used T=Tc

$T_c < T_a$ is used T=Ta

If the period exceeds the maximum period (T_{max}), then the period used is the maximum period (T_{max}). Instead, the basic period of approach (Ta) can be determined quickly using the given equation for buildings with up to 12 stories and a seismic resistance system of either the moment-resisting frames with the average stories height at minimum of 3 m:

$$Ta = 0.1N \tag{14}$$

where N is the number of story.

Natural Frequency

A vibration due to the dynamic load of the structure occurs in each mode with a certain frequency and vibration mode shape. The correlation of a natural period and a natural frequency of the structural system in the vibration modes are, [33]:

$$f_n = \frac{1}{T} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{15}$$

where:

f_n- natural frequency, T-vibration period, k- stiffness, and, m- the building mass.

III. RESULTS AND DISCUSSION

By modeling the building according to the site plan (Fig. 3.1) and sections with variations of bracing shapes of the V shape, inverted V (Λ) and X (in two floors). The Fig. 3.1–Fig. 3.3) describe the configuration and the shape of bracing on building models. SAP 2000 v.20 is used to model and analyze the dynamic response with combination loads. The input data materials in structure models existing are determined from test laboratory as shown in Table 1.

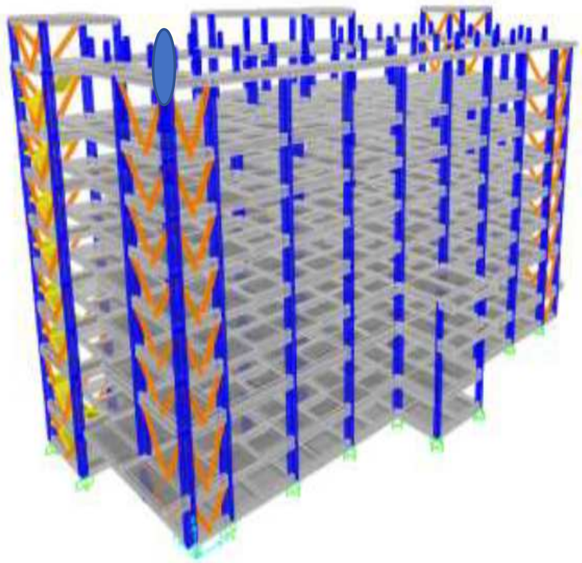

Fig. 4 The V braced building

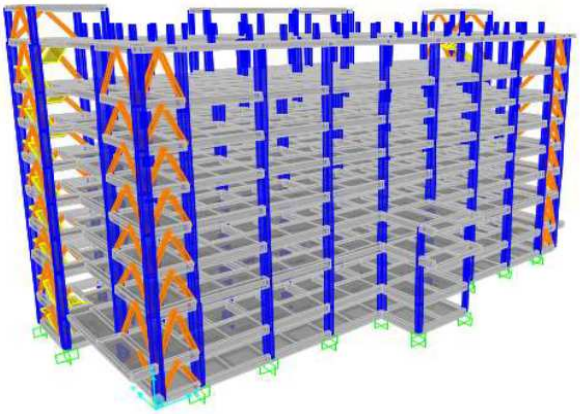

Fig. 5 The inverted V braced (Λ) building

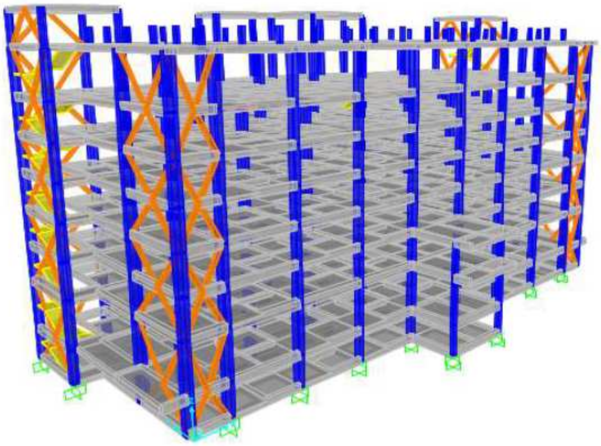

Fig. 6 The X brace (in two floor) building

A. *Structure Performance*

The model for calculations was created using SAP 2000 software. A linear elastic of the modal response-spectra analysis was investigated to assess the impacts of seismic activity. Some output analysis of structure stiffness, vibration period, natural frequency and drift of building were obtained.

1) *Structure Stiffness:*

Structural stiffness is the capability of a structure for deformation resistance. A structure needs to have enough rigidity in order to limit its movement. The rigidity of a building is influenced by both the stiffness of the material and the size of structural elements. The geometric configuration, structural member type, connection details, and construction materials all significantly impact structural dynamics. If a building has irregular characteristics, such as a non-uniform floor plan or vertical interruptions, the seismic criteria used for buildings with regular features may not be suitable. Therefore, it is recommended to avoid building structures with irregular features. For example, taking down the exterior walls on the first floor of a building will result in an open ground floor, the remaining columns on the ground level that can withstand lateral forces.

The application of load to a structure determines its static stiffness, while the position and direction of the load affect the stiffness at a point. Therefore, the stiffness value changes at various positions and orientations. At the same time, when subject to repeated dynamic loads at specific speeds and accelerations, the structure's material atoms and the structure itself undergo back-and-forth vibrations at a defined frequency known as the natural frequency. The displacement of atoms in materials and structures caused by dynamic loads is a repetitive oscillation, rather than a single sudden movement. Rigidity is another dynamic feature of buildings, along with mass. The self-characteristic is the special connection between a structure's mass and stiffness caused by dynamic loads. This special connection dictates the structure's angular frequency and vibration period. Comparison of structural stiffness using various braces on this research can be seen in Table 2 and Fig. 7.

TABLE II
BRACED-STRUCTURE STIFFNESS

No	Brace Type	Stiffness (N/mm)
1	V Brace	4.01509E+12
2	Inverted V Brace (Λ)	4.92865E+12
3	X Brace (on two floors)	4.5924E+12

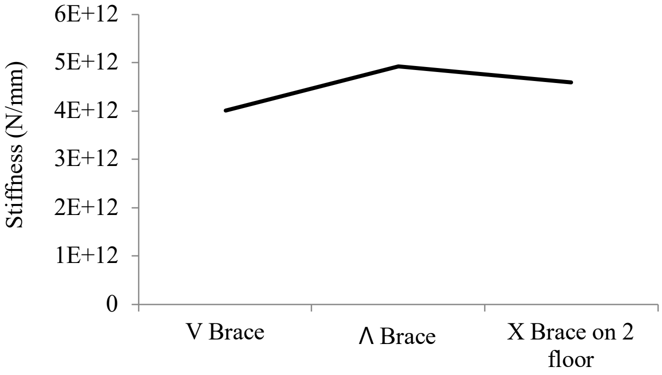

Fig. 7 The stiffness of the high-rise braced-buildings

Fig. 7 shows that the V bracing has the highest performance on the structure stiffness. Types of V braces, inverted V braces (Λ), and X braces have stiffness of 4.01509E+12 N/mm, 4.92865E+12 N/mm, and 4.5924E+12 N/mm, respectively. The stiffness of inverted V bracing has a higher performance of 18.53% compared to V bracing and 8.82% compared to X bracing.

2) *Displacement:*

During an earthquake, building structure behavior is related to vibrations. An increase leads to an increase in the force that can lead to buckling or crushing of columns and walls as the mass exerts downward pressure on a member that has been bent or displaced from its vertical position by lateral forces (P-δ effect). When flexible structures are subjected to lateral forces, the resulting horizontal displacements lead to additional overturning moments because the gravity load is also displaced. Furthermore, along with the overturning moments generated by lateral force V_u, the secondary force must be countered as well. This increase in time will result in more sideways growth. Change in position will continue to rise, causing transformation to increase. In highly adaptable forms, instability may lead to collapse, might happen. When evaluating seismic design forces, it is crucial to acknowledge the significance of the load-displacement impacts tend to have a greater impact on structures located in areas with low to medium levels of seismic activity. As in areas with high seismic activity, where lateral forces in design will be higher increased. Hence, in many cases, especially in areas with significant seismic design force.

Figures 8 and 9 show the displacement of all structures in the X and Y axes. The structures displacements in the X and Y directions are 157.5 mm, 144.53 mm, and 148.2 mm for V bracing, inverted V bracing, and X bracing. They are 90.36 mm, 108.86 mm, and 104.36 mm, respectively.

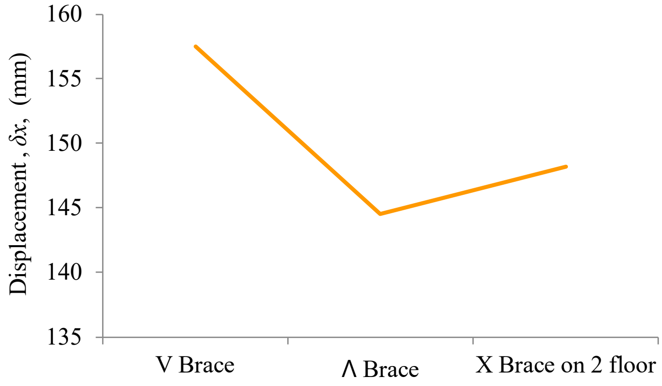

Fig. 8 Displacement of the high-rise braced-buildings in X direction

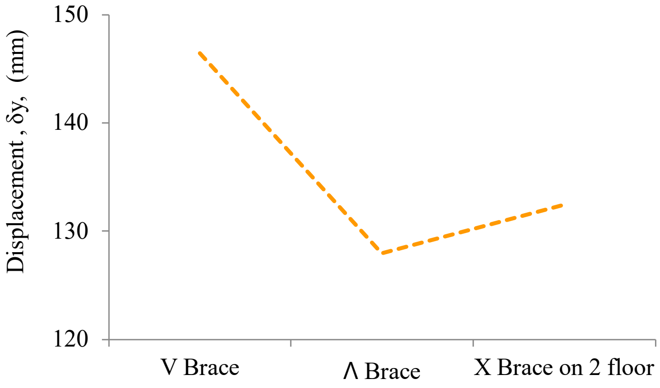

Fig. 9 Displacement of the high-rise braced-buildings in Y direction

3) *Drift:*

Drift is commonly described as the horizontal movement of one story in relation to the story beneath it. Having drift control is crucial in order to reduce damage to interior walls, elevators, staircases, glass, and exterior cladding systems. Stress or strength constraints in ductile materials may not always offer sufficient control over drift, particularly in the case of tall buildings with relatively flexible moment-resisting frames or narrow shear walls. The total building drift is the complete movement of a point in comparison to the base. Adjoining structures or neighboring parts of the same structure may not exhibit the same response methods, potentially resulting in them forcefully colliding. In a major earthquake, the building's floors can sway without damaging the columns due to the beams bending plastically. Nevertheless, the drift could be significant and result in harm to components firmly connected to the structural framework. Examples of elements such as brittle walls, stairs, pipes, exterior walls, and others that extend across multiple floors are prone to damage. As a result, a moment-frame building can sustain significant non-structural damage to its interior and exterior yet remain structurally secure. For some buildings, this system may not be a wise investment without implementing specific damage-control strategies.

Drift that occurred on the floors of basement, 1, 2, 3, 4, 5, 6, 7, RL, and roof were respectively 0.00 mm, 6.27 mm, 17.34 mm, 14.74 mm, 16.06 mm, 16.46 mm, 16.21 mm, 15.36 mm, 18.81 mm, and 12.83 mm. This is because in X direction. So, when an earthquake occurs, buildings tend to have a small sway. Meanwhile, the comparison of deviations between levels in the Y direction can be described in Table 3.

TABLE III

DRIFT DEVIATIONS OF BRACED-STRUCTURES IN X DIRECTION

Story	**V Brace (mm)**	**Λ Brace (mm)**	**X Brace (mm)**
Basement	0.00	0.00	0.00
1	8.53	6.33	5.33
2	22.53	18.67	24.10
3	17.17	15.53	14.23
4	18.17	16.97	18.23
5	18.43	17.63	16.73
6	18.00	17.30	17.57
7	17.07	16.23	16.07
Roof	20.43	19.07	19.50

The comparison of the deviation between stories in the Y direction above shows that structures using inverted V bracing (Λ) have smaller deviations between floors when compared to structures using other reinforcement. The levels of drift measured on each floor varied: basement - 0.00 mm, 1st floor - 6.30 mm, 2nd floor - 14.73 mm, 3rd floor - 13.93 mm, 4th floor - 15.27 mm, 5th floor - 15.70 mm, 6th floor - 15.43 mm, 7th floor - 15.13 mm, roof level - 17.13 mm, and roof - 14.33 mm. This is because structures using inverted V braces (Λ) have a stiffer structure than other reinforcements. When an earthquake occurs, the inverted V braces-buildings tend to have a small drift.

TABLE IV

DRIFT DEVIATIONS OF BRACED-STRUCTURES IN Y- DIRECTION

Story	**V Brace (mm)**	**Λ Brace (mm)**	**X Brace (mm)**
Basement	0.00	0.00	0.00
1	7.67	6.30	4.97
2	19.87	14.73	19.87
3	15.37	13.93	12.73
5	17.17	15.70	15.07
6	17.17	15.43	15.83
7	16.93	15.13	15.40
Roof	19.63	17.13	17.63

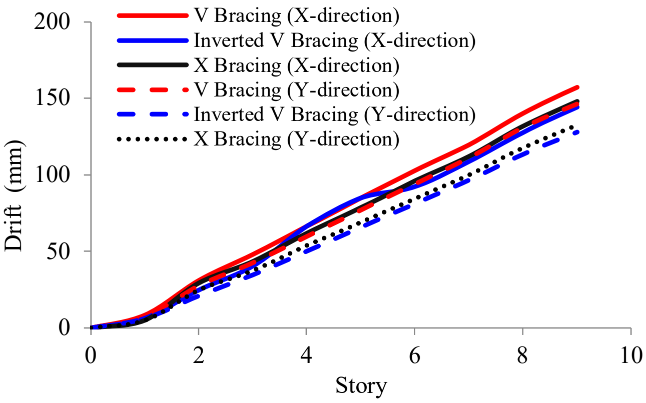

Fig. 10 Drift of the high-rise braced-buildings

4) *Structure Ductility:*

Ductility is the structure's capacity to offer support in the non-elastic phase of reaction. It involves the capacity to endure significant distortions and the capability to soak up energy through hysteresis, essential features for a building's resilience in the face of a substantial earthquake. Ductility is calculated by comparison between displacement at ultimate stage (δ_u) and displacement at initial yield (δ_y). The maximum ductility is typically represented by the ultimate displacement limit (δ_u), which usually corresponds to a specified limit for strength degradation. Once they reach this threshold, structural collapse may not happen, but failure or significant inelastic deformations can still occur.

As the structure starts to warp and deform in a non-elastic way, the period of the structure's response appears to extend. Numerous buildings lead to a decrease in the need for strength. Moreover, the lack of flexibility leads to this outcome in a notable level of energy absorption, also referred to as hysteresis damping. The impact, that adequate stiffness can undergo large deformations without collapsing. Generated a force which is significantly lower than the maximum elastic seismic force allowed, while still meeting the anticipated performance criteria under the designated ground movements.

Table 5 shows the displacement at initial yield (δ_y), displacement at ultimate stage (δ_u), and ductility of structures using various bracing shape of V, inverted V and X. Structure with V bracing has a bigger ductility than it with inverted bracing (Λ) and X bracing (on two floor). Structure with inverted V bracing (Λ) has a smallest ductility than others.

TABLE V
DUCTILITY OF BRACED-STRUCTURES

No	**Brace Type**	**δ_y (mm)**	**δ_u (mm)**	**Ductility (*R*)**
1	V Brace	146.47	377.50	2.58
2	Inverted V Brace (Λ)	127.97	377.50	2.95
3	X Brace (on two floors)	132.47	377.50	2.85

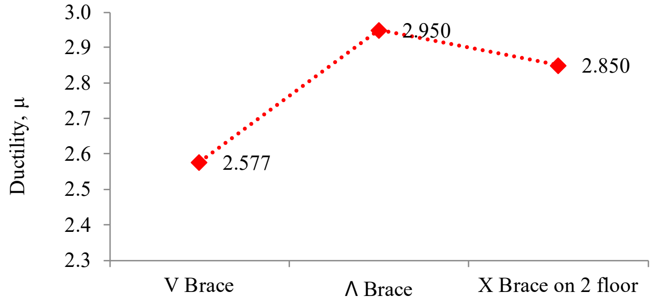

Fig. 11 Ductility of the high-rise braced-buildings

B. *Dynamic Response of Structure*

1) *Vibration Period of Structure:*

The dynamic parameters of a movement include the vibration period *T* and vibration mode. The period of vibration is the time permitted for a structure to perform one cycle of simple harmonic motion in one vibration mode. The dynamic parameters of a movement include the vibration period *T* and vibration mode. The period of vibration is the time permitted for a structure to perform one cycle of simple harmonic motion in one vibration mode. Meanwhile, what is meant by natural vibration mode is each characteristic form of displacement that occurs in a harmonic movement. A structure must have many degrees of freedom so that the system will have a solution which indicates the vibration mode of the system. A free vibration will occur in each mode with a certain frequency and vibration mode.

The vibration period of a structure (*T*) is obtained by comparing the parameters T_a (minimum period), T_c (program analysis results) and $T_{a,max}$ (maximum vibration period). Then, a vibration period value for the structure is selected that is below the $T_{a,max}$ value, the maximum allowable limit for the structure. A comparison of the vibration period values for the structure can be viewed on Table 6 and Fig. 12.

TABLE VI
VIBRATION PERIOD AND NATURAL FREQUENCY OF THE HIGH-RISE BRACED-BUILDINGS

No	**Brace Type**	**Vibration Period (second)**	**Natural Frequency (Hz)**
1	V Brace	1.240	0.806
2	Inverted V Brace (Λ)	1.120	0.893
3	X Brace (on two floors)	1.160	0.862

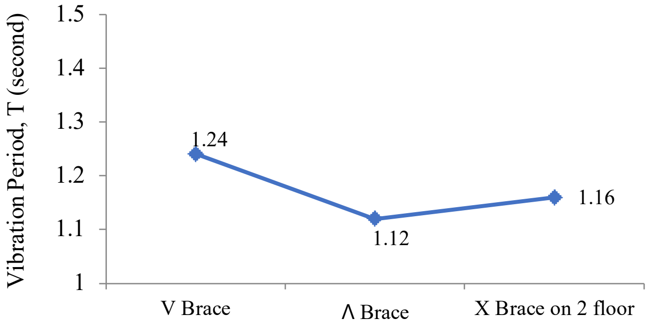

Fig. 12 Vibration period of the high-rise braced-buildings

The vibration periods results of models (T_c) using V-bracing, inverted-V (Λ) bracing and X- bracing are 1.24 second, 1.12 second, and 1.16 second. It showed that the smallest vibration period is found in the inverted V-shaped brace (Λ) of 1.12 second. This is because the structure using an inverted V-shaped brace (Λ) has a stiffer structure (can be seen in the stiffness analysis). So, when an earthquake occurs, the structure will tend to sway for a short time when compared to structures with other reinforcements. However, the period results in the three models a vibration period value that exceeds the maximum vibration period value ($T_{a,max}$), so the basic shear force analysis uses the $T_{a,max}$ value of 1,040 seconds in each model.

2) *Natural Frequency:*

The frequency of oscillation is the amount of cycles in a given time period. The system's inherent frequency is the rate at which it oscillates without outside influences if it sustains oscillations following an initial disruption. The n degrees on a system will show natural frequencies due to vibration. The frequency function represents the system's dynamic characteristics through a curve created by vibration measurements. The function comes from the connection between the input signal's Fourier transform and the output signal. The input signal comprises a force vector with magnitude and direction, while the output signal consists of displacement, velocity, and acceleration.

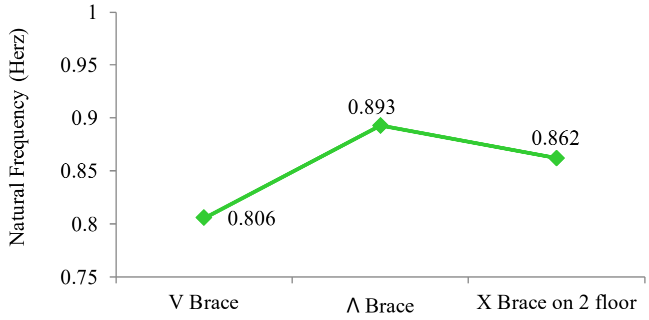

Fig. 13 The natural frequency of the high-rise braced-buildings

In addition, the formula $1/T_c$ can be used to calculate the natural frequency for each model, as shown in Table 3.6 and Figure 3.11. Table 3.6 indicates that the inverted-V shaped reinforced concrete brace (*Λ*) exhibits the highest natural frequency among different reinforcements, specifically 0.893 *Hz*. This occurs since the reinforcement has a short vibration period of 1.120 seconds, resulting in a high frequency.

C. Structural Damage

Dynamic loads such as earthquakes and wind loads can also cause extensive structural damage. Buildings, roads, and bridges can be damaged before collapse. Structural damage frequently leads to reduced load capacity, instability, and an increased threat of collapse, which can compromise the stability and safety of the affected structure. The structural damage should be linked and assessed to maintain the remedial measures of the structure.

The building safety parameter can be the dynamic response of natural frequency (f) and period (T). The building is safe if the design's natural building frequency (from modeling output) is less than the actual natural frequency (from spectra-response, which is input in the model). Safe condition refers to less potential for oscillation phenomena in the opposite case. Opposite to the natural frequency, if the design's period (from modeling output) is bigger than the actual period (from spectra-response, which is input in the model), then the building is safe. Based on the modeling outputs of dynamic response (vibration period, natural frequency), the existing structure is in safe condition from structural damage, as indicated in Table 7.

TABLE VII
DAMAGE PARAMETER OF THE HIGH-RISE BRACED-BUILDINGS

Damage Parameters of Dynamic Response	**V Brace**	**Inverted V Brace (Λ)**	**X Brace (on two floors)**
Actual Vibration-Period (spectra response record)	0.42 s	0.42 s	0.42 s
Design of Vibration Period (modeling output)	1.240 s	1.120 s	1.160 s
Actual Natural-Frequency (spectra response record)	2.38 Hz	2.38 Hz	2.38 Hz
Design of Natural Frequency (modeling output)	0.806 Hz	0.893 Hz	0.862 Hz

IV. CONCLUSION

Based on the modeling outputs of dynamic response (vibration period, natural frequency), the existing structure is safe from structural damage. According to the findings of structural performance, such as stiffness, vibration period, base shear force, lateral deviation (displacement), and drift between levels (drift), the most suitable variation of reinforced concrete braces is inverted V-shaped reinforced concrete braces (Λ).

The difference in vibration periods that occur in structures using reinforced concrete braces in the form of V, inverted V (Λ), and X (in two floors) is 0.32 seconds and 0.28 seconds, respectively. Inverted V-shaped reinforced concrete braces (Λ) have a smaller vibration period than other reinforcements.

The deviation of lateral displacement that occurs in the V, inverted V (Λ), and X (in two floors) in the Y-direction are 90.36 mm, 108.86 mm, and 104.36 mm, respectively. The variation in drift between floors observed in buildings with reinforced concrete braces in V, inverted V (Λ), and X configurations on two levels. When comparing to other reinforcements, this one has the lowest drift value in the vertical direction of *Y*.

ACKNOWLEDGMENT

The authors thank Universitas Negeri Malang for supporting all the materials, properties, data, and structures existing for modeling works in this paper.

AUTHORS CONTRIBUTION STATEMENT

All authors discussed the results and contributed to the final manuscript. Siti Nur Rahmah Anwar, Feryan Ernanda, and Mohammad Sulton developed and performed the simulations, analyzed the data, and wrote the manuscript. The first author also supervised the project. Siti Aminah Anwar contributed to the translation and final version of the manuscript.

REFERENCES

[1] Y. Deng, C. Yan, and P. Niu, "Hysteretic model of reinforced concrete bridge piers based on earthquake damage and corrosion from saline soil," *Soil Dyn. Earthq. Eng.*, vol. 166, Mar. 2023, doi: 10.1016/j.soildyn.2022.107732.

[2] M. Ferraioli, A. Concilio, and C. Molitierno, "Seismic performance of a reinforced concrete building retrofitted with self-centering shape memory alloy braces," *Procedia Struct. Integr.*, vol. 44, pp. 974–981, 2023, doi: 10.1016/j.prostr.2023.01.126.

[3] A. V. Shegay et al., "Evaluation of seismic residual capacity ratio for reinforced concrete structures," *Resilient Cities Struct.*, vol. 2, no. 1, pp. 28–45, 2023, doi: 10.1016/j.rcns.2023.02.004.

[4] D. Cook et al., "ASCE/SEI 41 assessment of reinforced concrete buildings: Benchmarking nonlinear dynamic procedures with empirical damage observations," *Earthq. Spectra*, vol. 39, no. 3, pp. 1721–1754, 2023, doi: 10.1177/87552930231173453.

[5] E. A. Opabola and K. J. Elwood, "Seismic performance of reinforced concrete beams susceptible to single-crack plastic hinge behavior," *J. Struct. Eng.*, vol. 149, no. 4, 2023, doi: 10.1061/jsendh.steng-11424.

[6] A. Habib, A. Al Houri, and U. Yildirim, "Comparative study of base-isolated irregular RC structures subjected to pulse-like ground motions with low and high PGA/PGV ratios," *Structures*, vol. 31, pp. 1053–1071, 2021, doi: 10.1016/j.istruc.2021.02.021.

[7] A. Aljaafreh et al., "Seismic performance of reinforced concrete structures with concrete deficiency caused by in-situ quality management issues," *Civ. Eng. J.*, vol. 9, no. 8, pp. 1957–1970, 2023, doi: 10.28991/CEJ-2023-09-08-010.

[8] N. A. Karimzada, A. Shirkhani, and E. Aktas, "Application of endurance time method in seismic assessment of RC frames designed

by direct displacement-based procedure," *Turk. J. Civ. Eng.*, vol. 35, no. 2, pp. 23–64, 2024, doi: 10.18400/tjce.1239730.

[9] M. Ubaid and R. A. Khan, "Effect of bracing configuration on the seismic response of buildings with re-entrant corners," *Innov. Infrastruct. Solut.*, vol. 8, no. 1, Jan. 2023, doi: 10.1007/s41062-022-01029-x.

[10] M. M. Bhargav, A. V. Rao, and I. S. Kishore, "Performance assessment of seismic evaluation of steel-framed structure using different bracing systems," in *Advances in Sustainable Construction Materials*, Guntur, India, 18–19 Mar. 2022, *AIP Conf. Proc.*, vol. 2759, p. 050006, May 2023, doi: 10.1063/5.0145310.

[11] A. Panjaitan et al., "The performance of concentrically braced frames (CBF) in Chevron V brace and diagonal configuration by considering various frame heights," *Aceh Int. J. Sci. Technol.*, vol. 12, no. 2, pp. 139–147, 2023, doi: 10.13170/aijst.12.2.30848.

[12] A. Panjaitan et al., "Structural performance of single and double-section CBF braces with different lengths under cyclic loading," in *AISCE 2023*, *E3S Web Conf.*, vol. 476, 2024, doi: 10.1051/e3sconf/202447601003.

[13] J. Zhao, H. Qiu, J. Sun, and H. Jiang, "Seismic performance evaluation of different strategies for retrofitting RC frame buildings," *Structures*, vol. 34, pp. 2355–2366, 2021, doi: 10.1016/j.istruc.2021.09.016.

[14] H. Beiraghi, A. Kheyroddi, and Z. Falaki Nafechi, "Behavior of reinforced concrete frames retrofitted by different configurations of concentric steel braces," *Iran. J. Sci. Technol. Trans. Civ. Eng.*, vol. 46, no. 3, pp. 2039–2052, 2022, doi: 10.1007/s40996-021-00799-1.

[15] M. Ghiasvandan et al., "Experimental and parametric study of a novel braced system to improve seismic performance," *Structures*, vol. 45, pp. 229–242, 2022, doi: 10.1016/j.istruc.2022.08.120.

[16] P. Castaldo, E. Tubaldi, F. Selvi, and L. Gioiella, "Seismic performance of an existing RC structure retrofitted with buckling restrained braces," *J. Build. Eng.*, vol. 33, 2021, doi: 10.1016/j.jobe.2020.101688.

[17] N. M. R. Solaimani and M. Mahmoudi, "Experimental and analytical evaluation of the seismic performance of Y-shaped braces equipped with yielding diagonal dampers," *J. Build. Eng.*, vol. 42, 2021, doi: 10.1016/j.jobe.2021.102362.

[18] S. Majid Zamani et al., "Experimental investigation of steel frames with single bays of symmetrical Y-shaped concentric bracings," *Sci. Iran.*, vol. 19, no. 2, pp. 195–210, 2012, doi: 10.1016/j.scient.2012.02.006.

[19] M. Dicleli and A. Mehta, "Seismic performance of chevron braced steel frames with and without viscous fluid dampers as a function of ground motion and damper characteristics," *J. Constr. Steel Res.*, vol. 63, no. 8, pp. 1102–1115, 2007, doi: 10.3390/buildings12111977.

[20] H. Chen et al., "Research on safety risk management of a steel bracing system based on catastrophe theory," *Buildings*, vol. 12, no. 11, Nov. 2022, doi: 10.3390/buildings12111977.

[21] A. Mishra and P. Alam, "Finite element method and P-delta analysis of G+10 multistorey frame building structure by using ETABS software," in *SESBT 2022*, Tamilnadu, India, 2023, *IOP Conf. Ser.*, vol. 1161, no. 1, p. 012012, doi: 10.1088/1755-1315/1161/1/012012.

[22] E. U. Syed and K. M. Manzoor, "Analysis and design of buildings using Revit and ETABS software," *Mater. Today: Proc.*, vol. 65, pp. 1478–1485, 2022, doi: 10.1016/j.matpr.2022.04.463.

[23] A. Z. Abdulhameed, M. A. Ahmed, and A. A. Karim, "The impact of bracing system distribution and location on seismic performance enhancement of multi-story steel buildings," *Math. Model. Eng. Probl.*, vol. 10, no. 5, pp. 1833–1841, 2023, doi: 10.18280/mmep.100536.

[24] H. A. M. Yazdi and N. H. R. Sulong, "Optimization of off-centre bracing system using genetic algorithm," *J. Constr. Steel Res.*, vol. 67, no. 10, pp. 1435–1441, 2011, doi: 10.1016/j.jcsr.2011.03.017.

[25] W. F. Chen and E. M. Lui, *Earthquake Engineering for Structural Design*. Boca Raton, USA: CRC Press, 2005, doi:10.1201/9781420037142.

[26] C. Thongchom et al., "Performance improvement of innovative shear damper using diagonal stiffeners for concentrically braced frame systems," *Buildings*, vol. 12, no. 11, p. 1794, 2022, doi: 10.3390/buildings12111794.

[27] Y. Bakhshayesh, M. Shayanfar, and A. Ghamari, "Improving the performance of concentrically braced frame utilizing an innovative shear damper," *J. Constr. Steel Res.*, vol. 182, Jul. 2021, doi: 10.1016/j.jcsr.2021.106672.

[28] *SNI 1726: Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Nongedung*. Badan Standardisasi Nasional (BSN), Jakarta, Indonesia, 2019.

[29] *SNI 2847: Persyaratan Beton Struktural untuk Bangunan Gedung dan Penjelasan (ACI 318M-14 dan ACI 318RM-14, MOD)*. Badan Standardisasi Nasional (BSN), Jakarta, Indonesia, 2019.

[30] ACI Committee, *Building Code Requirements for Structural Concrete (ACI 318-14)*. Farmington Hills, MI, USA: American Concrete Institute (ACI), 2014.

[31] F. Anastasia et al., "The performance assessment of the structural bracing model for multi-story building," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 14, no. 1, pp. 196–204, 2024, doi: 10.18517/ijaseit.14.1.19397.

[32] F. Fauzan et al., "Structural evaluation and strengthening strategy of the law faculty hall building in Andalas University, Padang, Indonesia," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 11, no. 4, pp. 1567–1578, 2021, doi: 10.18517/ijaseit.11.4.11613.