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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Dynamic Behavior of Connected Structures

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DOI: https://doi.org/10.30880/ijie.2022.14.06.033
Received 21 January 2022; Accepted 15 August 2022; Available online 20 November 2022

Abstract: The effect of connected structure on SMK Bukit Tinggi building was investigated based on their dynamic behaviour. The structure was constructed with four main buildings are interconnected. Ambient vibration testing (AVT) was used to predict the dynamic response and characteristics by using triaxial 1Hz seismometer and CityShark data logger. The AVT signals were analysed using GEOPSY software for Fourier Amplitude Spectral (FAS). All predominant frequencies (f_o) and mode shapes were identified and verified with previous research finding using similar testing approach on the same building, but with different instrument of accelerometer sensor and ARTeMIS software processing tool. Five modes of f_o were found from the FAS curves from this research, but only four f_o were obtained from ARTeMIS analysis. The highest deviation percentage was indicated at the 5th mode of building frequency at 9.5 %, but 0 to 2.5% to the rest frequencies mode (1st to 4th frequencies mode). Ununiformed buildings response behaviour was believed to contribute, and initiate active progressive shear cracking on the slab panels, columns, beam and at the reentrant corners between laboratory and academic buildings of Building C. It worst when the buildings were struck by several earthquakes' series. The unsynchronised oscillation between adjacent buildings to Building C had induced couple lateral and torsional deformations. The structural and non-structural damages mostly concentrated at the reentrant corners and mid-span of the building, which identical to the location of maximum deflection amplitudes. In conclusion, strict attention must be emphasized on the f_o and mode shapes based on their dynamic response and characteristics analyses, which could be altered by the presence of connected structures.

Keywords: Ambient vibration, connected structures, dynamic behaviour, predominant frequency, mode shapes

1. Introduction

Basic principles governing the conceptual design of a structures most refer to the structural configuration are uniformity, symmetry, torsional resistance and stiffness [1]. Twisting effect due to dynamic interaction could be resulted by single structural system which having a continuous multimassed buildings such in Fig. 1(b) and Fig. 1(d)

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[2]. However, the independent movement of multimassed buildings will be occurred if they are separated as in Fig. 1(a) and Fig. 1(c), but the movement is different due to difference in stiffness [2].

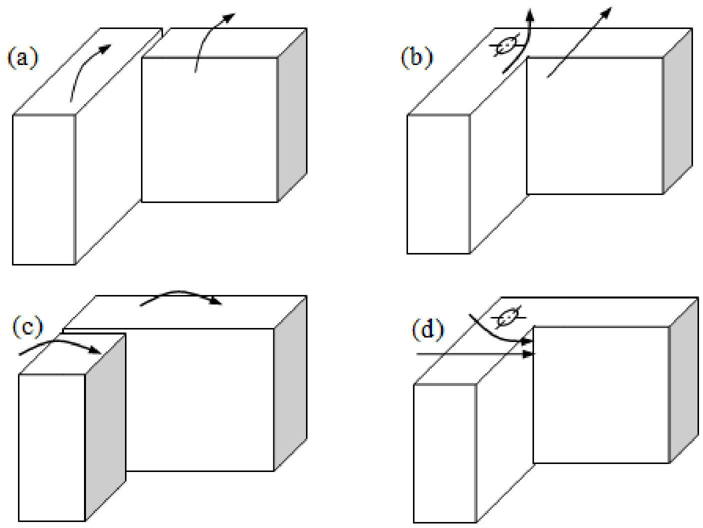

Fig. 1 - Seismic movements in multimassed buildings [2]

Friction between adjacent elements and cracking of important elements are the first cause of non-linear behaviour [3]. Stress concentration will occur at all point of discontinuity such as windows and door opening, changes in shapes of wall or connection between any separate parts of a building mass that must be studied to avoid for potential damage [2]. Thus, it is important for a building to function as an isolated in an urban complex, joints between it, and the adjoining building must be provided [4].

Frequencies are altered by the presence of adjacent buildings [5]. This is especially critical in situations where secure attachment between the structure and various nonstructural elements, such as windows glazing, can result in undesired transfer of force to the nonstructural elements as well [2]. From other study by Boutin and Hans [6], it has shown that the Eigen-frequency is modified by a systematic decreasing of frequency up to 10 %, when each adjoining building is removed (demolished).

According to Eze & Orie [7], adjoining building may have different fundamental periods and may vibrate out of phase with each other. In case of low rise and irregular plan shapes building with adjacent buildings, the identification of the f_o might be present of spurious frequencies coming from adjacent buildings [5]. Some caution might also be exercised for identification of modes, especially for the cases of low-rise buildings, for complex buildings or in cases of interaction either with adjacent buildings or with soil layers (the ambient vibration from soil may lead to spurious frequency attributed to the building) [3].

In order to determine the f_o, modern technologies through the ambient vibration testing allow in a short time (10 to 15 minutes) assessment of the translational dynamic properties of a single building, which then also able to conduct for a large number of constructions with only a limited effort is required [1]. Ambient vibration techniques are very robust to define building dynamic response (natural frequency, modal damping, and modal shape) and stiffness changes of a structure when as decrease of building natural frequencies it is always linked to a loss of stiffness [8]. However, it is important to place the sensors in a right place along the building's bays and floors so that all deformation modes either in translation or torsion could be obtained.

2. Methodology

2.1 Structures in SMK Bukit Tinggi

Bukit Tinggi secondary school is located at 3°21'17.35"N and 101°50'25.19"E. The school was constructed in 2002 and fully operational a year later. The enrolment of students currently achieved up to 240 students. Fig. 2 indicates elevations of four buildings in SMK Bukit Tinggi. All low-rise school buildings in SMK Bukit Tinggi were conventionally designed using reinforced concrete frame. The school was designed by Public Works Department Malaysia (JKR) based on the standard reinforced concrete design with typical building configuration. It has 3.60 m storey height, 3.00 m spacing between bays, 7.50 m building width, and 2.10 m length of cantilever corridor balcony with 1.05 m of parapet wall height. Each building is geometrically different and irregular in terms of its number of storey and room functions. The edges between buildings were connected. These building consist of the administration office, classrooms, and laboratories, whereas the single block building is for workshops.

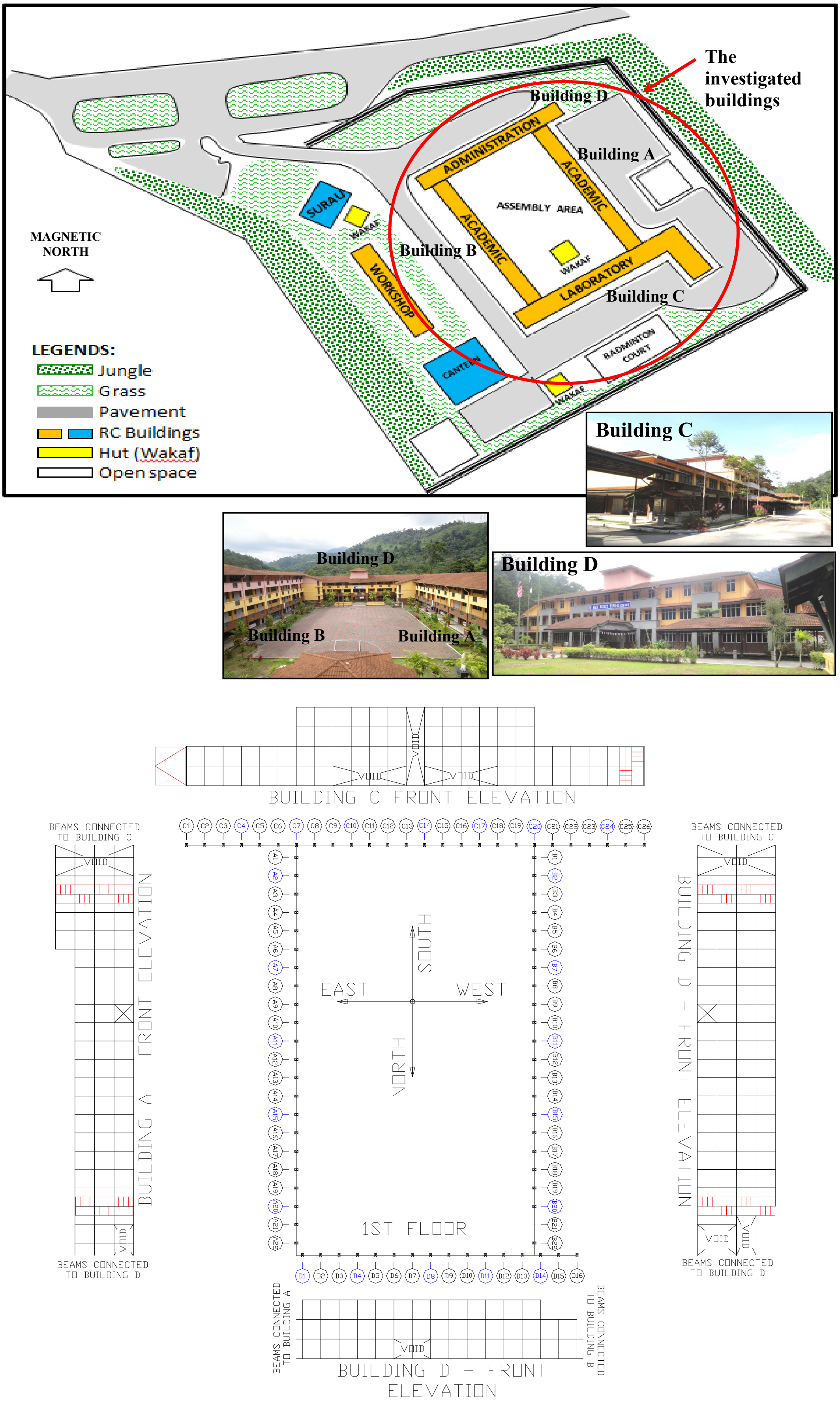

Fig. 2 - Buildings Layout in SMK Bukit Tinggi

2.2 Observation on Partially Damaged Building (Building C)

The first earthquake struck in Bukit Tinggi with the magnitude of 3.5 M_b (body wave magnitude) dated 30th November 2007 at UTC time 2.13, and continuously stroke to the maximum ever felt on 7th October 2009 at UTC time 21:51 with 4.2 M_b [10]. Approximately 27 earthquake events were felt until 4th December 2009, and the closest epicenter was located only 4.5 km away from SMK Bukit Tinggi (see Fig. 3).

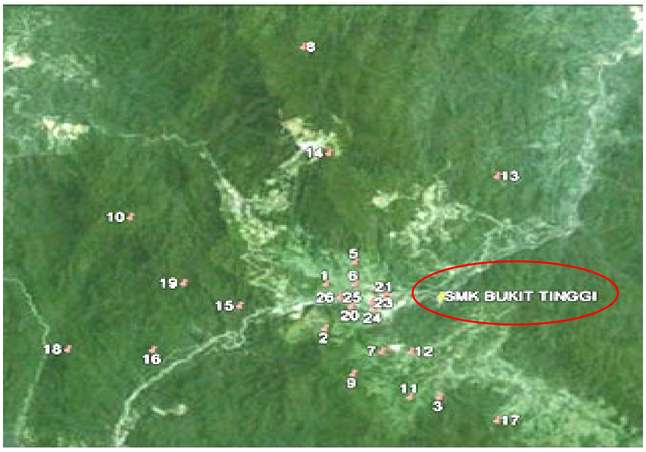

Fig. 3 - Earthquake epicenters in Bukit Tinggi region based on the local earthquake events from 30th November 2007 until 4th December 2009

The earthquake has caused panic to residents due to the tremors and a few buildings have several cracks including SMK Bukit Tinggi [11], [12]. No damage report was issued to other buildings (Building A, Building B and Building D). The information of the damages on Building C, and its damages sequence were collected via initial visitation and site observation made in October 2012 and followed by detailed ambient vibration test in January 2013. A briefing was also given by a school staff on the chronology of earthquake event and the sequence of damages observed from the school Building C (refer Table 1). However, none of the damages were reported by other buildings (Building A, Building B and Building D) after the earthquake events.

Table 1: Chronology of damages and type of structural failures on Building C [13]

Years	Events
2002	Completion of SMK Bukit Tinggi (Building A, Building B, Building C and Building D)
2003	Buildings are fully occupied and operated
2007	First earthquake tremor felts. Some cracking on side drain of 4-storey building were identified. Education District Office (PPD) and District JKR came for investigation.
2008	Cracking was expanded to Building C at level 3 and 4. Stagnant water is identified inside the cracked slab on the ground floor. Again, the officer from PPD and JKR District came for further investigation. Repairing work was carried out by filling up the cracked with concrete
2009	Repairing works was continued by patching on the cracked surfaces.
2010	Two columns at parking area were suddenly collapsed. PPD and JKR District came and investigated and all columns along the corridor path and parking area were removed. Meanwhile, the rest columns are mounted with steel angle-bracket.
End 2010	Severe cracking was identified in the art room and 3A2 classroom (at level 3 and 4). Due to that, PPD and JKR District, and JKR Putrajaya came for further investigation due to continuous cracking issue was still occurred.
July 2011	JKR Forensic Kuala Lumpur came for detail investigation on the structure.
2012	Visitation by PPD District due to the collapse of parapet wall between classes block and laboratory block (Building B and Building A). A letter for immediate repair was issued

To avoid for any casualties, the building is sealed for further investigation and rehabilitation. Fig. 4 shows the damages observed in 2013 of Building C and cracking images of structural and non-structural components. A point of worth noting is most standard schools in Malaysia are absent of the expansion joints between adjacent buildings, to induce the undesirable strain and movement hence leading to structural damage especially in seismicity region. Ununiformed buildings response behaviour was believed as the main factor which initiated to progressive shear cracking on the slab panels, columns and beams that concentrated at the reentrant corners between laboratory and academic buildings triggered by previous earthquakes. Besides, the shear cracks on the brick wall also can be seen along the access (void) at the center of the laboratory building, at every floor level. From visual observation made on the connecting academic buildings (Building A, Building B and Building D) are free from any damages.

Shear crack at column (photo was taken from the 3rd floor)

Slab cracks at joint to adjacent building (photo was taken on the 3rd floor)

Sealed slab (photo was taken from the 2nd Floor)

Cracking failure of slab, beam and column (photo was taken from the 2nd Floor)

Cracks and sealed brick wall (photo was taken on the 1st floor)

Sealed slab (photo was taken from the 1st floor)

Fig. 4 - Structural and non-structural cracks and repairs at Building C of SMK Bukit Tinggi

2.3 Ambient Vibration Measurement and Analysis

In this research, ambient vibration instrument was used to measure the microtremor recording for the buildings' responses. The instrument comprises of three units Lennartz portable tri-axial seismometer (velocitimeter) of 1 Hz eigenfrequency sensors (S) and 400 V/m/s output voltage, a 24 bit CityShark II digital acquisition system with 3 input sensors, and 1 GB memory flash card data storage. ReadCity software was used to extract the ambient vibration data which has been recorded by CityShark data logger.

AVT was carried out along the building corridor and closer to the beam-column joint. The seismometer sensor was aligned in horizontal and vertical sensor arrangements. Due to limited accessibility time for the fieldwork, only selected beam-column joints and floors were chosen for dynamic characteristic investigation (f_o and mode shape). The details of all sensor orientations and positions in each measurement which were carried out in Building A, Building B, Building C, and Building D are given in Fig. 5 to Fig. 7 and their arrangement are tabulated in Table 2 to Table 5.

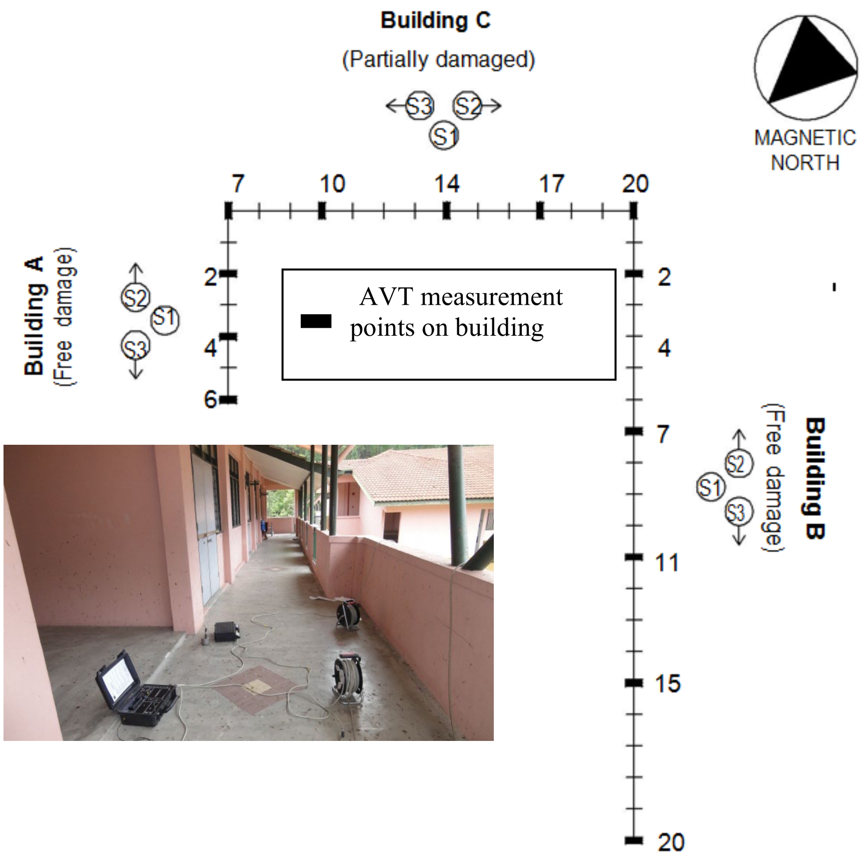

Fig. 5 - Ambient vibration testing and location of the measured beam-column joints on the 3rd floor of Building A, Building B and Building C

Table 2 - Arrangement of S1, S2 and S3 in vertical sensors arrangement at Buildings A, Building B, Building C and Building D

Vertical Sensors Orientation				
Measurement No.	**Position of Sensor**			**Column**
	S1	**S2**	**S3**	
23,24,25,26,27,28,29,30,31,32.	3F 3F	2F 2F	1F GF	**Building C:** **C1, C4, C8, C11, C14**
33,34,35,36,37	3F	2F	GF	**Building B:** **B2, B7, B11, B15, B20**
38,39,40,41,42	3F	2F	GF	**Building D:** **D1, D4, D8, D11, D14**
43	3F	1F	GF	**Building A: A2**
44,45,46,47	2F	1F	GF	**A7, A11, A15, A20**

Table 3 - Arrangement of S1, S2 and S3 in horizontal sensors arrangement on the 3rd floor for Building A, Building B and Building C

Horizontal Sensors Orientation – 3rd Floor							
Building	**Measurement No.**	**File No**	**Gain**	**Time**	**S2**	**S1**	**S3**
C	1	606	1024	9.25	C11	C8	C4
	2	607	1024	9.47	C14	C8	C1
B	3	609	512	11.06	B7	B11	B15
	4	610	512	11.27	B2	B11	B20
A	5	608	512	10.39	A2	A4	A6

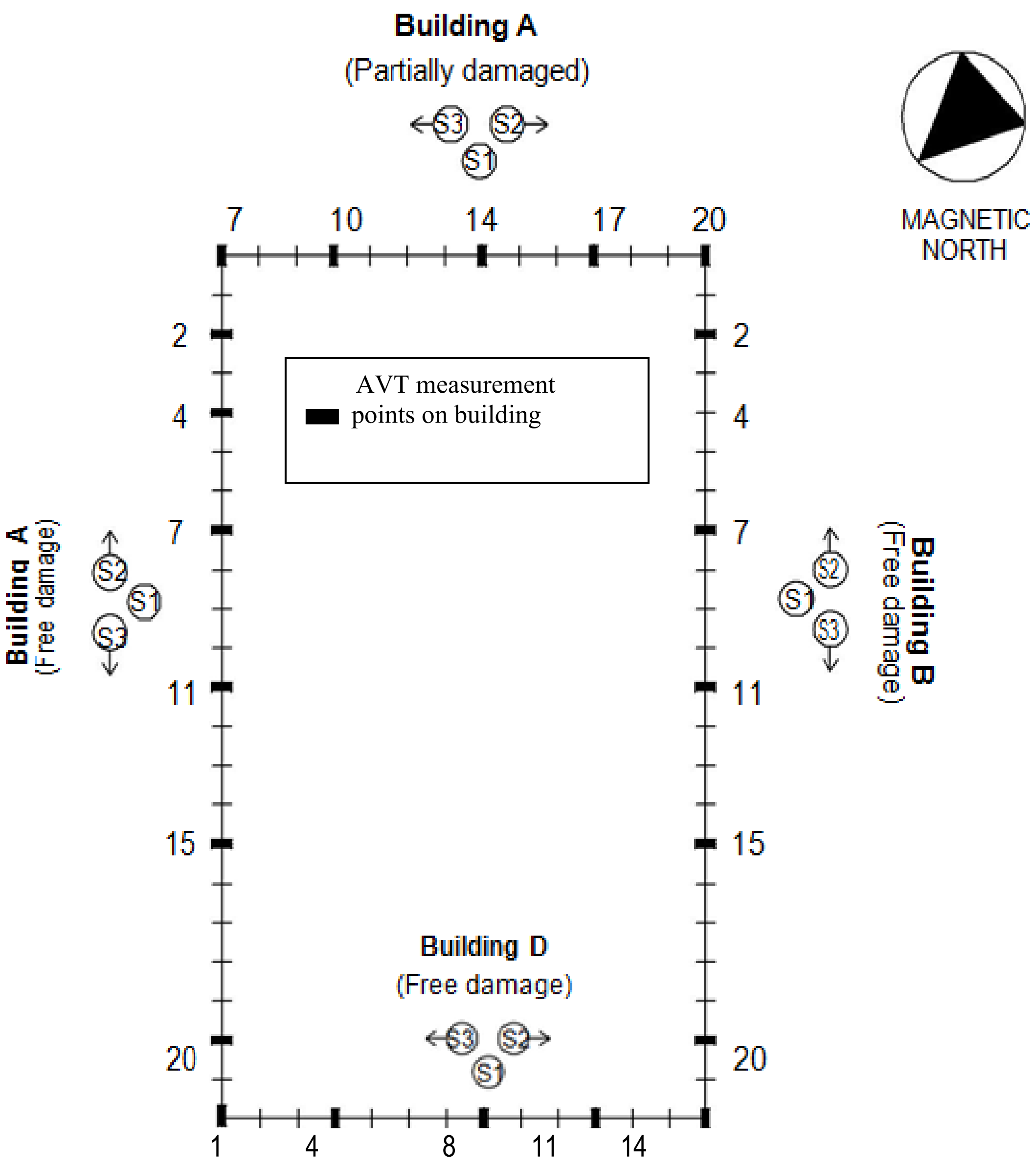

Fig. 6 - Location of the measured beam-column joints on the 2nd floor of Building A, Building B, Building C and Building D

Table 4 - Arrangement of S1, S2 and S3 in horizontal sensors arrangement on the 2nd floor for Building A, Building B, Building C and Building D

Horizontal Sensors Orientation – 2nd Floor							
Building	**Measurement No.**	**File No**	**Gain**	**Time**	**S2**	**S1**	**S3**
C	M6	611	1024	12.28	C11	C8	C4
	M7	612	1024	12.28	C14	C8	C1
A	M8	613	512	13.27	A7	A11	A15
	M9	614	512	13.53	A2	A11	A20
D	M10	617	512	19.02	D4	D8	D11
	M11	618	512	19.22	D1	D8	D14
B	M12	615	512	17.59	B7	B11	B15
	M13	616	512	18.28	B2	B11	B20

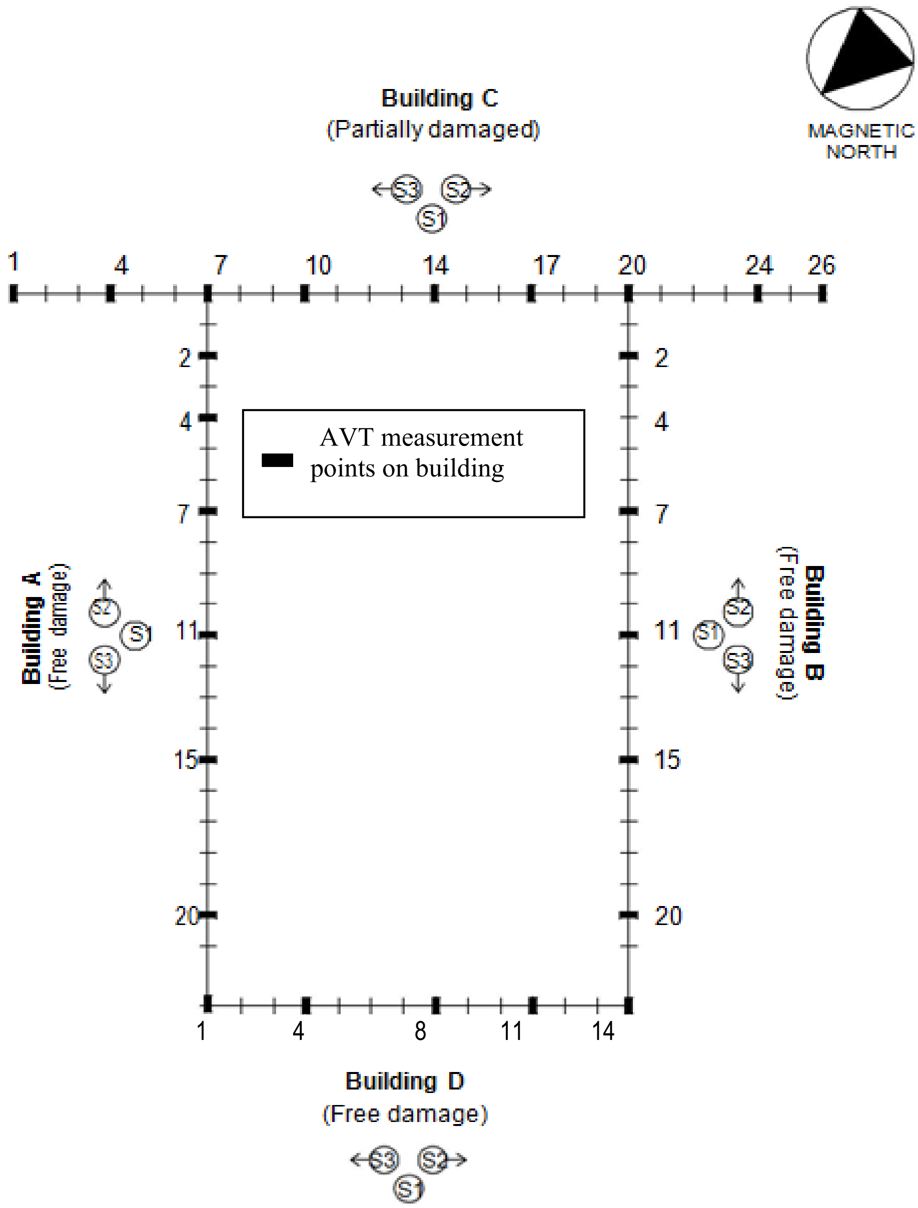

Fig. 7 - Locations of the measured beam-column joints on the 1st floor of Building A, Building B, Building C and Building D

Table 5 - Arrangement of S1, S2 and S3 in horizontal sensor arrangement on the 1st floor for Building A, Building B, Building C and Building D

Horizontal Sensors Orientation – 1st Floor							
Building	**Measurement No.**	**FI**	**G**	**Time**	**S2**	**S1**	**S3**
C	M14	619	1024	8.54	C17	C14	C10
	M15	620	1024	9.14	C20	C14	C7
	M16	621	1024	9.34	C24	C14	C4
B	M17	622	1024	9.59	B7	B11	B15
	M18	623	1024	10.18	B2	B11	B20
D	M19	624	1024	10.52	D4	D8	D11
	M20	625	1024	11.20	D1	D8	D14
A	M21	626	512	11.46	A7	A11	A15
	M22	627	512	12.19	A2	B11	A20

All ambient vibration signals from the seismometer instrument used in this research were automatically converted into FAS via GEOPSY software. The conversions of FAS from three components of North South (NS), East-West (EW) and Vertical (UD) ambient vibration time histories requires several processes such as signal corrections, sampling window selections, signal filtering, computation of Fourier spectra curves, calculations of mean and standard deviation. The modal frequencies are determined with the peak peaking method [14], from the spectra amplitude obtained through Fast Fourier Transform (FFT) applied to each window of the three signal components processed using the open-source software of GEOPSY [8]. From the output of the FAS curves, the discussions were focused on specific dynamic behaviours based on the main parameters of f_o and their respective mode shapes. Deformation shapes of the building are plotted via respective mode shapes of f_o such as translational or torsional deformation. Illustrations of mode shapes at respective f_o will explain the influence of the adjacent building, mass and geometric irregularities. Besides, comparative findings were also made against the prediction of f_o only on Building C based on the output of f_o from FAS curves produced by GEOPSY software against different instrument of accelerometer sensors and processing tool of ARTeMIS, based on similar testing of ambient vibration carried out by Ibrahim et al. [9].

3. Results and Discussions

3.1 Predominant Frequencies

Several peak frequencies were found from the evaluation made on the FAS curves from the NS and EW directions of Building A, Building B, Building C and Building D which are extracted as in Table 6. Five f_o were significantly dominated at Building C in two main deformation shapes which are translational (4.21 Hz and 8.66 Hz) and torsional (5.17 Hz and 6.35 Hz) in their respective transverse (parallel to NS direction) and longitudinal (parallel to the EW direction) axes of Building C.

Table 6 - Predominant building frequencies of Building A, Building B, Building C and Building D

Appearance Ranges	Building A (Free damage)		Building C (Damaged)		Building B (Free damage)		Building D (Free damage)	
	NS Direction	EW Direction	NS Direction	EW Direction	NS Direction	EW Direction	NS Direction	EW Direction
	Longitudinal Axis	Transverse Axis	Transverse Axis	Longitudinal Axis	Longitudinal Axis	Transverse Axis	Transverse Axis	Longitudinal Axis
4.21 to 4.66 Hz	4.21 Hz *(Adjacent freq.- Building C and D)*	4.35 Hz *(Adjacent freq.- Building C and D)*	4.21 Hz **(max)**$^{(1)}$ (Translational)	4.21 Hz$^{(2)}$ (Translational)	4.35 Hz **(max)**$^{(2)}$ (Translational)	4.21 Hz **(max)**$^{(1)}$ (Translational)	4.66 Hz **(max)**$^{(1)}$ (Translational)	-
5.17Hz	5.17 Hz **(max)** *(Adjacent freq- Building C)*	-	-	5.17 Hz **(max)**$^{(3)}$ (Translational)	-	-	-	-
6.14 to 6.58 Hz	6.58 Hz$^{(2)}$ (Translational)	6.14 Hz **(max)**$^{(1)}$ (Translational)	6.35 Hz$^{(4)}$ (Torsional)	-	6.35 Hz - **NSig** (Translational)	-	6.35 Hz (Translational - *Adjacent freq- Building A)*	6.14 Hz **(max)** (*Adjacent freq. freq.- Building A*)
7.29Hz	-	7.29 Hz - **Nsig** (Torsional)	-	-	-	7.29 Hz - **NSig** (Torsional)	-	-
8.08Hz	8.08 Hz - **NSig**	-	-	-	-	-	-	8.08 Hz$^{(2)}$ (Translational.)
8.66 to 8.96 Hz	-	-	8.66 Hz$^{(5)}$ (Translational)	-	8.96 Hz - **NSig**	8.66 Hz - **NSig**	8.65 Hz - **NSig**	-
9.59Hz	-	9.59 Hz - **NSig**	-	-	-	-	-	-

Max : Maximum amplitude frequency, (i=1,2,3,4,5) : Mode of frequencies, N_{Sig} : No significant peak curve frequency appeared in the NS or EW directions

Closer f_o prediction was given between FAS curves, and Ibrahim et al. [9] finding based on the analysis made via processing tool of ARTeMIS using Enhanced Frequency Domain Decomposition (EFDD) method and Stochastic Subspace Identification (SSI) method. According to the author, the f_o were found at 4.21 Hz, 5.04 Hz and 8.17 Hz of Building C which clearly indicated by the peak frequencies spectrum of EFDD, and SSI as respectively given in Fig. 8(a) and Fig. 8(b). From the result comparison made, it shows small percentage of different with less than 10 % as computed in Table 7.

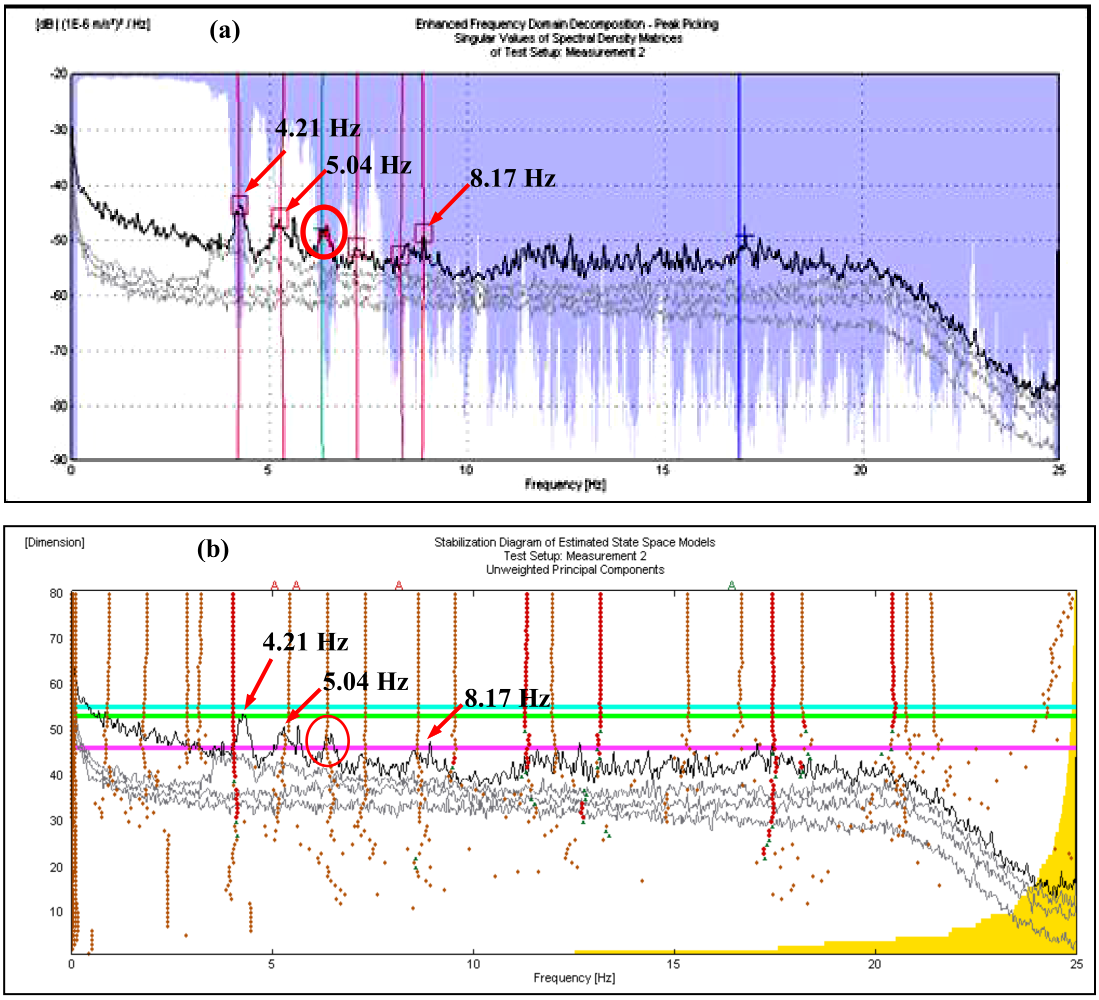

Fig. 8 - Peak picking of building frequencies from (a) EFDD spectrum, and (b) SSI spectrum from ARTeMIS software [9]

Table 7 - Deviation percentage of f_o between FAS method and ARTeMIS predictions

	1st mode	2nd mode	3rd mode	4th mode	5th mode
This research	4.21 Hz (NS)	4.21 Hz (EW)	5.17 Hz (EW)	6.35 Hz (NS)	8.66 Hz
Ibrahim et al. [9]	4.21 Hz		5.04 Hz	-	8.17 Hz
Deviation percentages	0 %		2.5 %	-	9.5 %

Several peak frequencies have been reported from the FAS analysis compared to the SSI and EFDD methods from ARTeMIS software. However, the existence of additional modes of f_o at Building C could be supported by a few reasons (4th mode). The building is restrained at both ends by adjacent buildings in transverse direction (by Building A and Building B). Thus, extra attention must be given to avoid false choice of f_o in investigating the dynamic behaviour of respective buildings. Besides, it is also influenced by other uncertainties such as below:

- Irregular building geometry
- Irregular mass due to the different room's functions and the existence of soft storey,

- Various distributions of ground resonance frequencies beneath respective buildings.

3.2 Mode Shapes

Fig. 9 to Fig. 12 show the mode shape illustrations of Building A, Building B and Building C at respective f_o of 4.21 Hz, 5.17 Hz, 6.35 Hz and 8.66 Hz. These natural frequencies are taken from the f_o observed from Building C. Similar deflection amplitude at these f_o are also analysed for Building A and Building B to evaluate the influence of the connected buildings (Building A and Building B) against Building C.

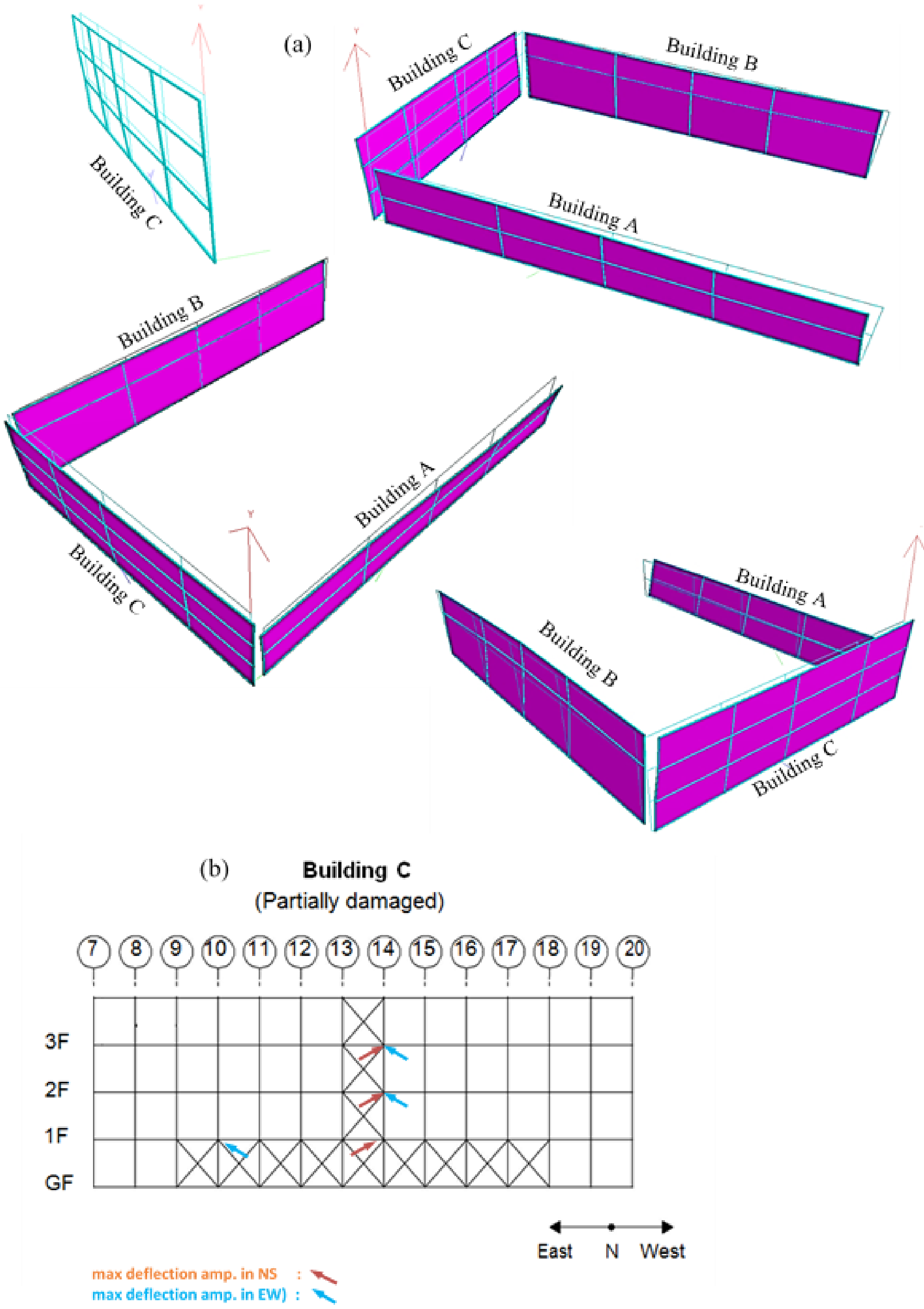

Fig. 9 - Illustrations of (a) 3-dimensional mode shape of SMK Bukit Tinggi at the 1st and 2nd predominant building frequency of 4.21 Hz, and (b) positions of the maximum deflection amplitude

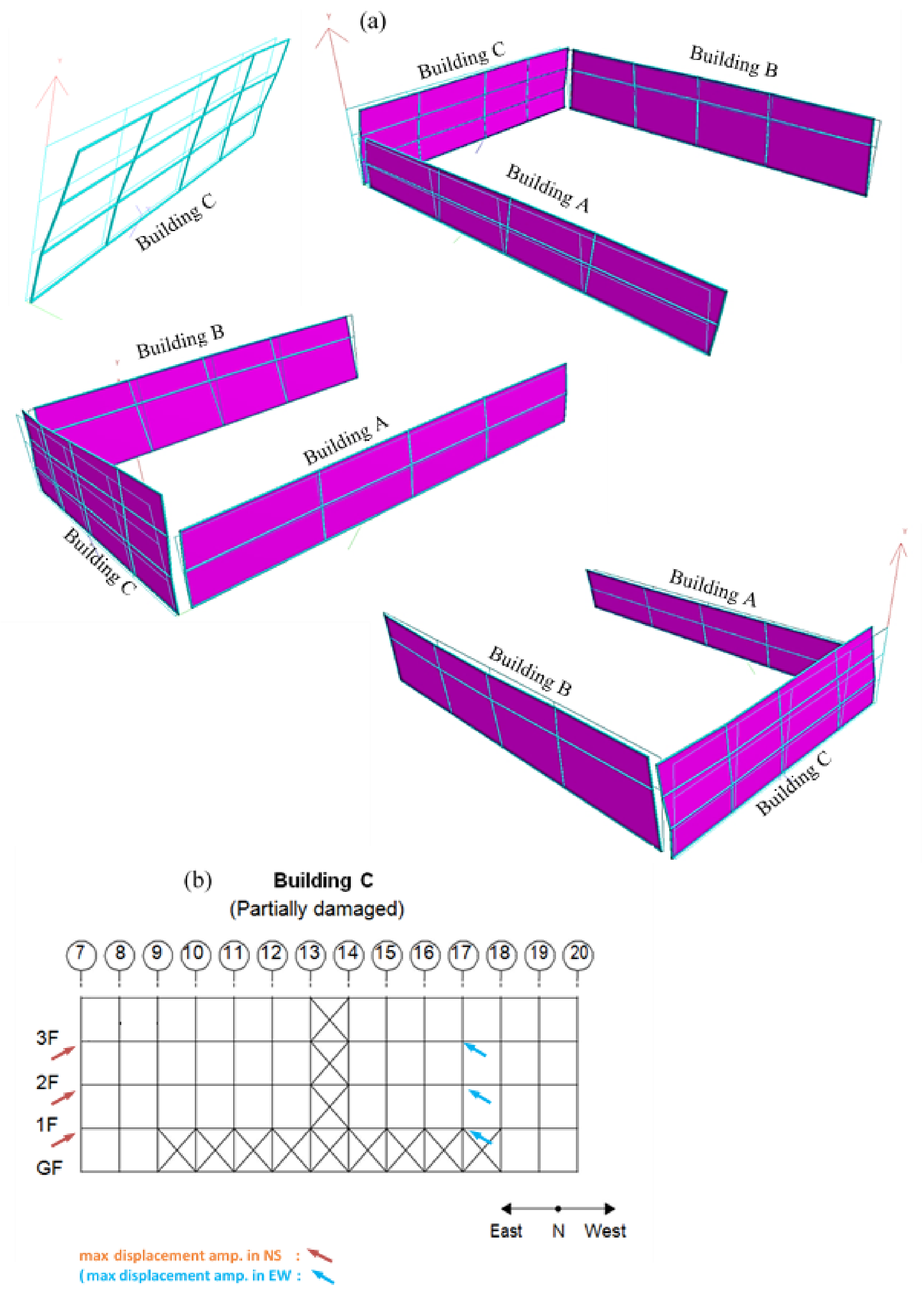

Fig. 10 - Illustrations of, (a) 3-dimensional mode shape of SMK Bukit Tinggi at the 3rd predominant building frequency of 5.17 Hz and, (b) positions of the maximum deflection amplitude.

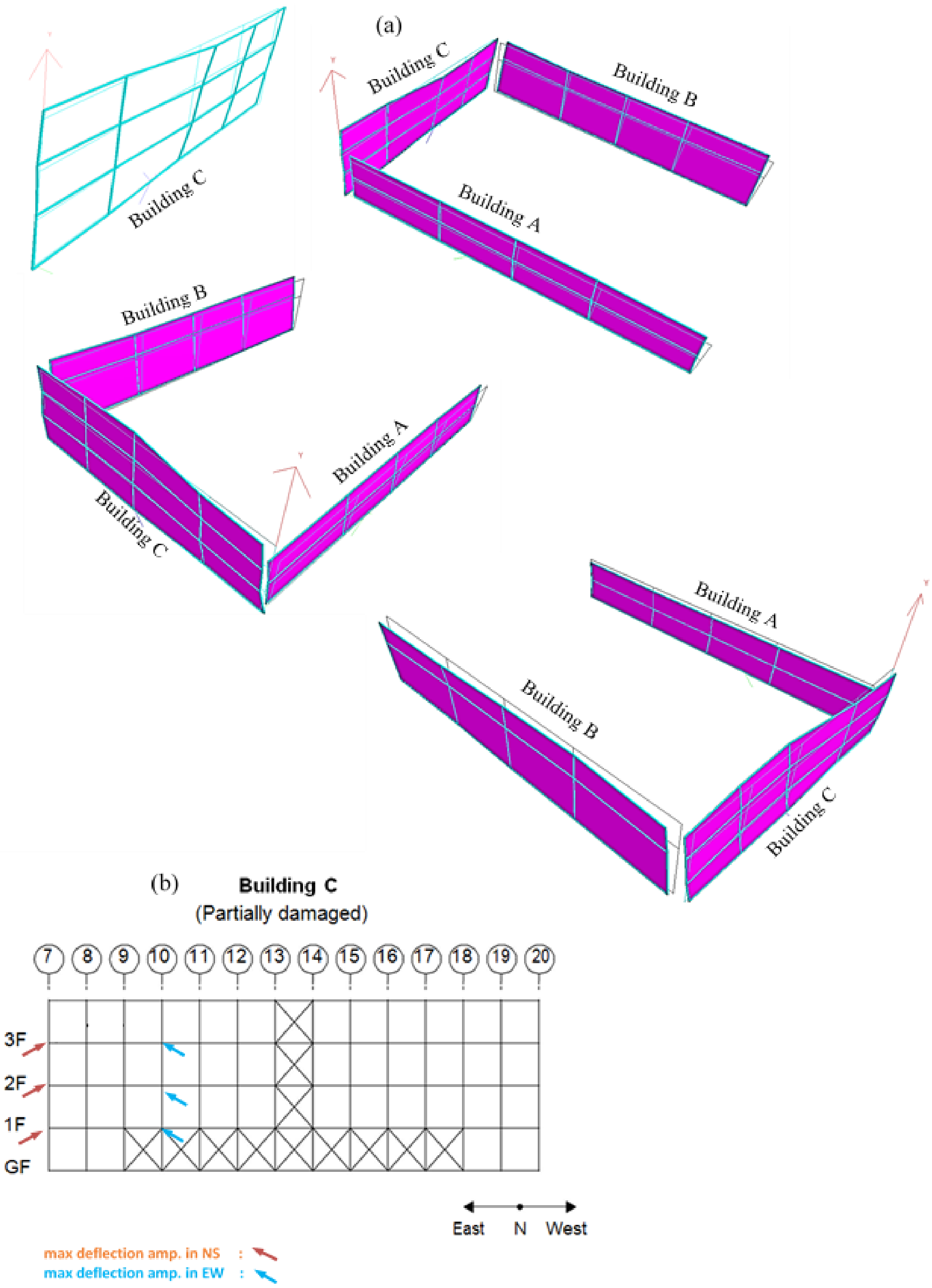

Fig. 11 - Illustrations of, (a) 3-dimensional mode shape of SMK Bukit Tinggi at the 4th predominant building frequency of 6.35 Hz and, (b) positions of the maximum deflection amplitude

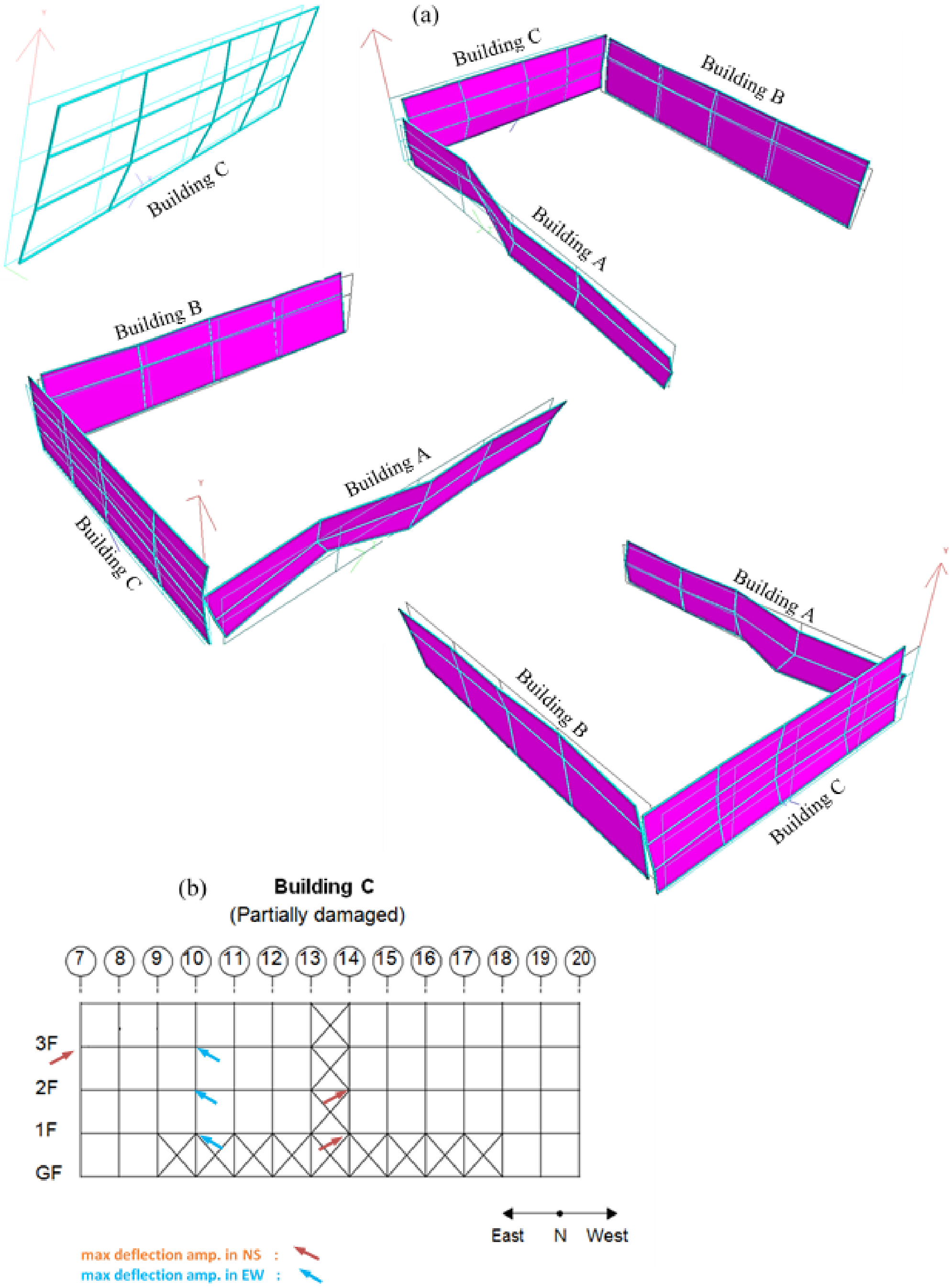

Fig. 12 - Illustrations of, (a) 3-dimensional mode shape of SMK Bukit Tinggi at the 5th predominant building frequency of 8.66 Hz and, (b) positions of the maximum deflection amplitude

3.3 Discussions

Structures are never perfectly regular; hence the designers routinely need to evaluate the likely degree of irregularity and the effect of this irregularity [15]. Multiple vibration modes are clearly observed from the FAS curves obtained on the measured building in SMK Bukit Tinggi. Difference configurations in terms of floor level and number of bays of Building A, Building B, Building C, and Building D create multiple building responses on respective f_o. Difference oscillations of Building C against respective motions of f_o by Building A and Building B created the unsynchronized movement between each building. In this case, Building C is more vulnerable due to the weaknesses of its building configurations (presence of soft storey and irregular mass concentration) compared to the adjacent buildings resulting in higher structural damages (see Fig. 13).

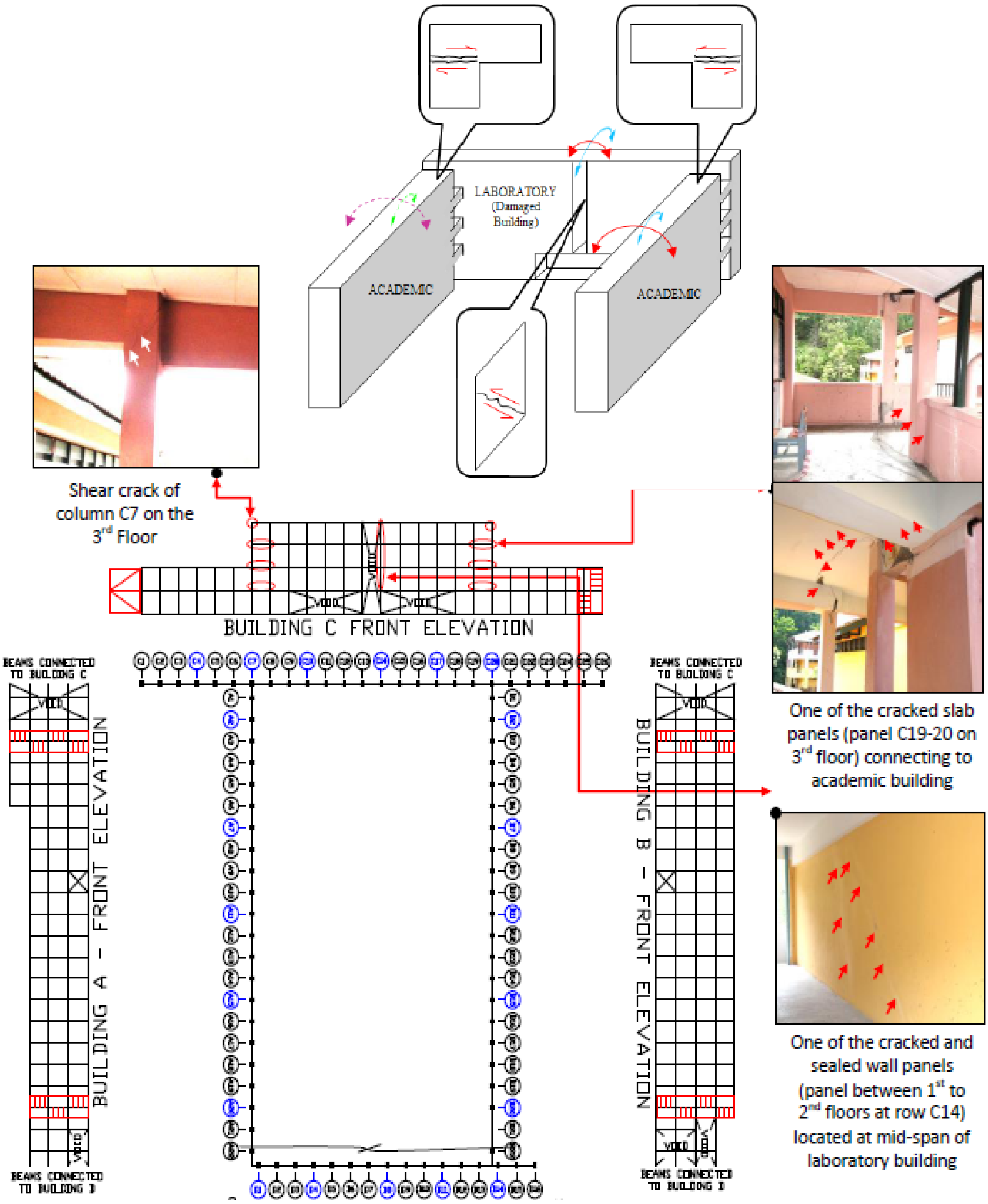

Fig. 13 - Location of structural damages and oscillations of Building A, Building B and Building C, SMK Bukit Tinggi

The first modes of vibration (translational) for Building C was found at 4.21 Hz in both transverse (NS) and longitudinal (EW) directions. The translational mode shapes at 4.21 Hz indicated maximum deflection amplitudes mostly concentrating at the mid span (at column C14) for every floor. This is due to the influences of concentration of storey mass, unrestrained condition by adjacent building, existence of soft storey area on ground floor and corridor access with the void compartment at every floor. Uniform mass orientation produces the least relative displacement amplitude compared to the other mass irregularities [16].

Meanwhile, the torsional behaviours of Building C were showed at 5.17 Hz and 6.35 Hz. It was observed that the fifth f_o was also found at 8.66 Hz. The torsional mode shape is clearly observed on the third f_o of 6.35 Hz at Building C. When Building A and Building B experience translational deformation at 6.35 Hz along respective longitudinal axis

(EW direction), Building C experiences torsional mode shape with excessive deformation at the middle of building (between columns C10 to C14) along its transverse axis (NS direction).

Differences vibration modes with the corresponding f_o from Building C and its adjacent buildings, contributed to structural vulnerability due to the irregularity's response of the buildings. When the building complex, various parts of the building may tend to move differently which can produce critical stress at the points of connection between the parts of the buildings [2]. The existence of soft storey on the ground level and open access (corridor) on the mid-span at every storey of Building C could create vulnerable potential on the weaken areas. Stress concentration occurs at all points of discontinuity such as window and door opening, changes in shape of a wall, or connections between any separate parts of building mass [2].

Most of the damages are also concentrated at the reentrant corners between Building C and adjacent buildings (Building A and Building B), as well as at the partition wall located at the mid span of building. Continuous frame between the laboratory (Building C) and both academic buildings (Building A and Building B) without provision of separations (expansion joint) does not allow the buildings to behave independently. The types of failures on columns, beams, slabs panels and brick walls are identified as shear failure. It is desirable to use seismic separation or expansion joint to divide the buildings into independent parts which may provide a regular seismic behaviour [17]. According to FEMA 454 [18], stress concentrations can be created by both horizontal and vertical stiffness irregularities, whereby in plan configuration the reentrant corners is the most likely subjected to produce higher stress concentrations.

According to Eze and Orie [7], adjoining building may have different fundamental periods and may vibrate out of phase with each other. There is no specific evident from previous report by the school administrator on the main reason that contributes to the structural damages on Building C. It is expected repetitive oscillation against these f_o could increase the width of diffused creep damages of building due to the growth of stress concentration at these vulnerable regions.

4. Conclusion

Ambient vibration analysis successfully carried out in this research for investigation dynamic behaviour on the connected buildings in SMK Bukit Tinggi. Different building configurations could govern to the modification of f_o and mode shapes for Building C. Translational and torsional mode shapes are clearly observed from respective buildings deformation. The adjacent buildings could excite spurious frequencies to Building C which created uneven oscillations and induce structural and nonstructural damages. This building experienced unsynchronized oscillations due to the influence adjacent buildings. It clearly proven by severity of structural failures found at the reentrant corners as well as at the partition wall located at the mid span of building due to excessive deflection amplitudes and high-stress concentration.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot H905). The authors would like to acknowledge and expressed gratitude to all Structural Dynamic & Computational Engineering, JRC research members for their great cooperation to the accomplishment of this research.

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