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Article

Sustainable Development of Elevated Shell Platform

Azizah Abdul Nassir[a], Yee Hooi Min[b,*], Syahrul Fithry Senin[c], Woo Yian Peen[d]

School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, Pulau Pinang 13500, MALAYSIA
E-mail: [a]azizahnassir@yahoo.com, [b,*]minyh@uitm.edu.mym (Corresponding author), [c]syahrul573@uitm.edu.my, [d]wy.peen@uitm.edu.my

Abstract. Shell structure has a unique thin, curved plate shaped yet strong enough to transmit applied forces by compressions but only being constructed as a roof structure with minor external load applied onto it. The objectives of this research are to study the feasibility in proposing elevated shell platforms in resisting heavy loading, to investigate the effect of shell geometric on elevated shell platforms and to identify the suitable shell geometric as economic and sustainable in construction development. Five different geometries of shell structure have been proposed which are dome, cone, pendentive, clam shape and leaf-like shape. LUSAS software has been used to analyze the different geometries of the shell and study the effect of stresses and deformation. The optimum height was determined by convergence test and proceeded to the modelling phase to obtain the output of stresses. In findings, this study has justified that the elevated shell platform is feasible to be applied in sustainable industry development and the effect of each different geometric has been identified by stress comparison. Most suitable geometric which is toroidal has been determined by extracting the least value of maximum stresses produced, with the optimum surface area provided to accommodate the maximum load applied.

Keywords: Shell, structure, geometric, sustainable, analysis, stress.

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1. Introduction

The method of constructing roofs by implementing shell structure of large areas without any intrusive intermediate supports method proved to be economical, efficient, and aesthetically pleasing. It is economical in terms of material used due to the ability of the shell under its own load to resist normal stresses but not bending moments [1]. The situation under dead load eliminates the requirement of thicker shells since it has the least bending moment to resist. Merits of shell structure that have a very high stiffness, large space covered, no interior columns and the aesthetic value. A primary difference between a shell structure and a plate structure is the unstressed state, where the shell has curvature compared to the flat plate [2].

Other than the issues of the shell's advantage in transmitting compression that is not fully utilized, the annual flood event occurring in Malaysia leads to damaged buildings also has a limited solution in terms of infrastructure. There is still no implementation of elevated shell platforms as the alternative in minimizing damage caused by the natural disaster or even applied widely as sustainable development in construction [3]. This study is not only applicable for Malaysia but also for other countries which are often affected by catastrophes like typhoons and earthquakes.

Several literature reviews have been made based on the relevant topics of shell structure, related with the scope of this study. There are several studies about the analysis of different shapes of shell, but the application was limited as a roof structure only. All the references have been cited in this section where most of the values used in the calculation of theirs' paper are adapted in this study. The previous research papers have been studied and the gap between all of it with this study has been identified. Most of the previous study were retrieved from journals and several from standards required.

A study regarding analyzing the deflection and stress of cylindrical shell and folded plates structure has been made. It was found that barrel roofs have definite advantage in stresses and deflections over the folded plates, affected by the load distribution on the surface of different shells [4]. Investigation on the effect of the configuration of shell surface with curve fold lines found that highest deflection has been found to occur at the center of the surface with the lowest deflection observed, in the case of fixed support. This is due to the stresses that tend to be concentrated on the curved portions of the model [5].

An evaluation in repairing and strengthening the techniques of elliptical paraboloid reinforced concrete shells with openings has been made and found that the shell with support opening increases the failure load by 14% compared to enclosed shell, which justify the effectiveness of shells without opening [6]. To identify the data source in this study, several references have been chosen based on the standard guideline. The minimum clear vertical height should be at least 6.5m [7]. Thus, any support opening proposed in this study should have a clear height more than 6.5m. Historical data for maximum height of flood occurred in Malaysia also has been done to identify the minimum height required of shell peak in this study. The worst flood event recorded was at Terengganu, Malaysia in 2011 with 2.11 meters above the danger level [8].

2. Methodology

Selection of parameters, outlining the variables and proposing the shell geometrics are included in this study flow. The modelling and obtaining outputs are using Finite Element method [9], LUSAS Software.

• Selection of Shell Dimension

To identify the most suitable height for all geometric, the maximum depth of flood determined from previous studied has been used as the reference. Based on the study, the maximum flood depth at 1,000-year ARI is calculated as 7.34 meters [10]. Thus, 20 meters peak height was chosen as it is practical to allow another 12 meters height that exceed the flood level to be used as the construction area and can fit the targeted number of houses with the proposed diameter of shells.

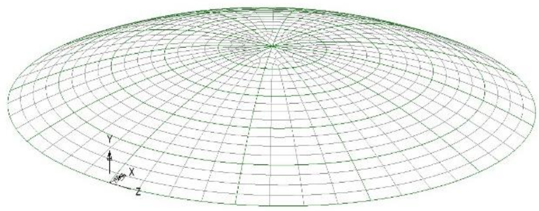
A fixed span of shell was chosen with 200-meter length as the area of 200-meter diameter can fit up to 230 number of houses, calculated based on common size of house in Malaysia [11].

• Variables

In this study, the constant variables are the height, span, material used, support geometry and the loading applied on the shell surfaces. The mesh size of surfaces also has been fixed for all geometric to uniform the interpolation process in LUSAS Software. The dependent variable in this study are the individual component stresses in direction X (Nx) and direction Y (Ny), and the equivalent resultant stress (Ne) of shells after applied with a heavy loading.

• Modelling

Modelling was done using LUSAS Software. The selection of geometric was based on basic shapes which are dome and cone and a common shape of shell structure, pendentive and toroidal. Adaptation of nature has been considered in clam and leaf-like geometric [12]. Dome is used as the control geometric in this study. The complete modelling of all geometrics are as shown in Fig. 1.



Dome

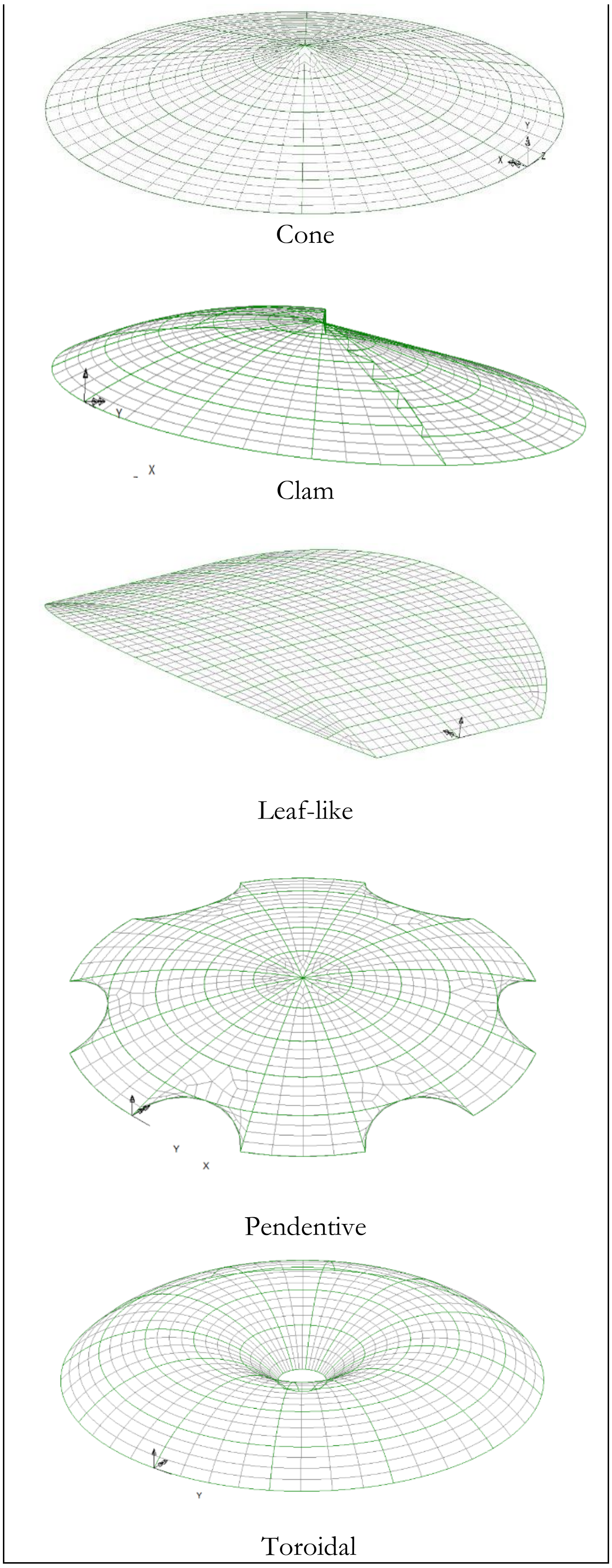


Fig. 1. Different geometric of elevated shell platform structures.

2.1. Results and Discussion

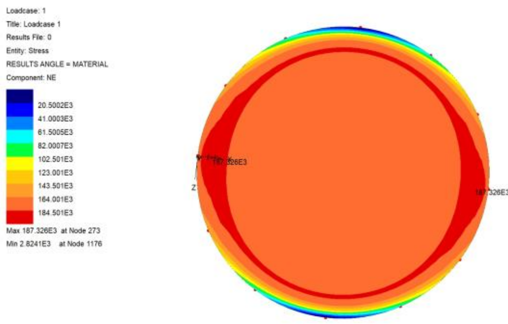
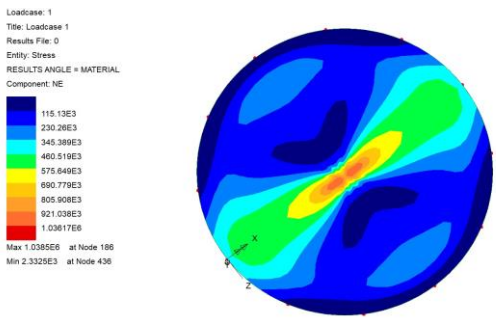
• Stress distribution contour

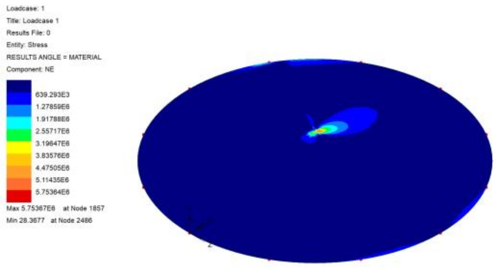
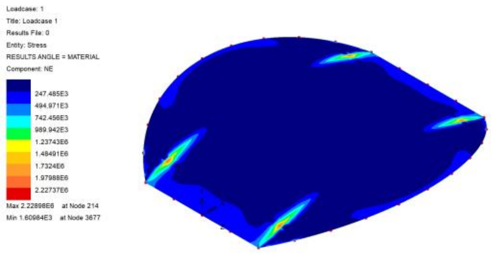
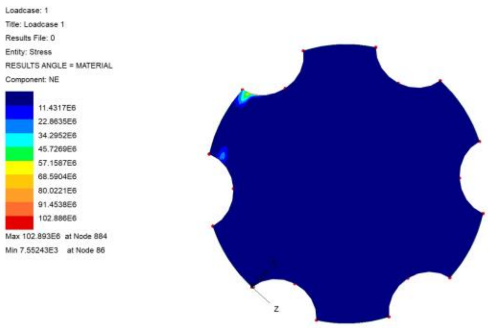
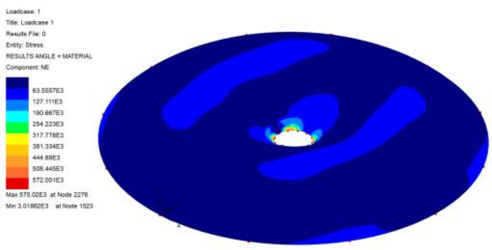
Contours of each geometric were recorded to identify the area of higher and lower stresses besides observation on the distribution for different curvatures. Contour is able to show the stress distribution act on the structure. Different geometries have given a different pattern of contour since the maximum stresses occurred depending on the surface curvature of the shell.

Contours display the results of the active load case on the model as color fringes or lines of equal results value. Contours were plotted using averaged nodal results to give a smoothed plot, or unaveraged nodal results to contour the results on an element-by-element basis, revealing any inter-element discontinuities. This is used to check the mesh discretization error and for displaying results across geometry or material discontinuities.

The appearance of the contour key was adjusted to specify the number of significant figures and draw red uppermost. Equivalent stress is the combined of individual component stresses in direction X and direction Y, in a scalar stress state [13]. The values are obtained from software output based on the von Mises yield criterion [14]. Table 1 shows the stress contour of Equivalent resultant stress (Ne) for each geometric.

Table 1. Equivalent Resultant Stress, N_e contour for each geometric.

Geo-metric	**Equivalent resultant stress (Ne) Contour**
Dome	 Max value: 187.33E3 Min value: 2.82E3
Cone	 Max value: 1.04E6 Min value: 2.33E3

Clam	 Max value: 5.76E6 Min value: 28.37
Leaf-like	 Max value: 2.23E6 Min value: 1.61E3
Pen-dentive	 Max value: 102.89E6 Min value: 7.55E3
Toroidal	 Max value: 575.02E3 Min value: 3.02E3

Based on Table 1, the stress contour of dome has shown a uniform stress distribution. This can be justified by the contours for all stress resultants generated has appeared and not concentrated at a certain point only. Shells with a constant radius across them have definite advantage in stresses and deflections. Cone shows a contour that concentrates at the peak of the geometric. This phenomenon shows the effect of stress surface towards load distribution on the shell.

Clam shows the distribution of highest stress obtained at the stress surface profile and the other half of it which is made of smooth surface profile has overall of intermediate stress level. The combination of surface profiles made the high stress concentrated at the junction between these surfaces. This finding was similar to previous paper that stated high stresses have been found to occur around the curved folds of shell and at the convergent points [15].

Leaf-like geometric shows most of the contour covered with low levels of stress. The maximum and minimum value of stresses obtained near to the surface intersection between closed support and open boundary condition. Even Though the total span of leaf-like is the same as other geometrics proposed, it has a different radius of curvature that contribute to a larger area of experience bending moments. It also has a non-continuous boundary condition with open base that was proven in a previous study which this condition produced higher stresses compared to the geometric with close base support.

Pendentive geometric generated almost the same pattern of stress distributions as leaf-like geometric since they have the same behavior with open boundary condition. Numerous openings at boundary conditions made pendentive as the highest equivalent stresses resultant generated among all of the geometric proposed.

Toroidal geometric contour shows majority in low stresses throughout its surface but highest stress have focused at the intermediate support boundary condition. All of the highest equivalent resultant stress from contour have been used to calculate the maximum stress of shells.

• Maximum stress

The tabulation of data in Table 2 below shows the stresses among each geometric as stated in the contour outputs. For a shell structure, the resultant stress is expressed in force per unit length. Thus, to obtain the maximum stress generated by each geometry, the resultant stress should be divided by the thickness to convert the stress into per unit area. Maximum stress is calculated using Formula 1 [16] and all stresses are in N/m unit and maximum stress in N/mm^2.

$$\text{Maximum stress} = \frac{Ne}{t} \tag{1}$$

Where,

N_e	-	Equivalent Stress
t	-	Thickness of Shell

The highest stresses obtained by pendentive followed by leaf-like geometric that are caused by the open and discontinuous boundary condition of both geometries which theoretically have larger bending moments occurred near the supports due to its curvature. Most of the models are showing negative stresses that indicated the surfaces are under tension. For those positive stresses generated by the geometrics still can be resisted by low reinforcement contact. As the rest of geometric, toroidal geometric has come out as the best stress distribution after dome. Patterns of stresses comparison can be shown as Fig. 2, based on the data tabulated in Table 3.

Table 2. Stresses of geometric.

Geometric	Equivalent stress, N_e (x 10^3)	Maximum stress
Dome	187.3	0.62
Cone	1,038.5	3.46
Clam	5,753.7	19.18
Leaf-like	6,498.3	21.66
Pendentive	102,893.0	342.98
Toroidal	575.0	1.92

Table 3. Resultant stresses for different geometries of shell structure.

Geo - metric	Local X, Nx (x 10^3)	Local Y, Ny (x 10^3)	Equivalent, Ne (x 10^3)
Dome	5.4	13.3	187.3
Cone	40.5	20.6	1,038.5
Clam	932.6	1,358.9	5,753.7
Leaf-like	526.0	251.4	6,498.3
Pen-dentive	60,277.4	15,637.5	102,893.0
Toroidal	79.1	74.4	575.0

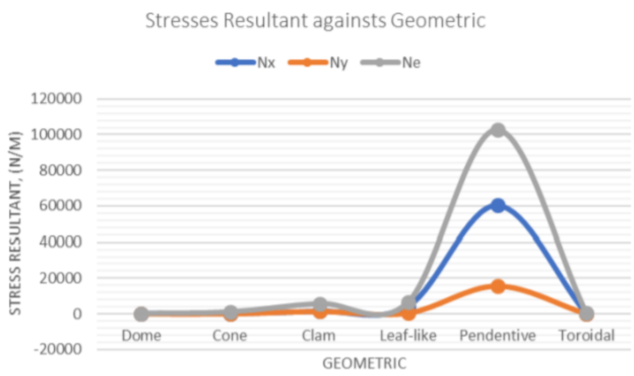


Fig. 2. Graph of resultant stress against geometrics.

• Stress-to-weight ratio

The comparison of ratio for all geometric towards control geometric is done as shown in Table 4 below. The density taken is 24 kN/m³ as the material use is concrete BS8110 with the compressive concrete strength of long term C40 [17]. Total area is in m² unit and total weight is in kN,

Table 4. Resultant stresses for various heights of dome geometric.

Geo - metric	Area	Weight	Max. stress	Stress to weight ratio (x10^3)
Dome	32,662	235,162	0.62	0.002
Cone	21,838	157,230	3.46	0.022
Clam	33,398	240,460	19.18	0.080
Leaf-like	21,706	156,283	21.66	0.139
Pen-dentive	28,113	202,413	342.98	1.694
Toroidal	35,030	252,216	1.92	0.007

All the geometrics have almost the same total weight but differ capability in resisting the stresses. Table 3 shows that the pendentive geometric has the largest stress-to-weight ratio which justified it is less effective in transmitting the load applied, providing a lesser area for the application of constructing buildings on it compared to other geometric with the lower ratio [18]. Contrast with dome that obtained the lowest ratio followed by toroidal and cone, resisted by a larger surface area with higher total weight. This finding can justify that low stresses produced with a larger total area will allow more loading applied onto it [19].

The analysis shows that different geometries of shell platform effect on the performance in carrying high load applied onto it. Calculation in identifying the comparison of maximum stress for all proposed shell geometrics was made as shown in Table 5, using formula 2 and 3 [20].

$$\text{Stress ratio} = \frac{\mathit{Maximum\ stress\ of\ dome}}{\mathit{maximum\ stress\ of\ geometric}} \tag{2}$$

$$\text{Weight ratio} = \frac{\mathit{Total\ weight\ of\ dome}}{\mathit{Total\ weight\ of\ geometric}} \tag{3}$$

Maximum stress of dome as the control geometric only generated 18% from cone's stress, 3.0% from clam's stress, 2.0% from leaf-like stress, 0.2% from pendentive stress, and 30% from toroidal stress even though all of them have almost the same total weight.

Table 5. Stress and weight ratio of geometrics.

Geometric	Stress ratio	Weight ratio
Cone	0.18	1.49
Clam	0.03	0.97
Leaf-like	0.02	1.50
Pendentive	0.002	1.16
Toroidal	0.3	0.93

2.2. Conclusion

As the conclusion, both objectives in this study have been achieved. Objective 1 was aimed to study the feasibility in proposing an elevated shell platform. The elevated shell platform is feasible to be implemented in industry since the maximum stress obtained from the control geometric is lesser than the concrete strength of characteristic used [21]; C40 (40 N/mm^2) except for pendentive. Theoretically, the ultimate strength of concrete used is adequate safety against limitation to resist the maximum stress generated by the elevated shell platform. The strength limit is used to reveal the strength and ductility capacity of the material [22]. Mostly, the stresses distributed on the shell surfaces are compression and the minor tension surfaces can be strengthened by reinforcement in future implementation [23].

Objective 2 is to investigate the effect of shell geometric on elevated shell platforms and identify the suitable shell geometric. All the analysis of contours, maximum stresses, stress-to-weight ratio, stress ratio and weight ratio have justified the performance affected by different geometrics proposed. Based on the justification, the suitable shell geometric can be decided with the basic geometric like dome and cone are the best among other geometrics proposed because despite of the ability to distribute the stresses uniformly, their stress-to-weight ratio, stress ratio and weight ratio are also proven more effective to be constructed than the complex geometric.

A structural mitigation should be made to control the building damage from natural disaster as based on the descriptive statistics of the function of buildings, 65.7% of residential house were damage consequence from the catastrophic event [24].

Various subsystems need to consider such as structures and material in ensuring the sustainable development of the construction industry. Shell structure implementation is important to assist the measurement of sustainable development in the construction industry by minimizing the material used [25]. This is because shell structure is a lightweight structure which requires lesser material to construct, thus able to reduce the construction waste disposal meanwhile being applied to minimize catastrophic effect towards economy and public safety.

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Azizah Abdul Nassir graduated with a Bachelor of Engineering (Hons.) Civil, from Universiti Teknologi MARA (UiTM) in the year of 2019 and Diploma of Civil Engineering from the same university in the year of 2016.

Azizah is currently working as a design engineer in Perai, Pulau Pinang since July 2019. She is a registered graduate engineer from Board of Engineer (BEM) and a corporate member of Malaysia Green Building Council (MGBC).

Hooi Min Yee graduated with a doctorate degree Structural Engineering, Master of Science Engineering and Bachelor of Engineering (Honours) Civil Engineering from the Universiti Sains Malaysia, Pulau Pinang, Malaysia.

Hooi Min YEE was a fellow at Universiti Sains Malayisa. After graduating, she worked as senior lecturer at Faculty of Civil Engineering, Universiti Teknologi MARA, Pulau Pinang, Malaysia and was promoted to Associate Professor in 2017. Her research interest is Computational Mechanics, Computational Analysis of Shell and Spatial Structures, Nonlinear Analysis, Environment, Engineering Education and Architectural Engineering. She is a supervisor of PhD and Master students. She is an external and internal examiner for the postgraduate students.

Associate Professor Ir. Dr. Yee is also certified as an 'International Professional Engineer', 'APEC Engineer', 'ASEAN Engineer', Professional Engineer with Practising Certificate of Board of Engineers Malaysia, Fellow of The Institution of Engineers Malaysia, Associate Fellow of ASEAN Academy of Engineering and Technology, The ASEAN Federation of Engineering Organisations, Construction Industry Development Board Malaysia and Concrete Society of Malaysia. She is an evaluation panel Engineering Accreditation Council and Engineering Technology Accreditation Council. She is a Professional Engineer Interviewer/Examiner for The Institution of Engineers Malaysia since 2016. She as an Executive Committee of The Institution of Engineers Malaysia (Penang Branch) from 2014-2016; 2017-2019;

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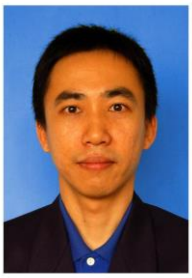
2019-2020 and 2020-2021. She as a sub-committee member under Women Engineers section in The Institution of Engineers Malaysia (Penang Branch) from 2014-2016 and 2017-2019. She as a coordinator of sub-committee member under Linkage and Collaboration with Universities section in The Institution of Engineers Malaysia (Penang Branch) from 2018-2019 and 2019-2020. She as a sub-committee member under Event & Activities and Newsletter sections in The Institution of Engineers Malaysia (Penang Branch) from 2018-2019 and 2019-2020. She as a sub-committee member under of Women Engineers and University Collaboration Portfolio in The Institution of Engineers Malaysia (Penang Branch) from 2020-2021. She as The Conference of the ASEAN Federation of Engineering Organisations (CAFEO) organizer committee on 2015. She has organized a technical visit to South Korea and Russia on 2016 and 2018, respectively under Women Engineers section in The Institution of Engineers Malaysia (Penang branch). She as an earthquake design sub-committee from The Institution of Engineers Malaysia (Penang branch) on 2019.

For her much appreciated leadership and contributions towards excellence in engineering, society enhancement and nation development; the international Engineering Fraternity conferred Ir. Dr. Yee the ASEAN Federation of Engineering Organisations (AFEO)'s Honorary Member Award by AFEO Governing Board which carries the abbreviation M.AFEO after her name on 2018. She conferred the status of International Professional Engineer and APEC Engineer by EMF International Professional Engineer and Asia-Pacific Economic Cooperation, respectively on 23 November 2017 together with the designatory letters IntPE and APEC ENGINEER. She conferred ASEAN Engineer award by the AFEO Governing Board together with the designatory letters ASEAN Eng. on 2015. ASEAN Academy of Engineering and Technology (AAET) AGM held on 29 May 2021 agreed to admit her as an Associate Fellow of AAET with the abbreviation "AFAAET" after her name. She is awarded Universiti Teknologi MARA 'Excellent Service Award'. She as a vice-chairman for the 2 international conferences have been held in Malaysia on 2015.

Associate Professor Ir .Dr. Yee has obtained 16 awards in Invention, Innovation and Research Design Platform and has published 92 up-to-date publications. Her other achievements include invitations as Keynote Speaker, International Invited Speaker, International Visiting Professor, Session Chairman, technical committee and publicity committee chair to over international and national technical conferences and seminars worldwide which include those in Czech Republic, United Kingdom, Ireland, Spain, Australia, Republic of China, Singapore, Indonesia, Thailand and Malaysia. She is a pilot for the MOU, cooperation program MOA and International Conference Agreement MOA between Universiti Teknologi MARA and King Mongkut's Institute of Technology Ladkrabang, Thailand. Pilot for the MOU between Universiti Teknologi MARA and Universitas Pertamina, Jakarta, Indonesia. Pilot for the MOU between Universiti Teknologi MARA and Jesin Construction Sdn. Bhd., Malaysia. Pilot for the MOU between Universiti Teknologi MARA and North Minzu University, Republic of China. She is a Resource Person for CES 523 Structural Steel Design and leader of Special Interest Group in Universiti Teknologi MARA, Pulau Pinang from 2016-2017 and 2019-2021. She is a member of "Penyelidikan, Entiti Kecemerlangan Tier 5 Universiti Teknologi MARA". She has supervised 36 final year project students.

Ts. Syahrul Fithry Bin Senin has started his career as academician at UiTM Cawangan Pulau Pinang since 2004. A graduate of University Malaya, he started his career by involving in structural and civil engineering consultancy works in the year of 1997. Currently, he is actively involved in using MATLAB and GNU Octave for his numerical methods-related research works and lectures. His focus areas of research are in Artificial Neural Network and Deep Learning for pattern recognition and predictions. This knowledge is also applied by him to analyse the Non-Destructive Assessments data from building inspections activities detected by the radar signals from electromagnetic wave sensors such as Ground Penetrating Radar and others.



Y. P., Woo was born in Taiping, Perak, Malaysia in 1971. He received the B.Eng degree in civil engineering from the University of Malaya, Malaysia in 1996, M.Sc. degree in structural engineering from the University of Science, Malaysia in 2008 and the Ph.D. degree in structural engineering from University of Science, Malaysia in 2017.

From 1996 to 2006, he was a civil and structural engineer in the building industry. Since 2010, he has been a senior lecturer with the Faculty of Civil Engineering, University Technology of MARA (Penang Branch), Malaysia. His research interests include shell and spatial structures and nature inspired structures.