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Study of Architectural Form and Structural Analysis of Central Tower Cluster of Angkor Wat

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In this study, we investigated the form and structure of the Angkor Wat temple complex using diagrams, ogive geometry, and structural analysis. The findings of previous research indicated the appropriate basic grid-cell size for the temple complex's planning. They were used as the main data for this research. An earlier analysis revealed the geometric code (basic module, BM) that controls the architectural design diagram and construction of the temple complex. The use of a center-shifting technique to avoid the numerical fractions occurring in grid cell modules resulted in the asymmetry of the temple, as evidenced by the unequal openings (windows) on the left and right sides of the first enclosure. The diagram 5:6, suitable for the inhabitants who were the *Vaiśyas*, is achieved by the center-shifting technique. The form analysis showed that the towers in the temple were of ogive shape of varying sizes, corresponding to Pythagoras' common-right-triangle combinations. The structural analysis demonstrated the use of low-tiered walls around the core structure of the central tower cluster, increasing the wall bearing of the core structure with exceptionally large wall corners to strengthen the bearing walls of the core structure. As a result, the maximum weight-induced deformation of the central tower cluster indicates the capability of the walls to sustain massive weights. An Angkor Wat central tower cluster was constructed on a slant base foundation. In this research, we unveiled the structure-follows-form and form-follows-structure principles in the construction of the Angkor Wat temple.

1. Introduction

In a previous study, "The Geometrical Relationship between Ancient Hindu Technical Treatises and the Planning and Organization of Angkor Wat",[1] in which the employment of a geometrical grid system in the planning of the Angkor Wat was studied, the sandstone sanctuary has revealed the suitable module or one basic module (BM) used in the planning, namely, 2.75×2.75 m^2 in the metric system or *5 hat 1 Thnob* in the local Cambodian system. The method of shifting the center, whereby the vertical axis through the center of the building cluster is much

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to the left of the principal image of God in the central tower, has also been found. The grid system of BM was again employed in this study for a deeper understanding of the relationships between structural planning and structural forms of the Angkor Wat buildings in terms of the design principle of Angkor Wat.

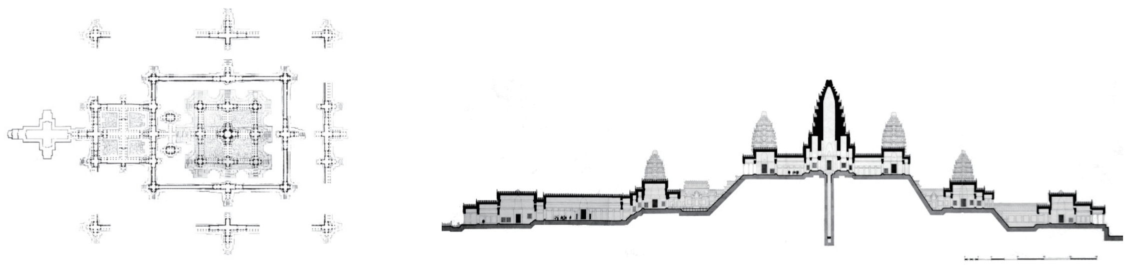
2. Literature Review

There is a certain lack of documentary evidence of Khmer architectural practice for the study of building construction. Nevertheless, artistic evidence such as the large carving on the wall of the east gallery at the lowest level of Angkor Wat, depicting the Churning of the Ocean of Milk, indicates the Khmers' acceptance of Hinduism at that time. The reexamination of Pythagorean theorem, which was widespread in ancient and medieval India and a piece of common knowledge among those who believed in the Brahmanical cult, will be a good basis for the geometrical study of Angkor Wat since the relevant evidence of direct Khmer origin is unavailable.

2.1 Geometry

In "Angkor Vat: Description Graphique du Temple",(2) Guy Nafilyan, a French architect, and his team, compiled architectural drawings for conservation and restoration work as shown in Fig. 1. His team was made up of Alex Turletti, MeyThan, Dy Proeung, and Vong Von. This book contains two volumes in French. The first volume is concerned with architectural aspects of the entire building cluster presented in more than a hundred architectural drawings, while the second contains photos and detailed descriptions of the various elements of the building. Those technical drawings of the building clusters are the best to have been published to date, and they are used as the basis for this research.

Parmentier,(3) Chef honoraire du Service Archéologique, Correspondant de l'Ecole Française d'Extrême-Orient, criticized the Khmer architects who built Angkor Wat as being underrated, and he said that there were repeated geometric mistakes, that this was unlikely due to negligence or religious motivation, and that they used their eyes to judge without using standard measurements. Parmentier could not explain why the Khmer architects used an asymmetrical technique at Angkor Wat.



(a) (b)

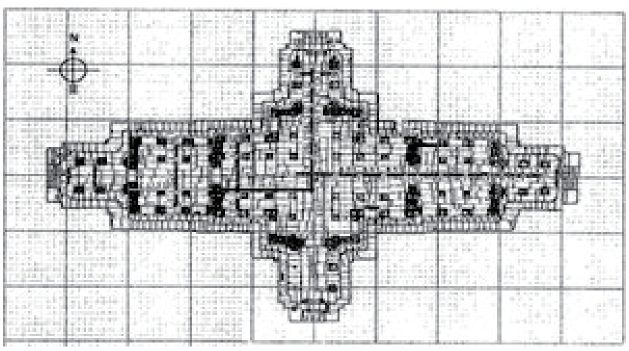
Fig. 1. Angkor Wat graphic description of the temple. (a) Angkor Wat's floor plan. (b) Long section (W-E).

In 1999, the paper "On the Measurement Planning of Angkor Wat: A Study on the Planning Method of Khmer Architecture"[4] by Tsuchiya Takeshi from the Department of Applied Physics of Waseda University, Tokyo and Nakagawa Takeshi, a research associate at the Institute for Molecular Science of Kyoto University, explained the theory of a grid system in the planning of Angkor Wat, using the 1d (*daṇḍa*) = 484.92 mm diameter of the north library columns, which were located in the corner of the third-level (outermost) cloister as the basic unit of the square grid system in analyzing the floor plan, with the original drawing by Naflyan as shown in Figs. 2(a) and 2(b). In addition, the central axis of the castle's inner hall often did not overlap with the axis of the master plan when the castle faced east-west. The axis line of the inner hall usually deviates to the south of the central axis line for a distance of approximately "three times the distance of 484.92 mm". This distance is usually more pronounced for north–south wall measurements than for the measurements in the opposite direction.

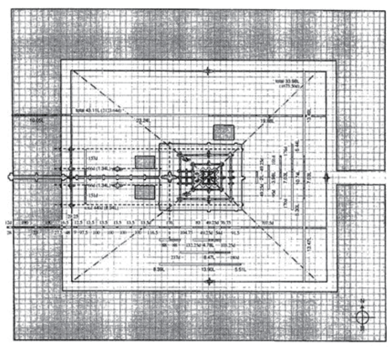
According to Hardy[5] in "The Temple Architecture of India", it is easy to imagine that a diagram in a plan is more significant than the building itself. Even if one's discoveries are there in the building, one cannot know for certain whether the building was designed in terms of geometrical figures, a grid, a system of measurement, a modular system, a set of proportions, or some or all things together, since the mystery is such that they all may contain one another.

As shown in the research "Geometrical Relationship in Architectural Design of the Khmer School of Master Builders in Thailand",[6] with financial sponsorship from King Mongkut's Institute of Technology Ladkrabang (KMITL), the two sandstone sanctuaries at *Prasat Phanom Rung*[7] and *Prasat Phimai*,[8] which have a similar layout (main buildings at the center of the rectangle enclosure) to that of the Angkor Wat complex, were built in the period earlier than that of Angkor Wat Schools of Master Builders.

This research dealt with the application of geometric systems using the field survey of architectural remains, satellite images from Google Earth, Autodesk's Computer-Aided Design (AutoCAD), and the 3D models and measurements generated by the Photo Modeler 6.5 program, together with the diagram in *Mayamatam,* one of the ancient Hindu sciences of designing and constructing buildings and the geometrical grid system, a useful tool for both engineering and architectural fields. These collective tools were employed in this research to portray the findings.



(a)



(b)

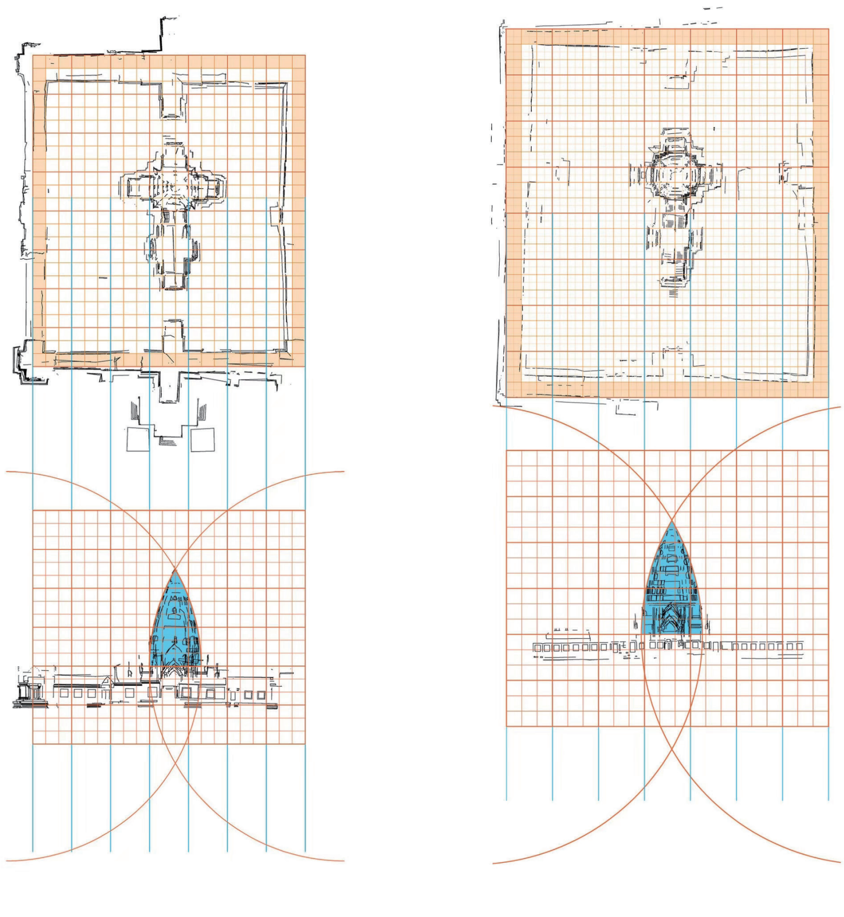
Fig. 2. (a) Drawing of northern library's plan. (b) Grid system analysis on the site plan of Angkor Wat.

The employment of geometry is achieved by the skillful arrangement of a 3D space using geometrical concepts and theorems, i.e., perpendicular bi-sectors and common right triangles, whose relationships in terms of width and length are in perfect sync.

The research brought to light the new finding of why the space on the right is less than that on the left one (when facing in). Similar to this is the Angkor Wat plan, which bewildered the French expert architect Parmentier, head of the École française d’ Extrême-Orient (EFEO).

In Fig. 3(a) showing the graphical analysis of the Prasat Phanom Rung floor plan with the principal grid module BM = 2.5625 × 2.5625 m^2, the larger grid module of 3 BM can be calculated as 3 (2.5625 × 2.5625 m^2). The proportion of the total plan of the Prasat Phanom Rung is also 7:8 similar to the 7th encloser of the Ankor Wat floor plan. The tower form analysis revealed the relationship of the two circles each with a diameter of 10 (3 BM) to the 6:8:10 common triangle in the investigation of the lancet-shaped roof of the central tower.

In Fig. 3(b) showing the graphical analysis of the *Prasat Phimai* building plan with the principal grid module BM = 3.3125 × 3.3125 m^2, the larger grid module of 3 BM can be



(a) (b)

Fig. 3. (Color online) (a) Graphical analysis of *Prasat Phanom Rung* building plan and lancet-shaped roof of the central tower. (b) Graphical analysis of *Prasat Phimai* building plan and lancet-shaped roof of the central tower.

calculated as 3 (3.3125 × 3.3125 m^2). The proportion of the total plan of *Prasat Phimai* is also 7:8 similar to the 7th encloser of the Ankor Wat floor plan. The tower form analysis revealed the relationship of the two circles each with a diameter of 10 (3 BM) to the 6:8:10 common triangle in the investigation of the lancet-shaped roof of the central tower.

2.2 Materials

2.2.1 Review of research paper

Material studies are necessary to examine the primary building materials to test the materials in real buildings and develop reference methods to ensure the long-term safety of the structure. In the 2003 research "The Construction Process of the Angkor Monuments Elucidated by the Magnetic Susceptibility of Sandstone",(9) Uchida *et al*. stated that "sandstone, laterite, and brick are the main construction materials in the Angkor monuments. Three types of sandstone are found in the monuments, but a gray to yellowish-brown sandstone (feldspathic arenite) is most common among them. The stones were transported from quarry sites at the foot of Mount Kulen to the Angkor Monument through a network of canals. The sandstones were skillfully cut into smaller rectangular cubes of varying sizes and stacked up to the desired structures without the use of adhesive. The strength of sandstone structures is the result of minimal crevices and sandstone weight. In addition, cast iron rods and molten lead are applied as fasteners where extra stability is required, e.g., the structure corner".

2.2.2 Physical and mechanical properties of sandstone

Structural design, construction methods, maintenance, and construction materials play roles in the sustainable longevity of the stone monuments in the world heritage site of Angkor. In particular, the stable and enormous central part of Angkor Wat, built of sandstone, shows significant Khmer strength and wisdom. Those sandstones show varieties of color, grain size, porosity, and hardness, which can be correlated with the Phu Kradung Formation of the Korat Group, Thailand.(10) Uchida(11) classified the properties of sandstones used in Angkor monuments on the basis of their mineral compositions and magnetic susceptibility (MS). The MS of Angkor monuments ranges from 0.1 to 0.8 × 10^3 SI unit.(12) Because the sandstone textures of Angkor monuments are similar to those of the Abu Agag and Um Barmil formations in Egypt, their MS was considered by applying the rock properties' correlation charts. The grain density, bulk density, and porosity of the sandstone of Angkor monuments can be correlated and had been shown as 2.60 to 2.70 g/cc, 2.35 to 2.62 g/cc, and 9.50 to 25.25%, respectively.(11) The sandstone's bulk density is within the range of those values of the Phu Kradung Formation of Thailand studied by Wannakao and Wannakao.(13) MS was widely used and correlated with porosity for the determination of petroleum reservoir rock.(11,14,15) Although the porosity has a wide range of values, the mean sandstone porosity is 14–18%, which is close to that of Angkor Wat.(16) Petrographic analyses of the sandstone of Angkor monuments and the sandstone tested and reviewed by Stück *et al*.(17) showed that sandstone porosity can be correlated with bulk density, compressive strength, water absorption, ultrasonic wave velocity, and flexural strength. The ultrasonic wave velocity range of 2.1 to 3.3 km/s measured from Angkor Wat[16] is related to the uniaxial compressive strength range of 30 to 90 MPa, which is similar to the range obtained by the compression test, as shown in Table 1.

2.3 SAP2000 structural analysis

Studies on the application of SAP2000 for the stability of Angkor Wat have not yet been found. There are many studies on ancient sites that use SAP2000 to analyze the stability of the dimension stone buildings and the appurtenance structures such as the examples below.

(1) SAP2000 was applied to study the behavior of the rock mass of the Kanfanar quarry in Croatia. It solved the stress and strain states of 3D models and defined the stability of the dimension stone at the underground rock mass.[22]

(2) The Timurtaş (Demirtas) Mosque in Turkey, the most visited mosque in Bursa Province, was constructed using natural stone, brick, wood, and mortar. SAP2000 was used to evaluate the historical structures, which showed that great stress concentrated at the low-tensile-strength wall. An analysis result is considered to restore the mosque.[23]

(3) SAP2000 provided the prediction function of the natural frequencies, related to the geometrical parameters of the building and assisted in the conservation of Zanzibar Stone Town, Africa.[24]

(4) The objective of the study "Structural Assessment of the Seismic Behavior of the Dome of the Taj Mahal" is to develop a simplified approach to enhance the conceptual understanding of the mechanism of load path/transfer in the dome of the Taj Mahal under both gravity and seismic loads, as well as to better understand the effect of the geometry of the dome on its structural behavior. Using the software SAP2000, a finite element model of the dome was created and analyzed under the action of gravity and seismic loads, with the seismic loading assumed to have a PGA of 0.25 g.[25]

(5) The paper "Analytical Evaluation of Repair and Strengthening Measures of Qasr al-Bint Historical Monument—Petra, Jordan" is concerned primarily with giving the historical monument Qasr al-Bint the ability to withstand future earthquakes without excessive damage. The Qasr al-Bint walls have been evaluated and tested for seismic resistance by the finite element method (FEM) using SAP2000. The FEM model considered the differences in sandstone and bonding mortar properties; hence, the model was layered with different shell elements and sections.[26–28]

Table 1
Calculated parameters of sandstone for SAP2000.

Properties	Range	Median	Use in SAP2000	Remark
Bulk density (g/cc)	2.35–2.62	2.50	2.50	Testing
Uniaxial compressive strength (MPa)	15.10–94.37	75	28.0	Refs. 13 and 18
Modulus of elasticity (Pa)	1.1E+09–5.1E+10	2.1E+10	2.50E+09	Ref. 13
Tensile strength (MPa)	4.5–16	12	null	Refs. 18 and 19
Poisson's ratio	0.1–0.25	0.20	0.25	Ref. 20
Shear modulus (Pa)	1.0E+09–2.125E+10	8.0E+09	1.04E+09	Calculation
Thermal expansion coefficient (/°C)	1.0E−05–6.51E−05	3.0E−05	9.90E−06	Ref. 21

(6) In the study "Structural Performance Evaluation of Historical Çardak Caravanserai in Denizli by Performing Linear Analyses 2020" by E. Şahin,(29) an assessment of historical masonry structures was found to be significant in terms of transferring cultural heritage to future generations. The software used for modeling and structural analyses was SAP2000 v20.2. For modeling, frame elements were used in the columns, whereas shell elements were used in the other structural elements. Self-weight, modal, and response spectrum analyses were conducted in terms of the assessment results.

3. Research Methodology

The architectural remains in the Angkor Wat temple complex revealed the strong influence of ancient India on the religious beliefs and practices of ancient Khmers.(30) In addition to the geometrical basic grid module, the authors also used ogive geometry and Pythagoras' theorem (i.e., common right triangles) in analyzing the forms of the towers and structure of the temple complex. Pythagoras' theorem appeared in ancient Indian texts and was widely used in ancient Indian architectural construction works.(31) Geometric conceptualization has always been among the essential mental tools required for the invention, modeling, and visualization of spatial building structures.(32)

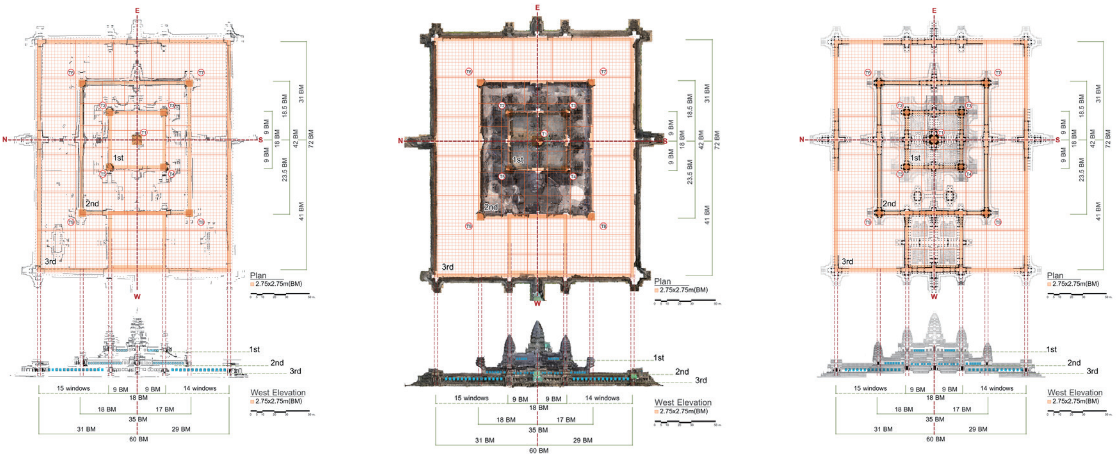
3.1 Form analysis

3.1.1 Grid system

The findings of the authors of "The Geometrical Relationship between Ancient Hindu Technical Treatises and the Planning and Organization of Angkor Wat"(1) were examined using a geometrical grid-cell system. The planning analyses of the building groups of the innermost, middle, and outer enclosures showed that the principal grid system of BM 2.75 × 2.75 m^2 can be applied to reveal their proportions as their simplifying ratios. This finding of 1 BM differs from Tsuchiya Takeshi and Nakagawa Takeshi's work of Angkor Wat.

The ratios of the Foundation Deposit, the central tower plan, the first innermost enclosure of the square enclosing the central tower, and the third enclosure of the rectangular shape enclosing the second enclosure are 1 BM:1 BM (2.75 m:2.75 m), 3 BM:3 BM, 18 BM:18 BM, 35 BM:42 BM (or 5 BM:6 BM), and 60 BM:72 BM (or 5 BM:6 BM), respectively. The traces of the grid system are apparent in the landscape of Angkor Wat, from the results of the LiDAR survey carried out by Damian Evans and Roland Fletcher in 2015.(33)

The left and right sides of the second and third enclosures enclosing the central tower were asymmetrical, as evidenced by the unequal number of windows (blue rectangle), similarly to the same era ancient Khmer sanctuary in Thailand, *Prasat Phanomrung* and *Prasat Phimai*. In the second enclosure, the number of openings on the left and right sides is 15:13. In the third enclosure, the number of openings on the left and right sides is 15:14, as shown in Figs. 4(a)–4(c). The grid system proofs the existing intentional construction of asymmetrical enclosers, which gives the answer to the criticism of Parmentier.(3)



(a) (b) (c)

Fig. 4. (Color online) (a) Graphical analyses of Angkor Wat building plan and front elevation of Angkor Wat sanctuary by BM 2.75 × 2.75 m^2 generated by (a) PhotoModeler Pro5 and (b) Polycam 5.0.20 (original image source by the research team in 2017), and (c) modified from the blueprint of ÉFEO.

Figure 4(a) shows that the biggest central tower is T1, the smaller ones at the four corners of the innermost enclosure are T2-T5, and the smallest ones at the four corners of the middle enclosure are T6-T9. This image was generated by PhotoModeler Pro 6.5 using the data source from photographs. Figure 4(b) shows the floor plan and west side elevation of the Angkor Wat sanctuary with the images generated by Polycam 5.0.20. This new technology gives more precise results with 3D images and dimensions of Angkor Wat.

Figure 4(c) shows the floor plan and west side elevation of the Angkor Wat sanctuary from EFEO with our grid system. By inserting the grid system of BM 2.75 × 2.75 m^2, the individual grid cell shows proportions and dimensions similar to the research findings in Figs. 4(a) and 4(b).

3.1.2 Method of form analysis

In the form analysis, field survey data, including the direct measurement of a long distance of 14 windows of the northeastern wall's corridor with a measuring chain and photographs of Angkor Wat sanctuary, are used to generate 3D images of the sanctuary using PhotoModeler[34] and Polycam.[35] The drawing of EFEO[2] is utilized alongside PhotoModeler and Polycam-generated 3D images for improved analysis results. Similarly to the previous study[1] (i.e., floor plan analysis), the unit of BM 2.75 × 2.75 m^2 will be used again to analyze the form in this study.

An ogive is the roundly tapered end of a 2D or 3D object. Ogive curves and surfaces are used in engineering, architecture, woodworking, and munitions. Figure 5 shows the ogive geometry with the diagram behind, where ogives of varying base widths and heights could be realized by shifting inward or outward either one of the two circles with identical diameters along the common horizontal line connecting the circle centers.

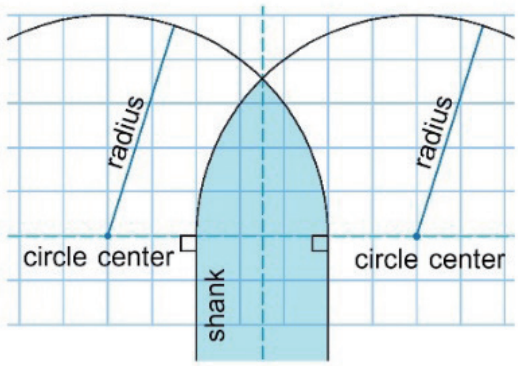


Fig. 5. (Color online) Graphical illustration of ogive geometry.

There are three sizes of towers in the Angkor Wat complex, the biggest is the central one, the smaller ones at the four corners of the innermost enclosure, and the smallest ones at the four corners of the middle enclosure. Figure 6 shows an ogive geometry of varying size, in relation to the 3:4:5, 5:12:13, and 6:8:10 common right triangle combinations, by moving both circles closer and further apart. The common right triangle combinations include, for example, 3:4:5, 5:12:13, 6:8:10, 8:15:17, 9:12:15, 10:24:26, and 12:16:20.

3.2 Structural analysis

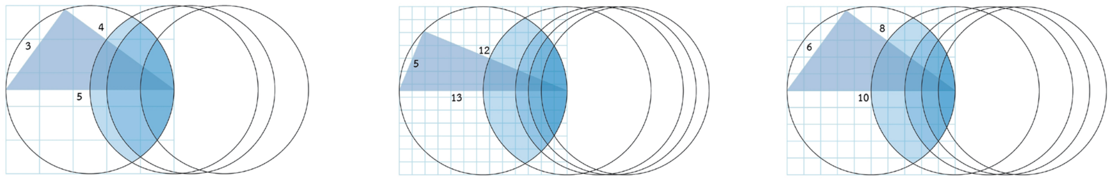
3.2.1 Structural model

We used SAP2000 25 software to analyze the 3D structural model of the group of buildings of the innermost enclosure including the central tower that is redrawn as three dimensions by AutoCAD from the results of data analyses by PhotoModeler and Polycam, and the drawing of EFEO. The analyzed model is imported from AutoCAD (Fig. 7) and assigned as a solid element.

Figure 7 shows parts of Angkor Wat generated by SAP2000, consisting of the central tower (T1), the four constituent innermost enclosure towers (T2–T5), and the base. In this research, the structural analysis focused on the central tower cluster because the cluster is the most important group of buildings in the Angkor Wat sanctuary. By analyzing the original base (slant base) and the modified upright base (erected base), the result can be used to consider which base pattern is more suitable. The central tower with the original corbel-arch roof form and the flat roof form are analyzed as well to consider which one is more suitable in terms of internal stress and deformation.

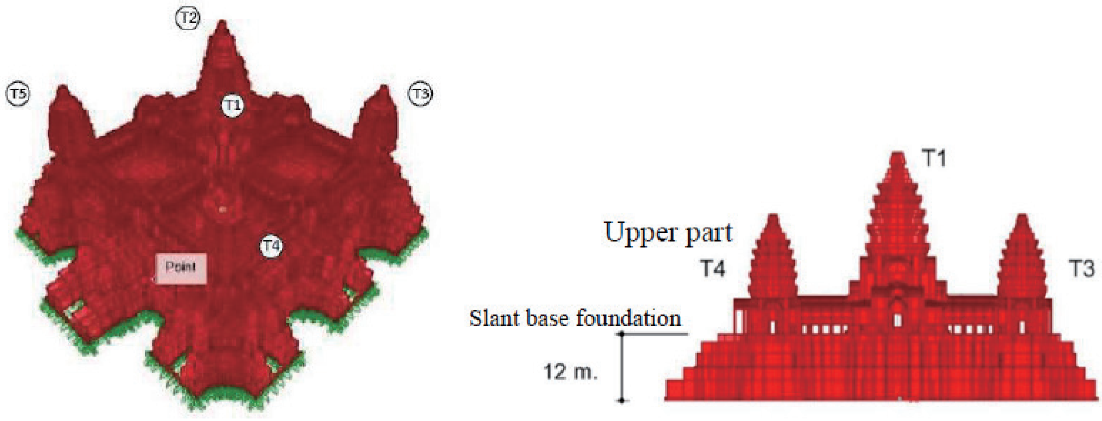
3.2.2 Material properties (input parameter of sandstone)

The sandstone used in Angkor Wat is known as the Phu Kradung Formation of Thailand.[36] A detailed study of the geochemistry of the rock samples obtained from the Phanom Kulen mountain and the adjacent area can be classified mainly as litharenite sandstone. Subarkosic



(a) (b) (c)

Fig. 6. (Color online) Graphical illustration of ogive geometry of varying size of common right triangle in relation to (a) 3:4:5, (b) 5:12:13, and (c) 6:8:10.



(a) (b)

Fig. 7. (Color online) (a) Isometric of the central tower group (CTG) generated by SAP2000. (b) Cross section of the CTG with 12 m slant base foundation.

sandstone and graywacke had been found in some samples.(37) These types of sandstone had conformed with the findings of Wannakao and Wannakao.(13) The range of Poisson's ratio and Young's modulus of sandstone were adopted from the work of Molina *et al.*(20) The shear modulus G of sandstone is obtained as

$$G = \frac{E}{2(1+\upsilon)}, \tag{1}$$

where G is the shear modulus, E is Young's modulus, and υ is Poisson's ratio.

The thermal expansion of a rock can be calculated as an average from its minerals, which applies between 20 and 400 °C.(21) In this study, the authors used the thermal expansion coefficient equal to 9.90E−06 per °C because of the low thermal expansion coefficient of feldspar. The parameters used for SAP2000 are tabulated in Table 1.

The structural analysis indicated that the specific gravity of the sandstone material at Angkor Wat was 2.3–2.7 ton/m^3, with the elastic modulus (E) of 10–40 GPa, Poisson's ratio of 0.1–0.2, and the ultimate compressive strength of 80–150 MPa. As mentioned in Sect. 2.2.2, the properties of the sandstone at Angkor Wat were similar to those of the sandstone of the Phu Kradung Formation in Thailand.[18]

3.2.3 Applied force

The force applied to the model is the superimposed dead load of the structure. The dimensions of the central tower are approximately 40 m in height and 11 m in diameter; therefore, the central tower itself is very heavy. The additional loads applied to the structure, which are the live and wind loads, are not considered in this study because they are significantly less than the weight of the central tower.

4. Results and Discussion

4.1 Tower form analysis

The actual measurement of the building is the foundation of this research. The architectural drawings of the long section (west-east), prepared by Nafilyan and his team for the conservation and restoration work, are used in the tower form analysis. The floor plan of Angkor Wat demonstrated three main enclosures enclosing the central tower: inner square, middle rectangular, and outer rectangular enclosures. The central tower (T1) was surrounded by eight towers of less significance, situated at the four corners of the inner (T2–T5) and middle enclosures (T6–T9). All nine towers (T1–T9) were of ogive shape of varying sizes of the circle diameter.

Figure 8 shows the details of the central tower, illustrating the section and floor plan of the central tower (T1) based on the basic grid module (BM) and submodules, where 1 BM and 1

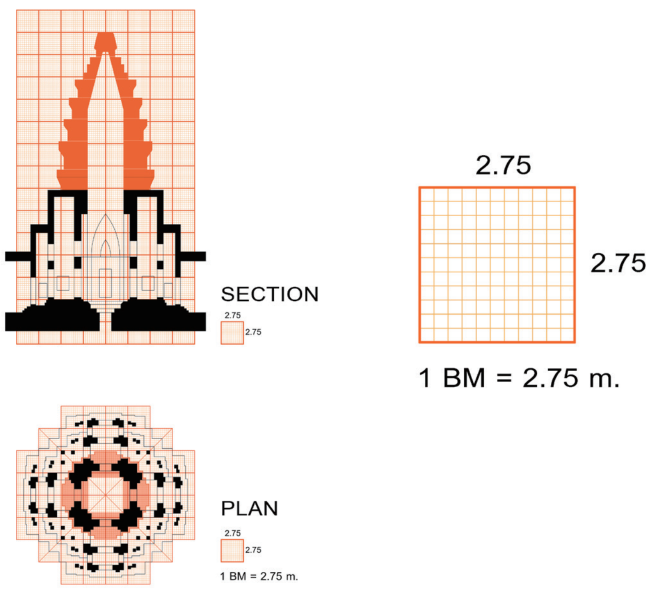


Fig. 8. (Color online) Section and floor plan of the central tower (T1) based on the basic grid module (BM) and submodules, given BM = 2.75×2.75 m^2 (1 submodule = 0.25×0.25 m^2).

submodule are 2.75 × 2.75 m^2 and 0.25 × 0.25 m^2 (2.75 ÷ 11), respectively. Specifically, 1 BM consisted of 121 submodules (11 × 11). On the basis of BM and submodules, the widest segment of the upper section of the ogive-shaped central tower is approximately 4 BM.

4.1.1 Form analysis of central tower (T1)

Figure 9 shows the form analysis of the Angor Wat temple complex's central tower (T1). In the figure, the widest segment of the upper section of the ogive-shaped central tower (T1), which is the area where two circles of identical diameter intersected, is approximately 4 BM in size (equivalent to 4 × 2.75 m^2), where 1 BM is 2.75 × 2.75 m^2 and the circle diameter is 25 BM (25 × 2.75 m^2). The circle diameter (25 BM) corresponds to the 7-24-25 common-right-triangle combination.

4.1.2 Form analysis of four-corner towers at innermost enclosure (T2–T5)

Figure 10 shows the form analysis of the ogive-shaped towers at the four corners of the Angor Wat temple complex's innermost enclosure (T2–T5). In the figure, the widest segment of the

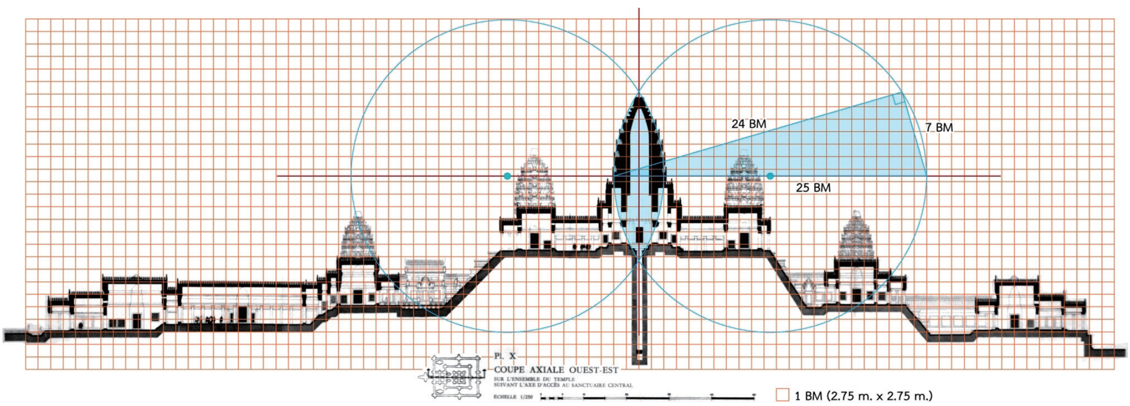


Fig. 9. (Color online) Form analysis of ogive-shaped central tower (T1) of Angkor Wat, given BM = 2.75 × 2.75 m^2 (cross-section W–E).

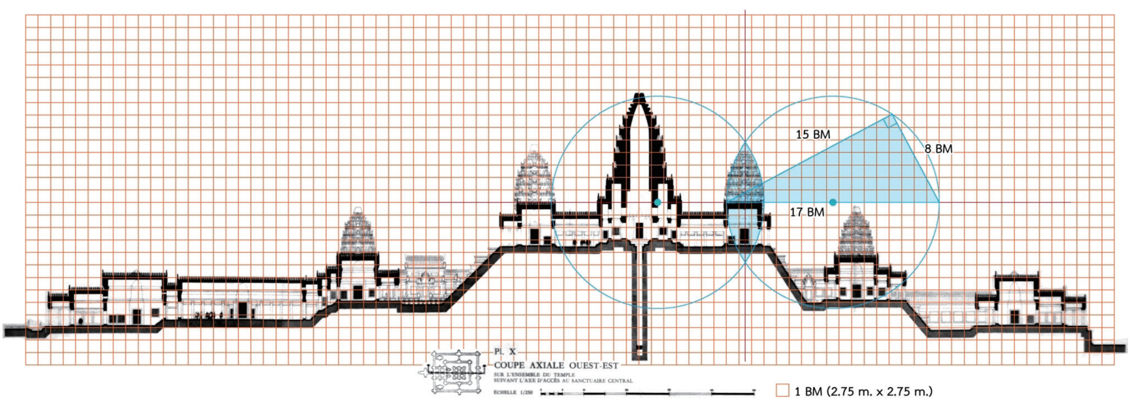


Fig. 10. (Color online) Form analysis of ogive-shaped towers at four corners of innermost enclosure (T2–T5), given BM = 2.75 × 2.75 m^2 (cross-section W–E).

upper section of each of the ogive-shaped towers at the four corners of the innermost enclosure (T2–T5) is approximately 3 BM in size (equivalent to 3 × 2.75 m^2), where 1 BM is 2.75 × 2.75 m^2 and the circle diameter is 17 BM (17 × 2.75 m^2). The circle diameter (17 BM) corresponds to the 8:15:17 common-right-triangle combination.

4.1.3 Form analysis of four-corner towers at middle enclosure (T6–T9)

In Fig. 11, the widest segment of the upper section of each of the ogive-shaped towers at the four corners of the middle enclosure (T6–T9) is approximately 2.5 BM in size (2.75 × 2.75 m^2), where 1 BM is 2.75 × 2.75 m^2 and the circle diameter is 15 BM (15 × 2.75 m^2). The circle diameter (15 BM) corresponds to the 9:12:15 common-right-triangle combination.

The ratio of the overlapping distance (X) to the diameter of the circle (D) of the central tower and the accompanying towers in Table 2 (X:D ratio) and illustrations of the three sizes of ogive geometry show the methodology of creating beautifully connected shapes by overlapping perfectly proportioned circles, which corresponds to the common-right-triangle combination. The ratio of the overlapping distance of the circle of the three towers (X) to the diameter (D) of the circle is approximately 2% (16.0–17.6%), showing a similar proportion of base and height.

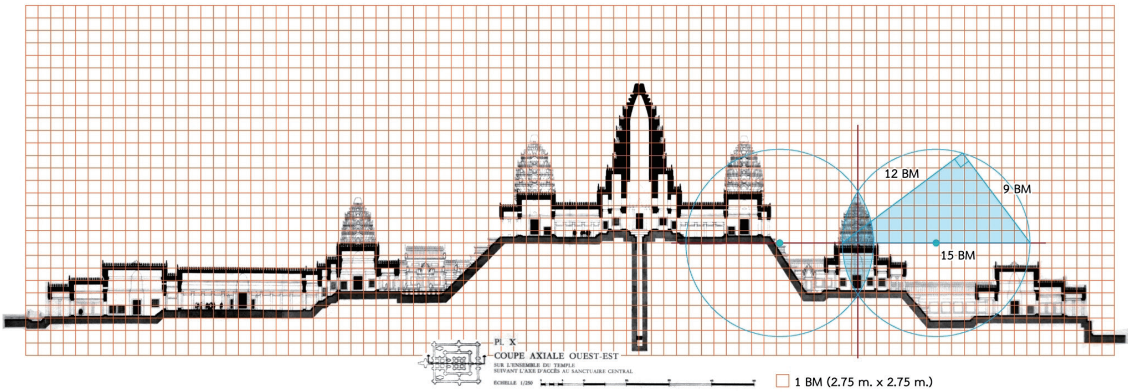


Fig. 11. (Color online) Form analysis of ogive-shaped towers at four corners of middle enclosure (T6–T9), given 1 BM = 2.75 × 2.75 m^2 (cross-section W–E).

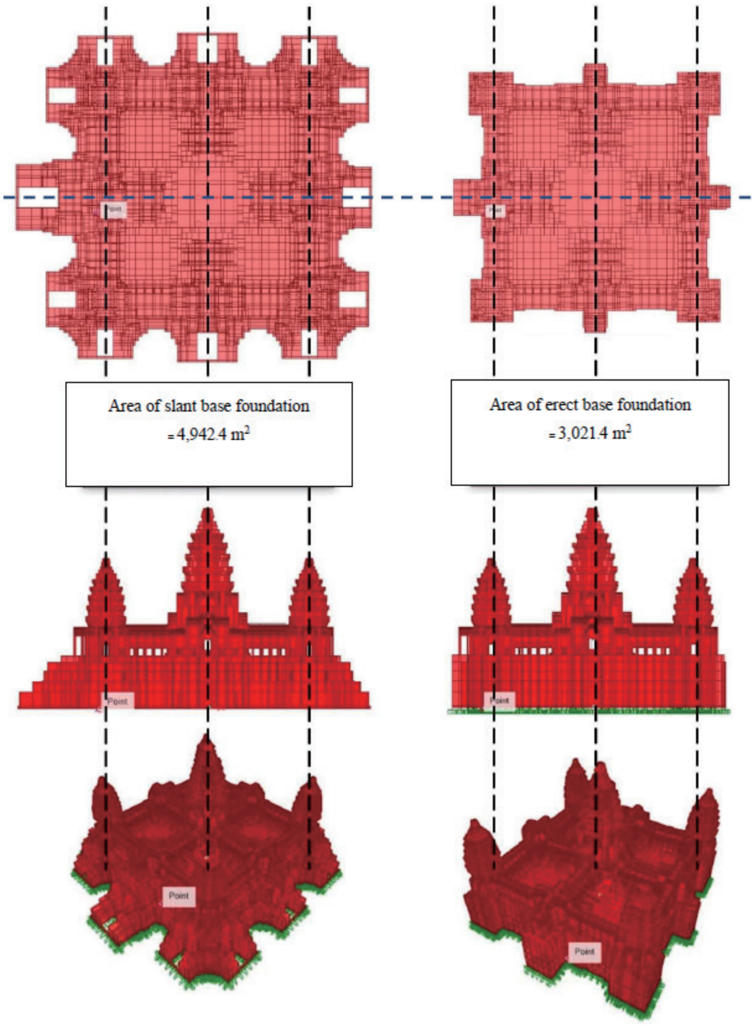
Table 2
Approximate proportions of lancet-shaped roof of nine towers at the center and corners of the second and third enclosures of the Angkor Wat sanctuary.

Lancet-shaped roof	Common right triangle length	Overlapping distance, X	Diameter of circle, D	X:D ratio
Central tower	7:24:25	4 BM	25 BM	0.160
Towers at corners of first square enclosure	8:15:17	3 BM	17 BM	0.176
Towers at corners of second rectangle enclosure	9:12:15	2.5 BM	15 BM	0.167

4.2 Structural analysis

4.2.1 Structural analysis of central tower cluster

Figure 12 comparatively shows the elevation views of the central tower cluster sitting on the 12 m slant base foundation [Fig. 12(a)] and erect base foundation [Fig. 12(b)]. The structural analysis revealed that the total reaction on the 12 m slant base foundation is 133375 T and the total reaction on the erect base foundation is 104398 T. This is because the slant base foundation has a larger mass than the erect base foundation. From the AutoCAD drawing, we found that the area of the 12 m slant base foundation is 4942.4 m^2 and that of the erect base foundation is 3021.4 m^2. As a result, the bearing stress values of the slant base foundation and central tower cluster (erect base foundation) are 26.99 and 34.55 T/m^2, respectively. The bearing stress of the erect base foundation had been increased to 28% of the bearing stress of the slant base foundation. As



(a) (b)

Fig. 12. (Color online) Analyses of total reactions of the (a) slant base foundation = 133375 T and (b) erect base foundation = 104398 T.

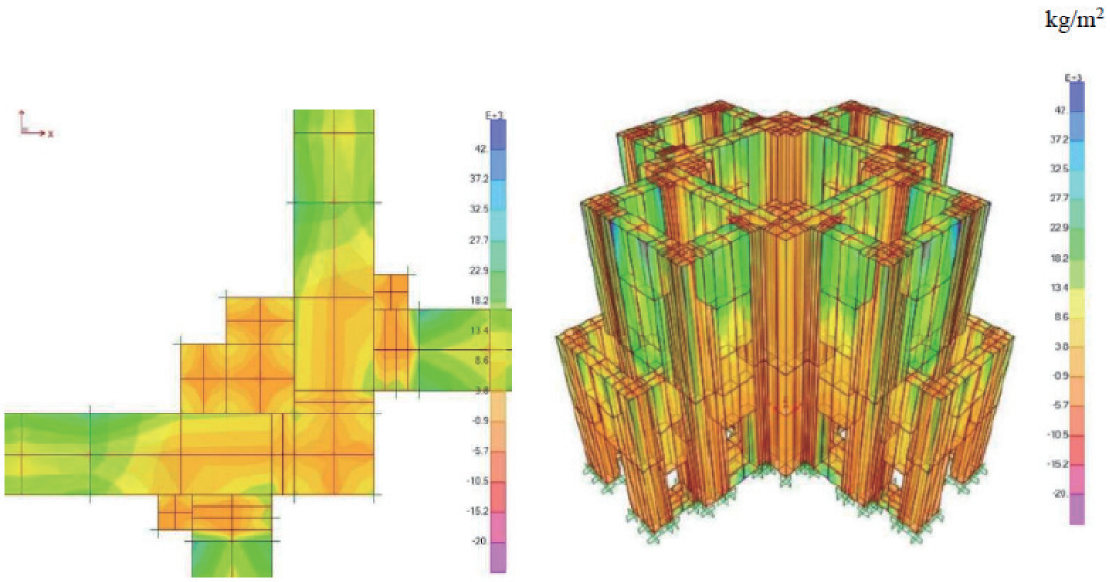
shown in Figs. 12(a) and 12(b), the advantages of the slant base foundation used in Angkor Wat are the function of the slant as a stair and a larger area for load distribution, demonstrating that this structure was designed according to the form-follows-structure principle.

4.2.2 Structural analysis of core structures of central tower

Figure 13 illustrates the stress contour of the bearing walls of the central tower cluster of Angkor Wat, excluding the ogive-shaped upper section and corbel arches. The perspective view was rendered, given the minimum stress of −20000 kg/m^2 and the maximum stress of 42000 kg/m^2.

The erect and tall walls of the core structure of the central tower cluster were braced (on all sides) by low-tiered walls to increase the wall bearing of the core structure. The finding thus demonstrated the structure-follows-form principle of the Angkor Wat sanctuary.

The wall corners of the core structure are exceptionally large to strengthen the bearing walls. Figure 13(a) shows the stress contour of a wall corner of the core structure of the central tower cluster, given a narrower stress range of −20000 to 42000 kg/m^2. Figure 13(b) shows the perspective view of the stress contour of the bearing walls of the central tower cluster of Angkor Wat, excluding the ogive-shaped upper section and corbel arches. The result from the applied load, the self-weight of Angkor Wat, presents a stress lower than the uniaxial and tensile strengths of sandstone. From Table 1, the conservative compressive and tensile strengths of sandstone are −15 and 4.5 MPa, respectively; these conservative values are still higher than 10 times the maximum stress in the building. The architectural shape of the central tower is ogive



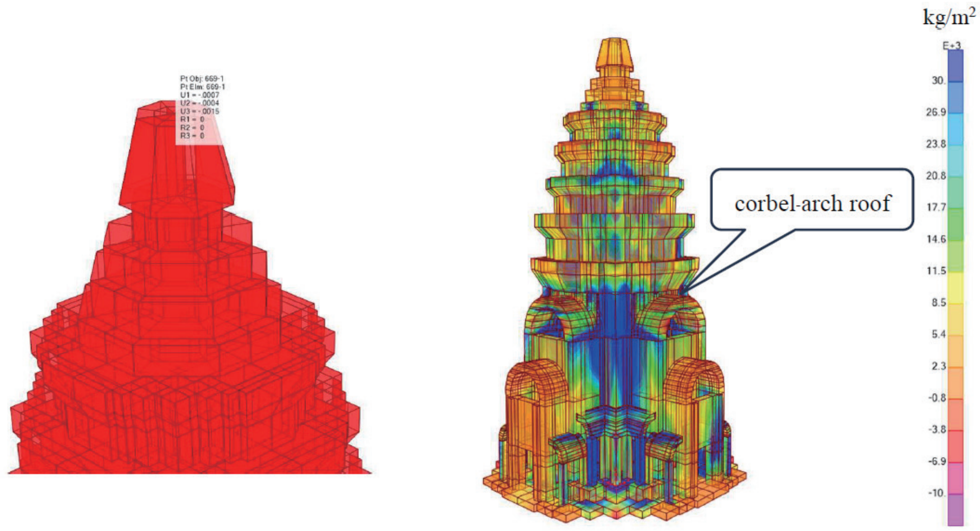
(a) (b)

Fig. 13. (Color online) (a) Stress contour of a wall corner of the core structure of the central tower cluster and (b) perspective view of stress contour of bearing walls of the central tower cluster.

and the core structure is constructed following the architectural shape, as shown in Fig. 13(b), resulting in the bracing of the central tower in all directions, which indicates the structure-follows-form principle.

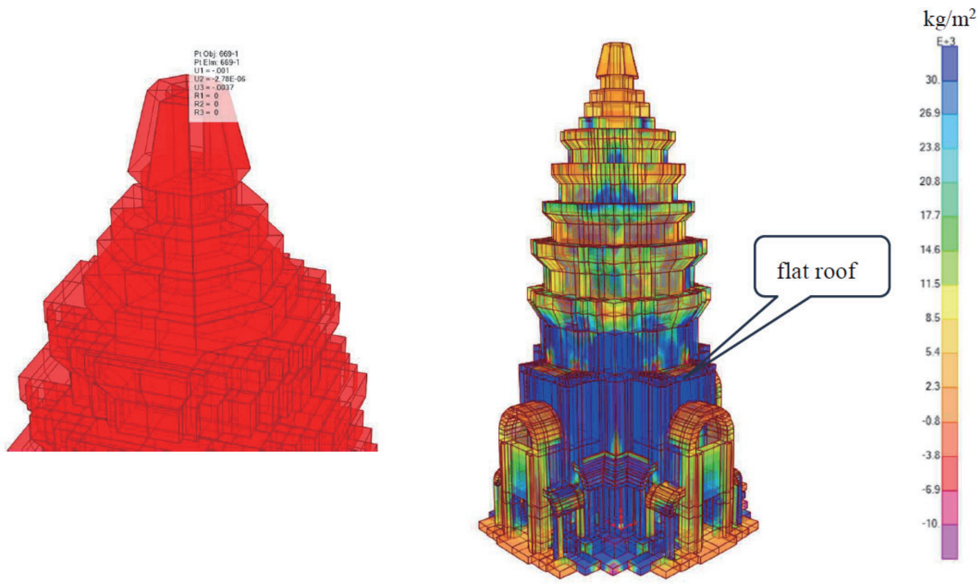
4.2.3 Comparison between corbel-arch and flat-roofed bracing walls of central tower

Figures 14 and 15 show the central towers of Angkor Wat (T1) with corbel-arch and flat-roofed bracing walls, respectively. The central tower with corbel-arch bracing walls has a less



(a) (b)

Fig. 14. (Color online) (a) Displacement of the top of central tower with corbel-arch bracing = 1.5 mm. (b) Contour of maximum stress in solid element of central tower with corbel-arch bracing.



(a) (b)

Fig. 15. (Color online) (a) Displacement of the top of central tower with flat-roofed bracing = 3.7 mm. (b) Contour of maximum stress in solid element of central tower with flat-roofed bracing.

intensive stress distribution than that with flat-roofed bracing walls. Because of the behavior of the distributed load, which transfers from top to bottom, the geometry of each member affects its load-bearing capacity. Likewise, the displacement of the top of the central tower with corbel-arch bracing walls (1.5 mm) is less than that with flat-roof bracing walls (3.7 mm). This indicates that corbel-arch bracing walls not only make the central tower more aesthetic but can also be used to strengthen the structure of the central tower, which indicates the structure-follows-form principle.

5. Conclusions

The precise and harmonious geometry of Angkor Wat and its structure, with regards the design principle, can be summarized as follows:

The study of the Angkor Wat plan with BM = 2.75×2.75 m^2 shows that the ogive shapes of the central tower and eight towers of the inner and middle enclosures are of varying sizes based on the common right triangle corresponding to the 7:24:25, 8:15:17, and 9:12:15 Pythagorean ratios. The ogive shapes of the central tower and others can follow the curve of the arc generated by the circle with the ratio of the overlapping distance (X) to the diameter of the circle (D) being between 0.160 and 0.176, as indicated in Table 2.

The analysis of the central tower cluster base shows that the bearing stress of the slant base foundation is less than the bearing stress of the erect base foundation. This indicates that the slant base of the Angkor Wat central tower cluster was designed according to the form-follows-structure principle.

The analysis of core structures of the central tower also shows that the maximum compressive and tensile stress values in the solid element are significantly less than the conservative compressive and tensile strengths of sandstone. The ogive shape of the central tower also gives the lateral bracing of the erect and tall wall in all directions at the base, resulting in the low compressive and tensile stress values in all the elements. The comparison of the analyzed results of corbel-arch bracing and flat-roofed bracing shows that the stress distribution of the central tower and the displacement of the top of the central tower in corbel-arch bracing is less than those in flat-roofed bracing. These show that the structure ogive shape and corbel-arch bracing of the central tower are designed according to the structure-follows-form principle.

In conclusion, the structural analysis of the central tower cluster of Angkor Wat using the architectural geometry form showed that stress in all the elements does not exceed the material strength. These results prove that the buildings not only look magnificent but also robust and have been standing for the past hundreds of years.

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