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Stress analysis of four-story building to detect the crack location under the earthquake loading

Alfinna Mahya Ummati[1,2*]

[1]*Department of Civil Engineering, Institut Teknologi Sumatera, Lampung Selatan, 35365, Indonesia*

[2]*Department of Civil Engineering, National Central University, Taoyuan, 320, Taiwan*

[*]alfinna.ummati@si.itera.ac.id

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ABSTRACT

A 3D frame element modelling conducted in order to identify the crack location of the educational building on South Lampung City. Many cracking visually appeared in a building and many of leaking observed that the building performs an over displacement. This research proposed an analysis in order to detect the crack location due to the building's overstressed before and under the certain earthquakes loading. First, the building subjected to the deadload and service loading and was found that the building in a health condition and there is no cracking identified. Second, an El-Centro earthquake normalized and fitted with the site location and loaded to the building. Under 200-gal earthquake which similar to MMI scale VI to VIII with the moderate damage that possibly occur in Lampung, the crack detected in all member of the building, either major or minor cracking. This research proposed the method which considerable to use in observing the cracking location, generally.

Keywords: building; crack; earthquake; stress

1 Introduction

With the purpose to do prediction based on the degree of failure of a building by identifying the stress analysis of the structure, this research has the aim to check the crack location possibility before and after excited by the earthquake loading. Liu et.al. in 2018 involved the role of ESMD method to identify the building stability with the shear wall modelling [1]. Local stress distribution is able to observe within the numerical software in finite element based, Ohsaki et.al. perform the finite element analysis of laminated rubber bearing and compared with the experimental result in order to identify the stress distribution subjected to the earthquake loadings [2]–[5], this research do the stress analysis of four-story building using numerical software analysis of SAP2000. the design resistance method of a reinforced concrete analysis considered the nonlinearity, which is the cracks happen after elastic phase passed during the failure. Kochkarev et.al. in 2020, develop the basic analysis to design the uniform beam structure in order to perform an effective structure analysis for beam reinforcement and reconstruction [6], in further, this research provide the stress and cracking analysis which applicable as the reference to perform the concrete structure retrofitting. Beam-column join is the critical zone in reinforced concrete building [7], such as the analysis result of the model in this research, there are stress concentration in beam and column intersection which indicate the beam column join of the building need to observed in further for the future works. Hence, the behavior of the reinforced concrete building affected significantly with the beam column joint performance [8], [9]. Stress concentration in a building caused by many factors, one of them is due to the connection problem which is not as rigid as the original member. Thus, the reinforcement in the connection zone is more special than in the other part. Stress concentration induce the existing of a plastic hinge, yet in sometimes, plastic hinge locations are arranged to avoid it to develop in the specific member. Kaish et. al. overcome this situation with strengthening the area under the concentric load with the ferrocement jacketing method [10]. The retrofitting and improvement method may different for other cases.

Response of the structure due to the earthquake ground motions is transferred from the ground as the original vibration source to the structure itself through the building's member which located start from the lowest to the highest elevation. It is closed related with the stiffness of the building, if the flexibility can be reduced by reducing the building stiffness, then the building is able to harmonize with the earthquake wave and the shear force which transferred to the building is able to reduce[11].

The building which observed in this research is located on Lampung Province, Indonesia. Lampung has the complexity in geographical condition. There are two plate in between, Indo-Australia and Eurasian plates. Lampung is inside in Semangko trench zone, it is categorized as the Sumatera Transform Fault Zone which crossed along the body of Sumatera Island. Indo-Australia Tectonic plates observed to move 6-14 cm per year, this tectonic activity become the main reason of the high intensity earthquake which happen either in the land or the sea as the triggered of Tsunami. This phenomenon proofed as the reason of the Tsunami which happened previously such as: Tsunami Aceh (2004), Tsunami Nias (2005), and Tsunami Mentawai (2010) [12], [13]. Krakatau Volcanic Mountain, one of the volcanic mountains under high observation of BMKG (Metrological, Seismicity, and Geophysical Bureau, Indonesia) located in Lampung, beside the tectonic activity due to the plate movement, but also the volcanic activity of the Krakatau Mountain caused Lampung become one of the provinces with the high seismicity region.

2 Data and Methods

Three dimensions of the frame element analysis was carried out in order to study the four-story RC building to identify the damage location possibility subjected to the earthquake loading. Bandar Lampung building located on Lampung Selatan, Indonesia, and actively used as an academic building.

Figure 1. Bandar Lampung building

Preliminary observation was done in order to mark the crack existing which appear more than prediction. Finite element analysis performed in order to identify the building condition, specifically to identify the crack location possibility subjected to the deadload and seismic excitation with the consideration that the building located in the region with high seismicity. The Figure 1. Shown Bandar Lampung building and Figure 2. Shown finite element modelling by SAP-2000. Finite element analysis performed using numerical software of SAP2000 considering the modelling complexion, accuracy, and effectiveness. In real building on **Figure 1** shows there are three wings in left, right, and front center of the building, all that architectural element assumed as the external loading which loaded in the same location.

The building located on the region with the high seismicity caused by both tectonic and volcanic activity, hence the deadload including the building function and earthquake are considered as the loading in this case. Earthquake pattern adopted from the original El-Centro earthquake on 1940 with the

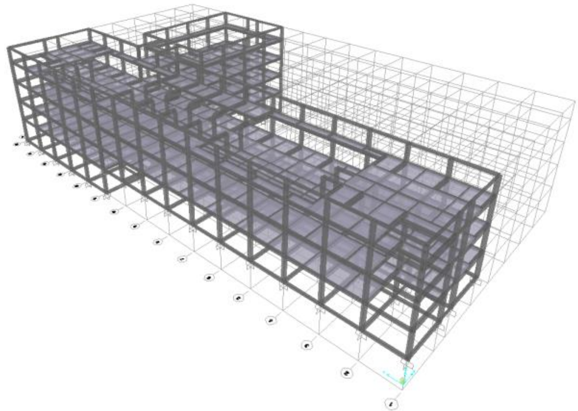

Figure 2. Finite element modelling

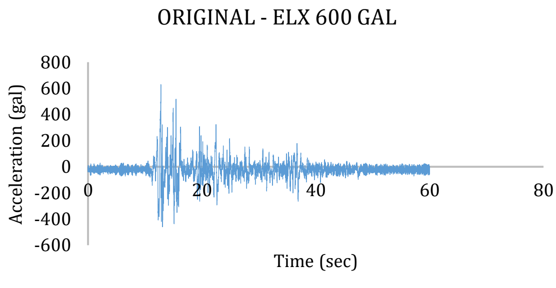

Figure 3. Original ground motion 600-gal

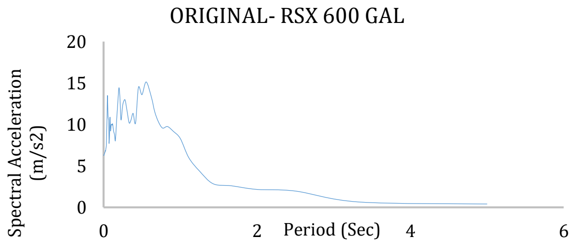

Figure 4. Response spectrum of the original GM

magnitude of 900-gal, **Figure 3** shows the original earthquake pattern and **Figure 4** shows the response spectrum of the original earthquake.

Adopted earthquake pattern which previously occur in different location supposed to be normalized regarding with standard design code [14], which normalized regarding the site and soil condition following the Indonesian Standard Code issued by Puskim, Department of National Highway and Infrastructure. The code provides the local prediction of response spectrum which happen if the original earthquake occurs in the building location, compare both response spectrum with in a specific period regarding the maximum modal mass participating ratio, the period at the certain mode is about 0.814 second. Describe further in **Figure 5.**

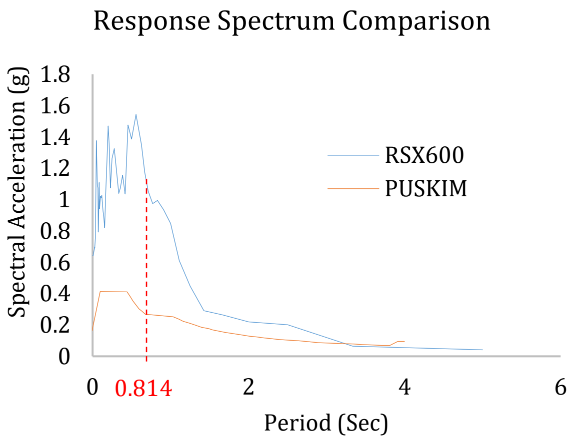

Figure 5. Response spectrum comparison

Based on **Figure 5**, it was identified that the original ground motion supposed to be reduced 0.313 times in order to adapt the building location. Hence, with the normalized coefficient, the original ground motion reduced from 600-gal to 200-gal.

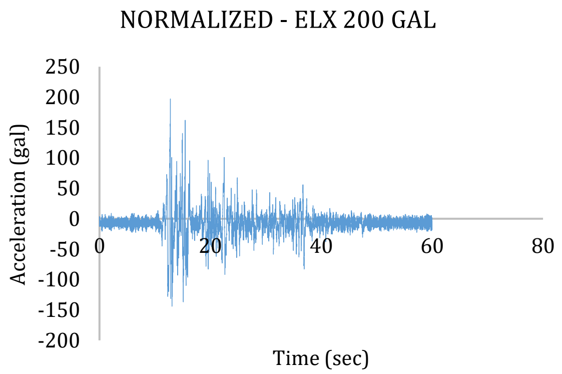

Figure 6. Normalized ground motion

Analysis performed in two stages: first stage the building is loaded by the deadload itself, and second stage added by the earthquake loading. The deadload is the building self-weight and the earthquake loading is the normalized ground motion which described in Figure 6. The stress compared with the limitation of the allowable shear stress to locate the crack existing.

3 Results and Discussion

First stage of the research is to analyze the building under the deadload. The building self-weight including its reinforcement and service load in order to know the building condition after construction. This phase is important in order to match the current condition in real structure and the ideal condition.

For the first stage of analysis, it was identified that the frequency and period of the building subjected by its own deadload is 0.833 Hz and 1.201 Sec., respectively. And the highest and second highest of the modal mass participation ratio regarding the translation along the short axis of the building is 0.240 and 0.229 which is on mode 8 and mode 1, respectively.

Table 1. The first three modes period and frequency for the first stage analysis

Mode	Period (sec)	Frequency (Hz)
1	1.201	0.833
2	1.164	0.859
3	1.080	0.825

Building displaced about 0.211 cm according to the longest axis and 1.204 cm according to the shorter axis.

Table 2. First stage analysis displacement

Axis	Max Displacement
Long Axis	0.211 cm
Short Axis	1.204 cm

The stress analysis was done in order to locate the member with the overstress condition. Since the cracking and displacement of the building is close related with the concrete flexure tensile strength, and the strength is affected by many conditions, such as the size, age, confinement, and many more. The stress distribution for the first stage described in the contour diagram, shown in **Figure 7.** The stress distribution described on the colors contour with the scale of -4900 kN/m^2 to 4200 kN/m^2. The negative sign shows the element is under compression, and positive sign shows the element is under tension. From the **Figure 7** all the columns stresses are under compression, opposite with the beam elements which mostly under tension. Put more attention into the beam and column joint region, either in the outer or inner side of the building, the stress in this zone is varied and unpredictable. The study about the beam-column joint for this building supposed to be developed in further.

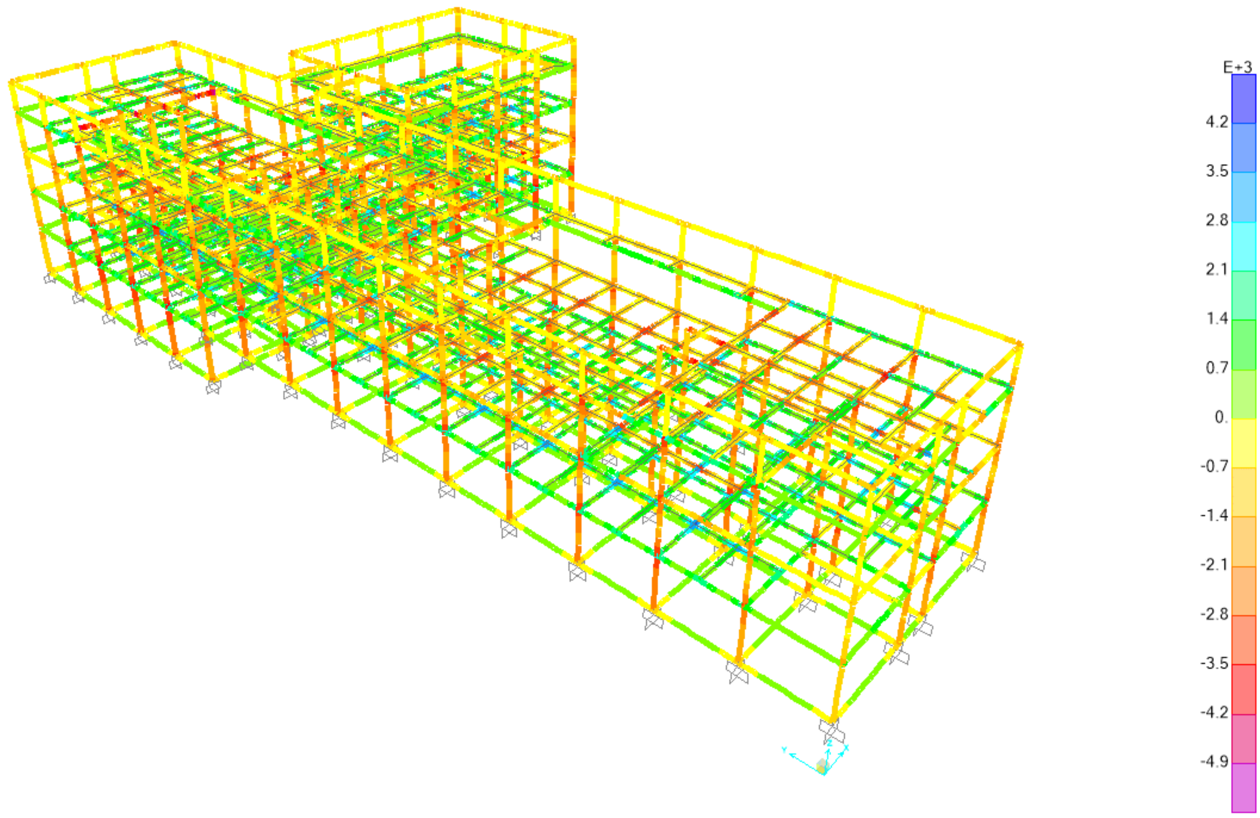

Figure 7. Stress distribution of the first stage analysis (unit: kN/m²)

ACI [15] determine the allowed flexural tensile stress is about power half of the concrete compression strength, which means that this value is the stress-stress limit before cracking.

$$f_{r(ACI)} = 1.0\sqrt{f'_c} \quad (1)$$

In 2016, Ahmed et.al. performed an experimental study in order to identify the value of the flexural tensile strength considering the age and confinement condition which is not explained in ACI standard code. The empirical equation proposed differently from ACI since they refer to power 2/3 instead of poser ½ of the concrete compressive strength [16], [17], bellow is the proposed equation:

$$f_{r(Ahmed)} = \lambda_1\lambda_2 0.45 {f'_c}^{2/3} \quad (2)$$

Where:

λ_1 =1, for 28 days
=0.95, for 7 days
=1.05, for 56 days

λ_2 =1.45, for confined conditions

λ_1 and λ_2 are the coefficient of concrete age and confinement. Ahmed said that the Eq.2 is applicable for a concrete including the factors affecting the flexural strength in wide range level.

The concrete compressive strength of the building is 25 MPa. Regarding with Eq. 1 and Eq. 2, the exact value of the flexural strength is about 5 MPa and 5.579 MPa, respectively. Both $f_{r(ACI)}$ and $f_{r(Ahmed)}$ which calculated from Eq. 1 and Eq. 2 used as the flexural strength limit to define the crack. Crack defined in the elements with the stress beyond both values as the preferred reference.

In the first stage of the analysis, the maximum stress is about 4.629 MPa, and Table 1 shows three biggest stress value of the building. Comparing the maximum stress value with the flexural stress limit proposed by ACI and Ahmed, the building stress is under the warning level. It is concluded that there is no early cracking which happen right after the construction finished.

Table 3. Stress analysis condition on first stage analysis

Element ID	Stress (MPa)	$f_{r(ACI)}$	$f_{r(Ahmed)}$	Condition
685	4.629	5.0	5.579	
687	4.551	5.0	5.579	Uncrack
817	4.541	5.0	5.579	

For the second analysis, considering the highest displacement which mention in Table 2 was happened on the short axis, then the earthquake loading as in Figure 6 load in the short axis direction as the ground motion that subjecting to the building. Assumed that the ground motion performing non-linear analysis with direct integration of the Newmark method. The damping analyzed within the Rayleigh damping parameter considering the modal mass participation factors and modal damping at i and j-th mode.

Rayleigh damping **c** is a classical damping method, with the equation of:

$$\boldsymbol{c} = a_0\boldsymbol{m} + a_1\boldsymbol{k} \quad (3)$$

where a_0 and a_1 is the mass proportional damping and stiffness proportional damping which able to defined by the damping ratio in i and j-th mode, **m** and **k** is the mass and the stiffness matrix of the structure. Referring to the n-th mode of the damping ratio:

$$\zeta_n = \frac{a_0}{2}\frac{1}{\omega_n} + \frac{a_1}{2}\omega_n \quad (4)$$

Similar with the damping ratio, ω_n is the angular frequency on n-th mode. Considering Eq. 3 and Eq. 4, the damping ratio in the specific modes can be expressed into the matrix below:

$$\frac{1}{2}\begin{bmatrix}1/\omega_i & \omega_i \\ 1/\omega_j & \omega_j\end{bmatrix}\begin{bmatrix}a_0 \\ a_1\end{bmatrix} = \begin{bmatrix}\zeta_i \\ \zeta_j\end{bmatrix} \quad (5)$$

Assume the damping ratio in both modes are the same, the matrix in Eq. 5 is the solution to determine the value of both coefficient a_0 and a_1 [18].

$$a_0 = \zeta\frac{2\omega_i\omega_j}{\omega_i+\omega_j} \quad (6)$$

$$a_1 = \zeta\frac{2}{\omega_i+\omega_j} \quad (7)$$

This method used in SAP2000 to determine the damping method that used for the numerical analysis. For this research, the ground motion applied on the short axis of the building. Then, i and j-th mode are the mode where the modal mass participation ratio reaches the highest and the second highest value, respectively. Then ω_i and ω_j are the natural frequency calculated from the period in the specific modes which had been chose.

Table 4. Period in the specific modes

Mode	Period sec	Modal mass participation
8	0.740561	0.24023
1	1.201065	0.2287

The numerical analysis for the second stage considering the earthquake loading performed in order to identify the building behavior under the contribution of the deadload and earthquake
For the maximum displacement of the second analysis are shown in the table below:

Table 5. Maximum displacement comparison for the first and second stage analysis

Axis	First Analysis	Second Analysis
Long Axis	0.211 cm	1.796 cm
Short Axis	1.204 cm	7.248 cm

The critical point defined as the location with the maximum displacement under the specific loading. In targeted building, the critical point observed the point ID 1129 which marked by the red point below:

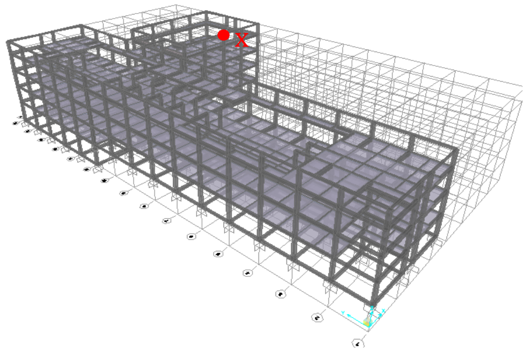

Figure 8. Point observed

the earthquake subjected to the building contribute the displacement induced by the mass of building. **Figure 9** and **Figure 10** are the displacement history along the long and short axis of the building, respectively.

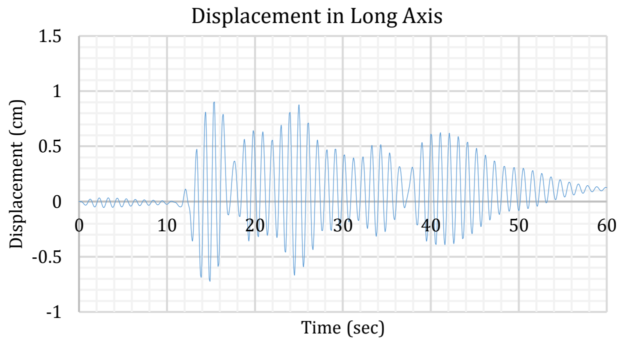

Figure 9. Displacement in long axis

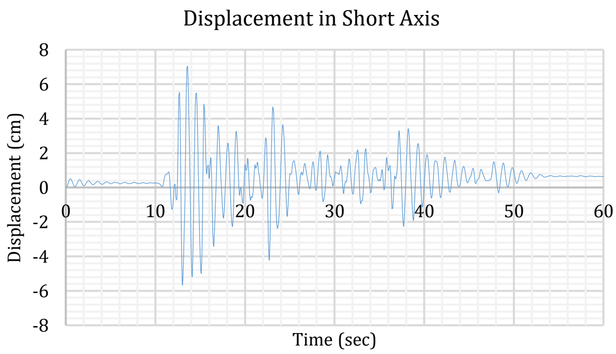

Figure 10. Displacement in short axis

The heavy mass of the building causes displacement period longer than the original earthquakes period. For the specific earthquake which had been normalized, the building displaced 0.901 cm and 7.037 cm along the long and short axis of the building which observed in point x right after reaching the peak ground acceleration. The displacement pattern in both directions are different, it is related with the building stiffness and will explain further in the future works.

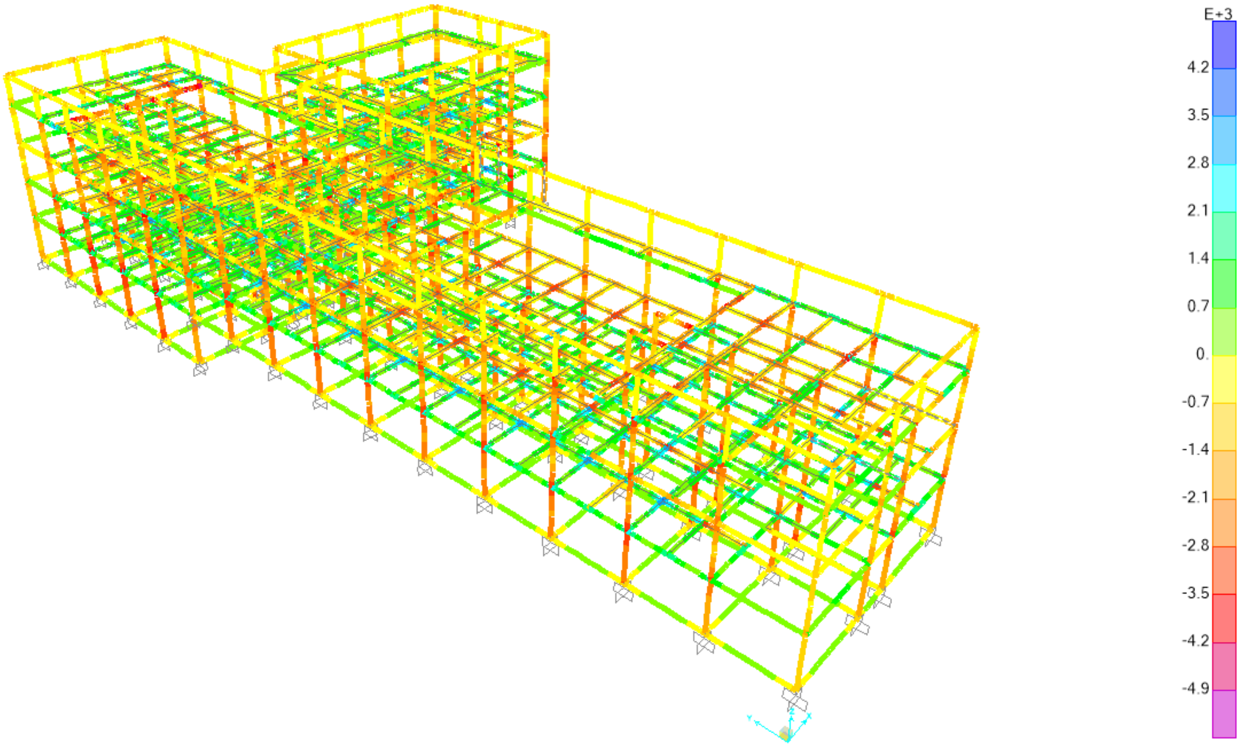

Figure 11. Stress distribution of the second stage analysis (unit: kN/m^2)

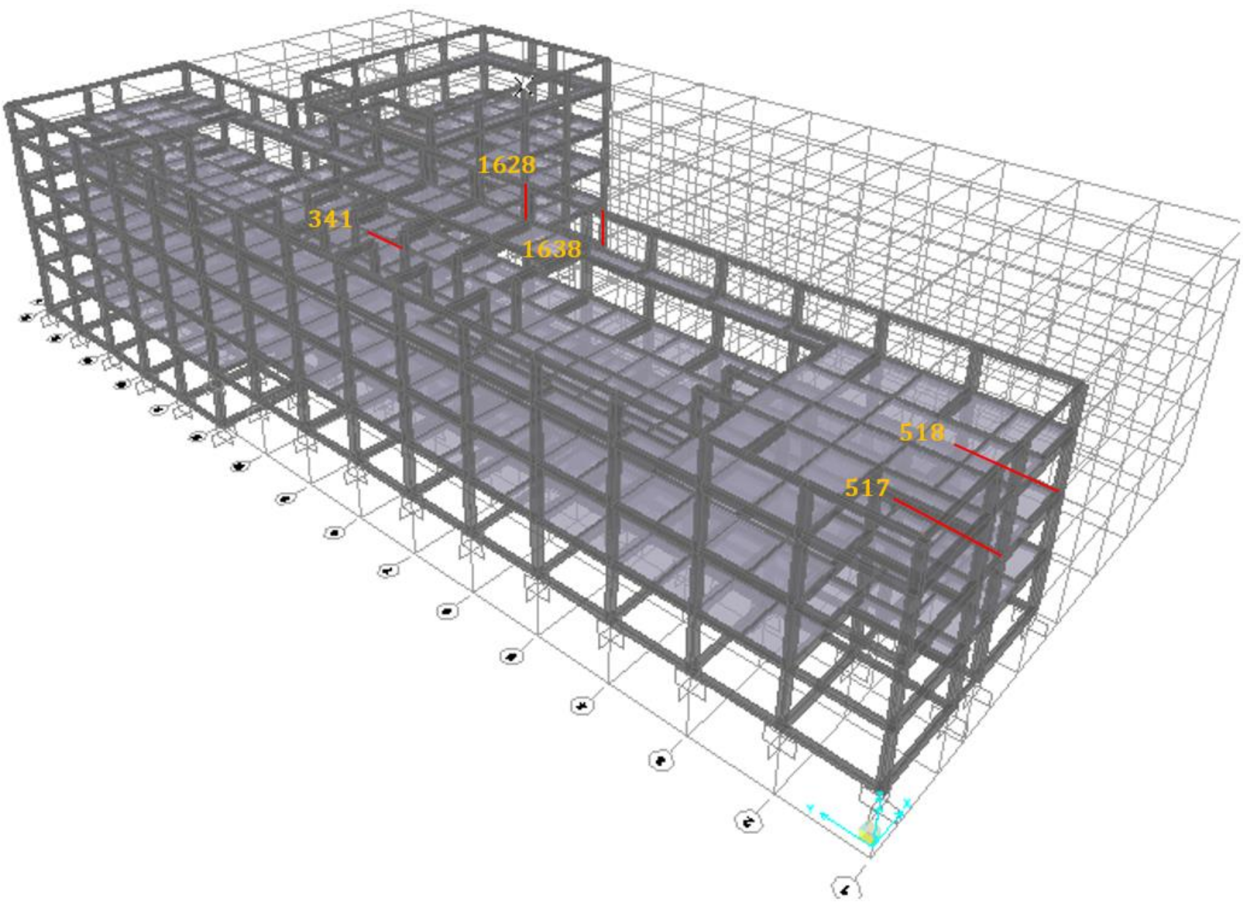

Figure 12. Location of the 5 most critical elements

Table 5. Stress analysis condition on second stage analysis

Element ID	Stress (MPa)	$f_{r(ACI)}$	$f_{r(Ahmed)}$	Condition
341	18.892	5.0	5.579	Cracks
1638	18.693	5.0	5.579	
1628	18.370	5.0	5.579	
517	18.262	5.0	5.579	
518	18.108	5.0	5.579	
1631	17.901	5.0	5.579	
1628	17751	5.0	5.579	
170	17.708	5.0	5.579	
207	17.708	5.0	5.579	
169	17.704	5.0	5.579	

For the stress analysis, Figure 11 shows the element stress for all member subjected to the earthquake. This picture is roughly described that in some points the color of the stress indicator became bolder than before, especially for the positive stress value. The positive value means the member is under the tension, meanwhile the negative value means the member is under the compression.

Take the concern to the positive stress value, cracks which happen to the concrete member is caused by tension stress which over the allowable tensile stress. Now we observe the stress according to the second stage analysis, remember that the second stage of analysis is the combination loading between the deadload and normalized earthquake ground motion. And the member of concern is the element with positive stress value. The maximum positive stress that more than the allowable tensile strength shows the critical member which necessary to perform the retrofitting action. Table 6 shows the 10th biggest stress value to indicate the structure condition **Table 5** indicate the 10 members with the highest stress which over the allowable tensile strength 5.0 MPa and 5.579 MPa according to the ACI design code and Experiment by Ahmed et.al., from the 10 highest stress data, 5 elements with the highest stress value marked as shown in figure 12.

4 Conclusion

A research conduct in order to observe the cracks possibility of a concrete structure under a certain earthquake. Study case on the Bandar Lampung building as a four-story concrete modelled as a finite element modelling, was observed before and after the earthquake excitation. The analysis performed by comparing the stress of the element with allowable tensile stress of a concrete. Earthquake which loaded in to the building proofed to give significant effect to the building since the motion induced more energy from the earthquake through the structure shear force by the displacement that increase after the earthquake loaded. This research explained the method to predict the location of the crack that may occur due to the external loading. ACI and Ahmed mentioned that within the certain compressive strength of the concrete, the allowable tensile stress is 5 MPa and 5.579 MPa, respectively. The analysis identified that there are no cracks which happen to the structure right after the construction since the maximum stress of the building is 4.629 MPa, this indicate that the satisfactory of the construction design. Under 200 gal of earthquake, several members show the stress which up to 18.892 MPa is larger than the allowable tensile stress, the member with stress which larger than the tensile stress limit marked as the member which containing some cracks

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