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The modal strain measurement in an abandoned building under ambient and forced excitations in comparison with a numerical analysis

C. Panitchayangkul, P. Thammarak & H. Le
Asian Institute of Technology, Thailand.

ABSTRACT

The health monitoring of horizontal load resisting structures is essential for the damage detection and the safety evaluation of high-rise buildings in the earthquake-prone areas. The widely-used monitoring technique is conducted by means of floor acceleration response measurement by accelerometers along with signal processing and vibration data interpretation in frequency domain. Predominant frequencies and mode shapes have been used as the indicators for damage detection. However, these indicators can also be affected by some ambient conditions, e.g. temperature and directions of solar exposure onto a building. Furthermore, small damages could hardly be identified by acceleration-based techniques. Thus, the detection of non-severe damages could not be precise. There were some efforts to use modal strains, stemmed from dynamic strain measurement, for damage detection instead of acceleration-based techniques due to its superior performance. However, those studies were conducted in scaled models, and the forced excitation was higher which made general resolution strain measurement (1 micro strain resolution) possible. In this research, we explored techniques to construct the modal strain signatures in a real 26-story building. The resolution of measurement was enhanced by the use of piezo-resistive type strain gauges, applied on the predetermined high-strain locations on the concrete surface of structural walls. The forced excitations, generated by humans, synchronized by a metronome, were applied at the first fundamental frequencies in each vibration mode of the building, determined from ambient acceleration measurement. The modal strain signatures were constructed successfully from this framework, and good agreements with results from the modal analysis by FEM were observed. The actual implementation in real buildings is viable and justified by this work

1 INTRODUCTION

As engineering is developed for a period of time, the service time of structure such as bridges and buildings become longer and longer. In between their service life time, many structures could have been damaged and need the maintenance. The damage normally extends and become more severe as it is left unrepaired. The time that the damage be detected has affect the severity of the structural damage condition. This could lead to the safety of the structure itself and also people that use those buildings or bridges. The repairing process is selected accordingly which could lead to other issue such as the difficulty and the cost of the operation. By these reasons, the damage should be detected as early as possible to simplify the repairing process, save the cost of operation or even save life.

There are many techniques that have been used in full-scale health monitoring in order to investigate the status of the structure. One option is through the dynamic characteristic of the structure. The traditional approach is to measure the acceleration time history and follow by signal processing to extract the dynamic properties such as natural frequency and mode shape. These dynamic parameters could be used as an indicator to imply the status of the structure whether it is still be as initial or not. However, these indicators could be affected by the surrounding condition such as the temperature shift throughout the day. In addition, the value of natural frequency is mostly relevant to the global response of the structure and will be clearly show the difference when the whole structure has been damaged with rather high severity. This approach is not so sensitive to the early state of the damaged as well as the location of the local damage cannot be spotted precisely too.

Recently, dynamic strain is also selected to be a parameter for the structural dynamic property's determination. By the fact that, the strain is also sensitive to the local behaviour of the structure. Therefore, this approach not only be able to determine the global behaviour of the structure but also can be extended to detect and locate the local damage of the structure as well. This idea was tested in the laboratory using the scaled model where the excitation and the severity of the damage could be fully control and was able to detect the damage successfully. This research, we explored techniques to construct the modal strain signatures in a real 26-story building.

2 NUMERICAL ANALYSIS

The numerical model, shown in Figure 1, is created using ETABS software base on the geometry and material properties determined at the site visitation. The typical floor plan is used in every floor. North and East direction is set to be positive Y and X direction respectively. The stiffness modification is all set to be one which mean the structure has no damage occurred. The vertical and lateral load resisting member for this building are mostly come from the structural wall which located all over the floor area. The column is neglect because the cross-sectional area is very low compare to the wall. The maximum slab meshing size is set to be 1 meter in both x and y direction. The wall meshing for the lower part is set to be 0.5 meter to get high resolution result but then reduce to be 1 m at higher floor to save analysing time.

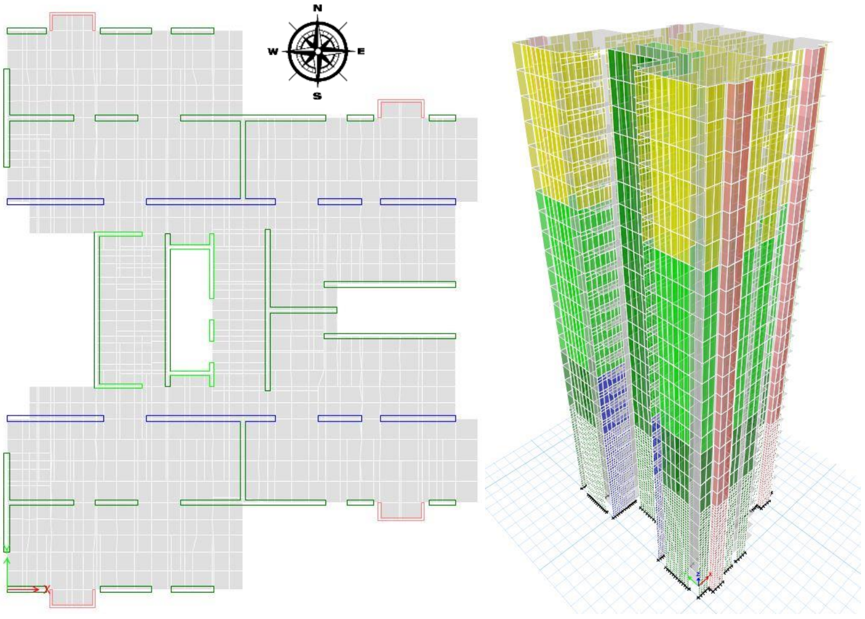

Figure 1: Numerical Model : Floor Plan (Left), Three Dimensional View (Right).

After modal analysis, the modal properties of the first fundamental vibration mode are considered. The natural frequency and the modal direction factors are summarized in Table 1. It can be seen from modal direction factors that the first mode has primary translation in Y direction in couple with torsion, the second mode is pure translation X and the third mode has primary torsion in couple with translation Y. The modal strain, in vertical direction, will be shown in comparison with the modal strain signature later.

Table 1: Natural Frequency and Modal Direction Factors

Mode	Period (sec)	Frequency (Hz)	UX	UY	RZ
1	1.135	0.881	-	0.58	0.42
2	0.935	1.070	1.00	-	-
3	0.890	1.124	-	0.42	0.58

3 FORCE EXCITATION BY HUMAN

As the studied building has abandon without finishing wall installed, the wind is able to flow through the building and generated too low excitation for dynamic strain measurement under ambient condition though the piezo-resistive type strain gauge is used. Higher level of structural response is needed in order to achieve higher signal to noise ratio. In this case, the excitation is generated using human force pushing in a rhythm that match with the natural frequency of the building to trigger the resonance effect.

To determine the natural frequency of the building, the power spectral density generated from one day acceleration measurement on 26th floor under ambient condition (Figure 2) is considered to determine the dominant frequency. Later on, the unit of the frequency will be shift into Beat Per Minute (BPM) to match with the input unit of the *metronome*, originally is the device to generate regularly interval click sound. Then, all human forces can be controlled to be in the rhythm of each mode of vibration.

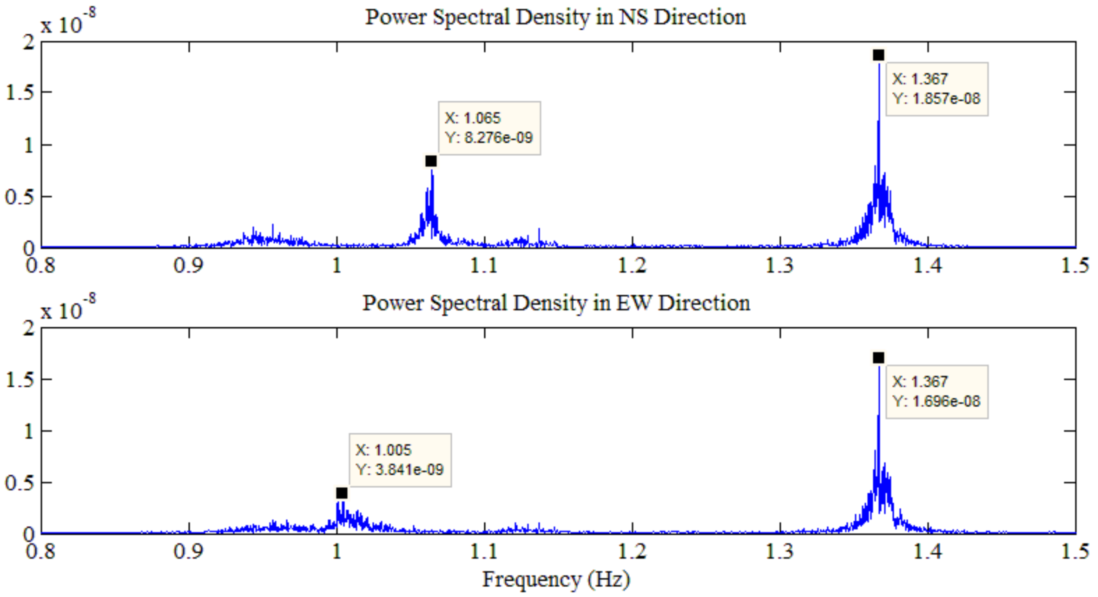

Figure 2: Power Spectral Density of One-day Acceleration under Ambient Excitation

Along with the frequency, the direction and the location (Figure 3) to apply the force are also needed to be incorporated as listed below.

- Y translational mode, 1.065 Hz or 64 BPM, is triggered by apply the force near the centre of floor mass in NS direction.
- X translational mode, 1.005 Hz or 61 BPM, is triggered by apply the force near the centre of floor mass in EW direction.
- Torsional mode, 1.367 Hz or 82 BPM, is triggered by apply the force at a distance away from the centre of floor mass in NS direction.

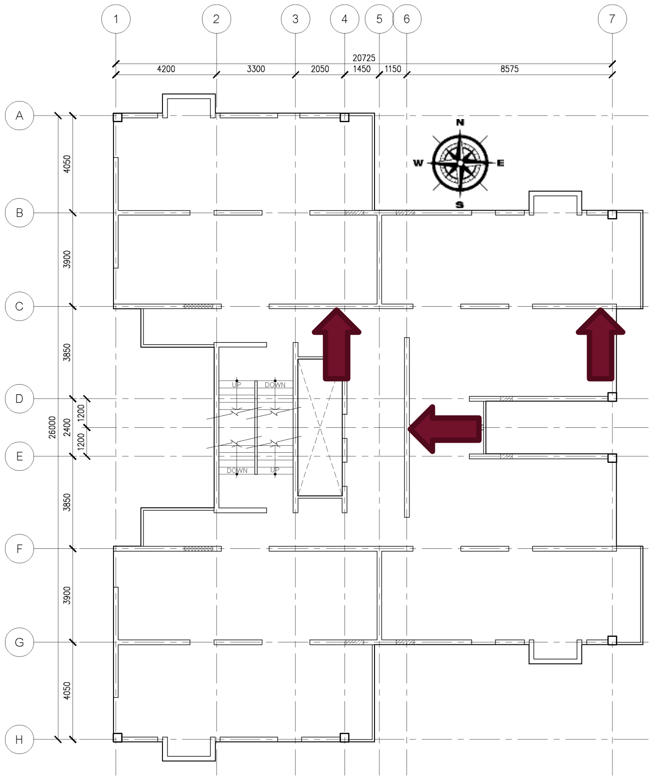

Figure 3: Location and Direction of Human Excitation.

To monitor the human excitation, the acceleration measurement is conducted away from the centre of the floor plan in both directions. The human excitation time history (Figure 4) contains three triggering condition associated to the fundamental vibration mode. In one mode, the excitation is repeated three cycles. In one cycle, total duration is 3 minutes which have 30 seconds of excited period and 150 seconds of decay period.

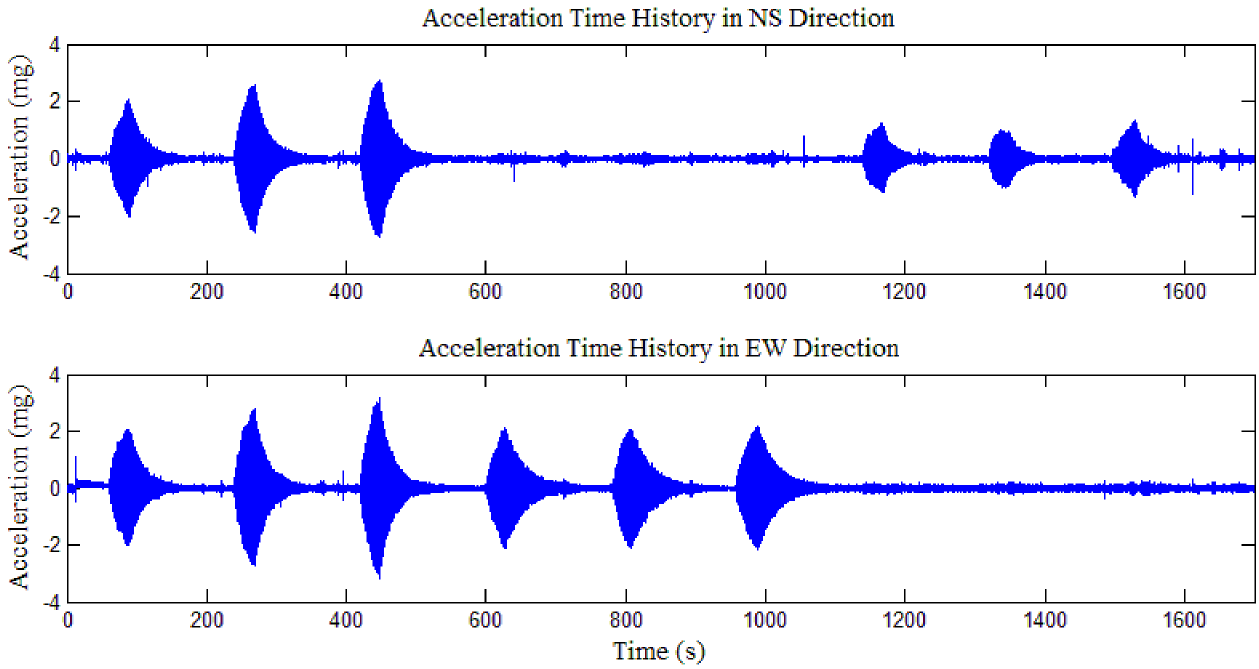

Figure 4: Human Excitation Acceleration Time History.

The data processing is done in such a way that each decay section is transformed into frequency domain individually and then be averaged within its corresponding mode. Then, the averaged frequency domain of human excitation for all modes in both directions are shown in Figure 5.

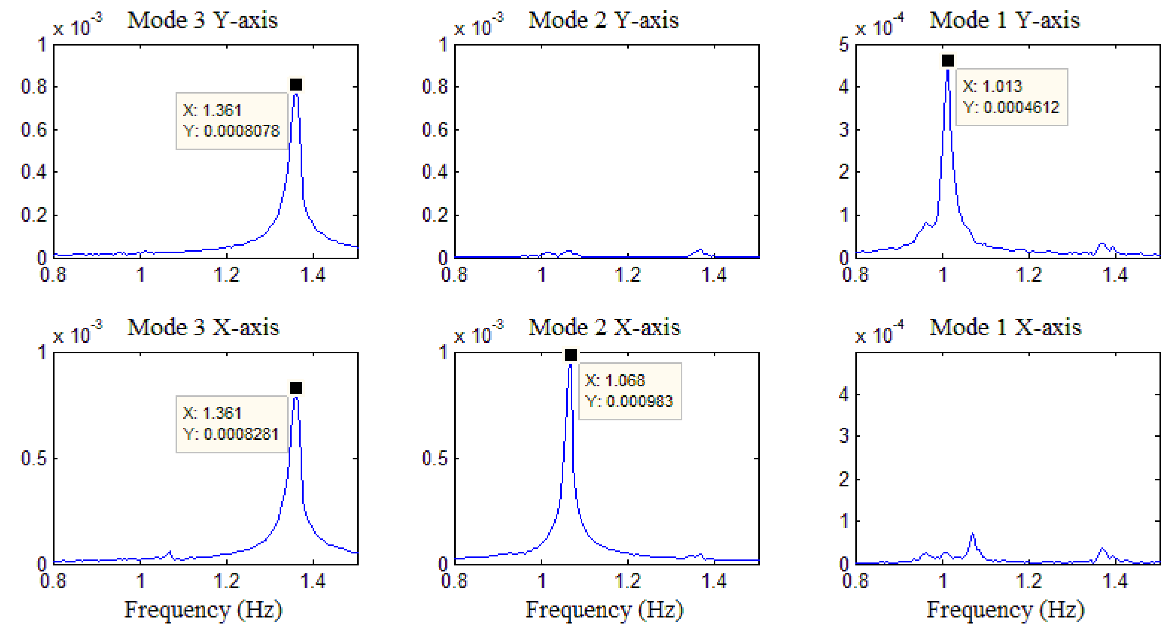

Figure 5: Averaged Frequency Domain of Human Excitation in Each Vibration Mode.

4 STRAIN MEASUREMENT UNDER HUMAN EXCITATION

Piezo-resistive type strain gauges, 40 gauges, are installed in expected high strain location, determined from numerical analysis as shown in Figure 6. Dynamic data acquisition system, measured at 200 Hz sampling rate with 16 channels available, is used in the measurement. As the number of channels is not adequate, the measurement is divided into 3 subtests with 4 reference gauges that have been in every test. Therefore, all subtests are united by normalization of the reference gauges.

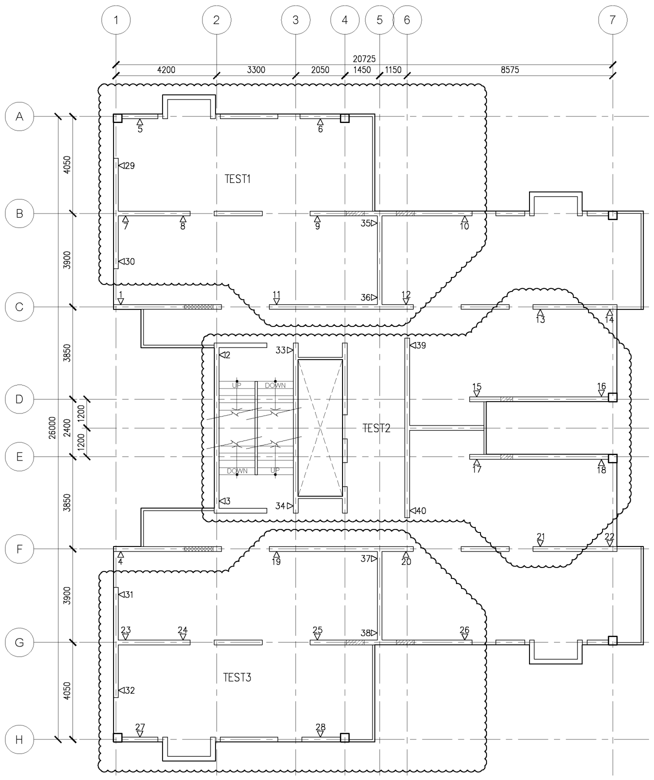

Figure 6: Strain Gauge Installed Location for Dynamic Strain Measurement

Before the attaching of the strain gauge, thin layer of epoxy resin is applied to provide more smoothness and to prevent air and moisture penetrate into the bonded surface between the strain gauge and the concrete wall surface. Thus, the cyanoacrylate glue, typically used for strain gauge installation on steel surface, which have high liquidity and fast setting time is used as an adhesive material instead of epoxy glue, typically used for strain gauge installation on concrete surface.

The acceleration measurement is also conducted in parallel to the dynamic strain measurement as the excitation can be monitored in real-time. It is also easier to capture the excitation timing from the acceleration time history. The same timing can be used when dynamic strain signal is processed using the same procedure as stated before to get the averaged frequency domain in each mode. In each subtest, the peak magnitude for each location is then normalized by the average of the reference locations measured in the same subtest.

Finally, the *modal strain signature* is created by fill-in the magnitude of normalized modal strain contour on the wall where the strain gauges are installed. The signatures are compared to the vertical modal stress pattern from modal analysis. Note that the colormap interpretation is different. The colormap from the modal analysis is also incorporated with the sign of the stress, meaning that the high tension and compression are shown at the two-opposite side extreme and the low magnitude is at the centre. Whereas, the colormap from the modal strain signature is the absolute value in comparison, meaning that the low magnitude is at the lower extreme and the high magnitude is at the higher extreme.

The comparison between vertical modal stress from numerical model and normalize modal strain pattern for the first mode (Y translation couple with torsion) is shown in Figure 7. For horizontal wall, the magnitude is low near the centre line and increasing together with the distance away. For vertical wall, the magnitude is higher near the central of the floor where the wall is close to the core while the lower magnitude is observed on the left where the wall is spread out in more distance.

The comparison of the second mode (X translation) is shown in Figure 8. In vertically plain view, the low magnitude occurs at the central while the magnitude is higher at further distance from the centre.

The comparison of the third mode (torsion couple with Y translation) is shown in Figure 9. The contour has shown in radial shape that has lower magnitude inside and increasing together with the radius.

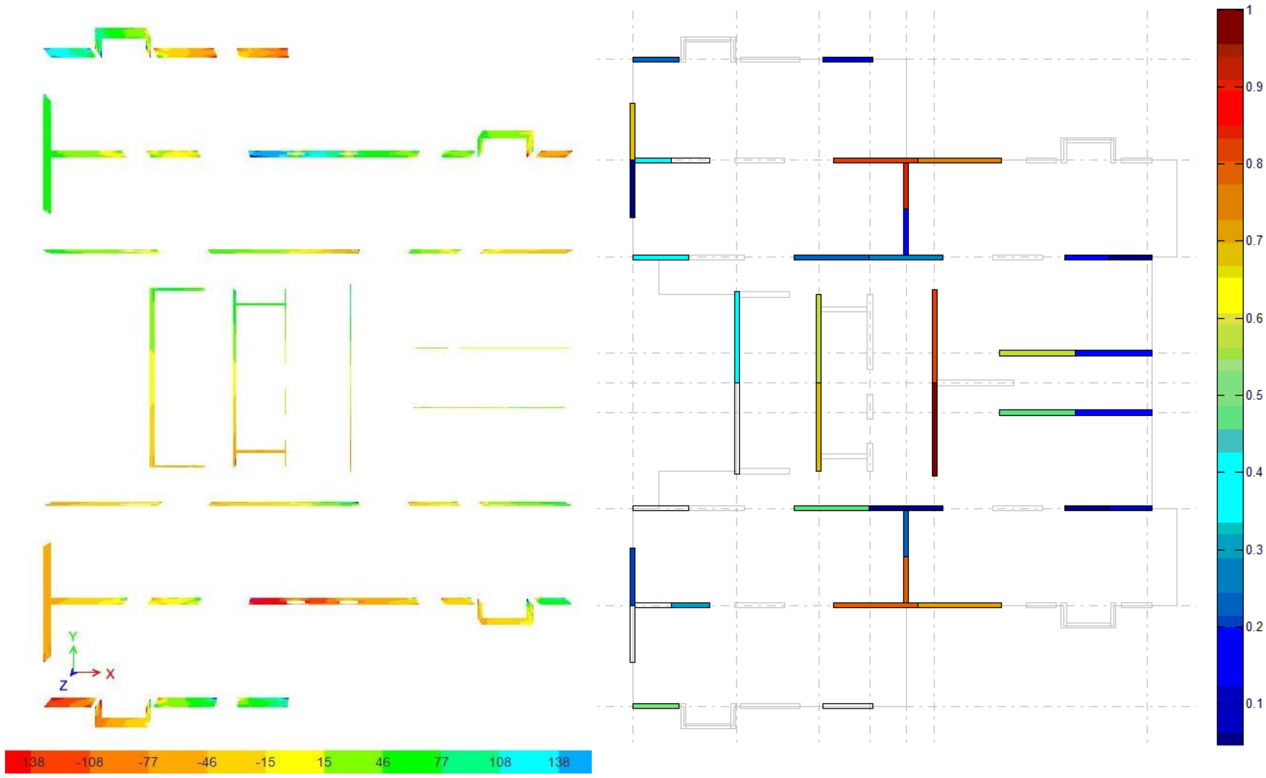

Figure 7: Comparision Between Vertical Modal Stress from Numerical Model (Left) and Normalize Modal Strain Pattern (Right) of Mode 1

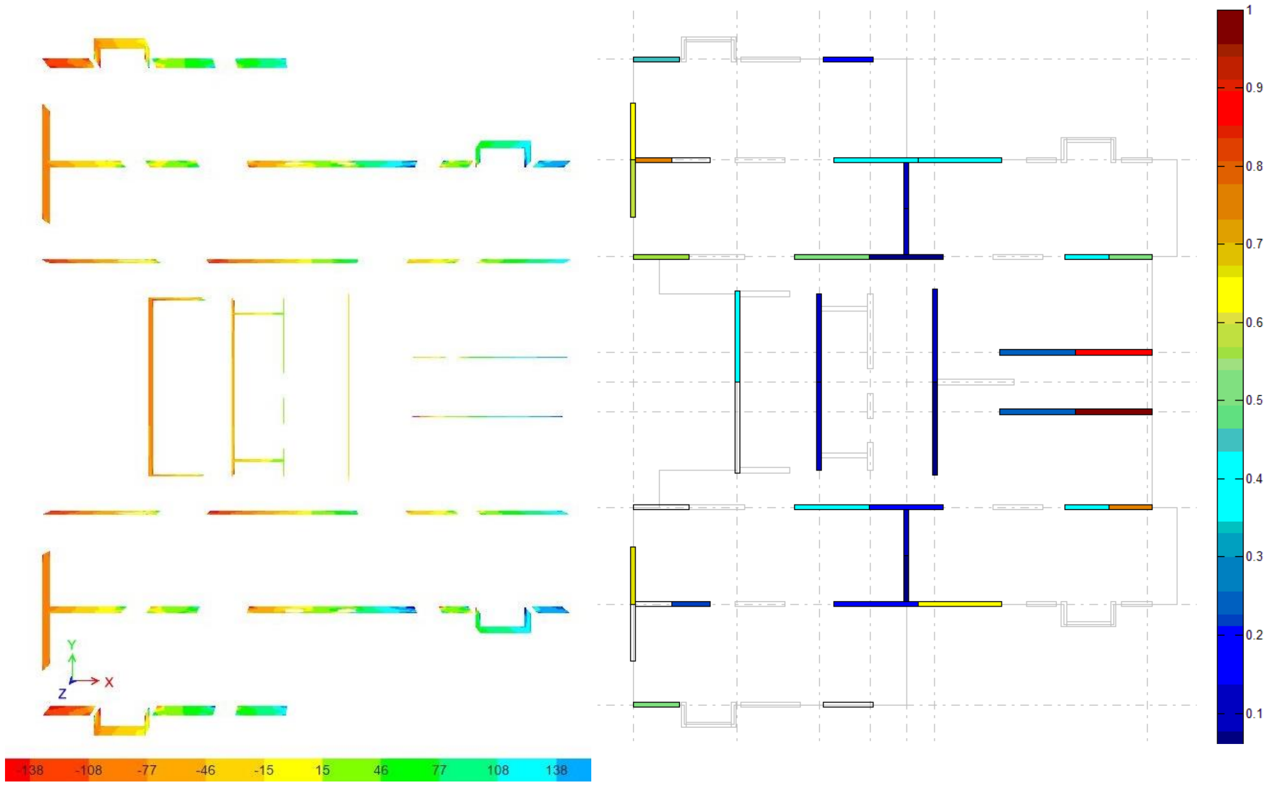

Figure 8: Comparison Between Vertical Modal Stress from Numerical Model (Left) and Normalize Modal Strain Pattern (Right) of Mode 2

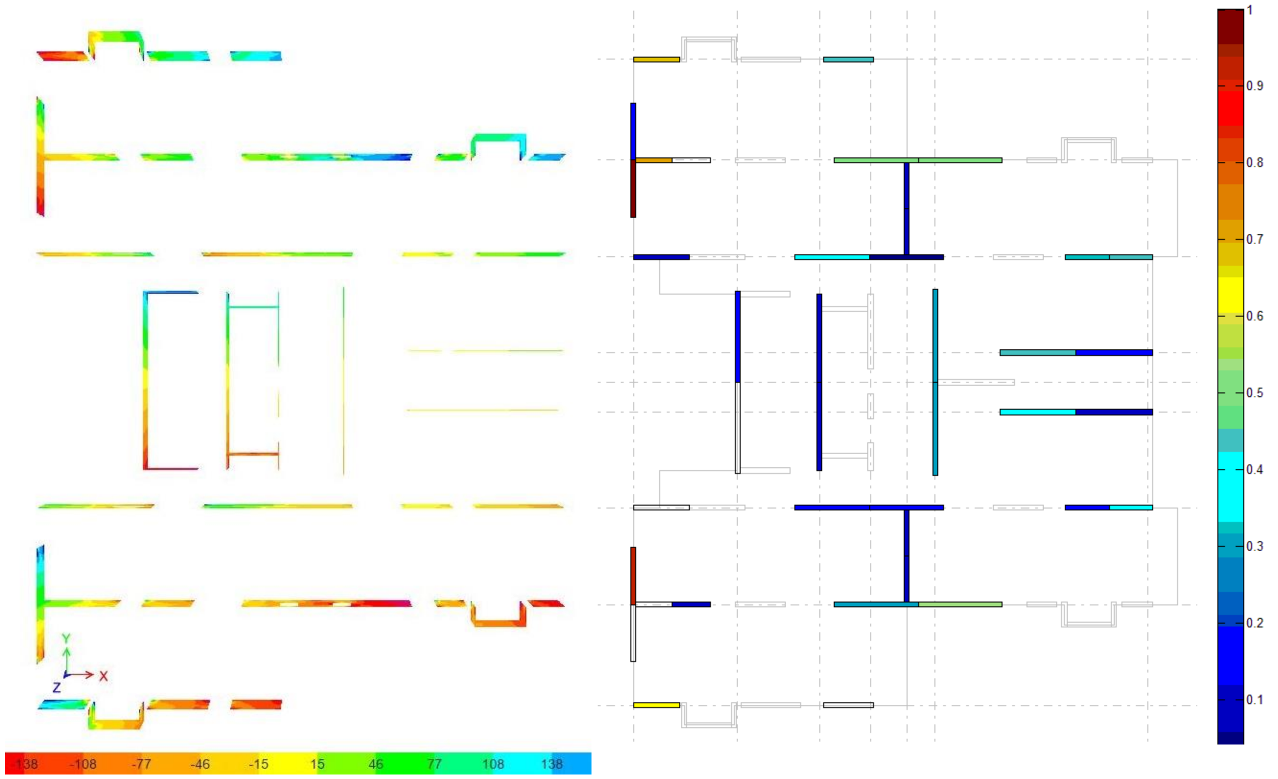

Figure 9: Comparision Between Vertical Modal Stress rom Numerical Model (Left) and Normalize Modal Strain Pattern (Right) of Mode 3

5 CONCLUSION

The numerical model of 26-story building is created in order to perform modal analysis. The ambient vibration measurement is conducted using acceleration approach in order to determine the natural frequency of the first fundamental vibration modes which are in the same range compare to the numerical analysis result. Dynamic strain measurement is performed while the building is under the resonance effect, triggering by human forces, synchronized by metronome. Piezo-resistive type strain gauges has enhanced the measurement resolution by its high sensitivity. Finally, the modal strain signatures are successfully created and show consistency to the vertical strain pattern extracted from the numerical model.

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