THE STRUCTURAL PERFORMANCE OF THE "PADMAKARA" STUPAS UNDER GRAVITY LOADING

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Sri Lanka is a country with one of the longest histories in giant brick structures, and most of these are Stupas. The "Padmakara" shape is one of the architectural shapes that is said to be used for the construction of stupas in Sri Lanka. However, presently there are no surviving ancient stupas that can be used to identify the exact architectural shape of this Stupa type. Some archaeologists/architects have proposed different imaginary shapes for this Stupa type. Nevertheless, any structural performance analysis of these proposed shapes has not been previously performed. Thus, this study focused on the analysis of the structural performances of different architectural models proposed for the "Padmakara" shape under gravity loading, which is the governing design load case of a stupa in general. According to the analytical results of this study, fairly large areas, where considerable tensile stresses existed were found in both the architectural designs considered for the analysis relevant to the "Padmakara" shape. Such large areas under tensile stresses have not been reported in previous studies carried out on other common architectural shapes that exist in ancient stupas. It may hint that the structural inefficiency of this shape, which could be one of the reasons for the non-existence of any surviving ancient "Padmakara" stupas in the country.

Keywords: Stupa, "Padmakara" shape, tensile stress, structural performance

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INTRODUCTION

The construction of stupas is considered an act of great merit by Buddhists. Historically, the purpose of building stupas was mainly to enshrine the sacred relics of the Lord Buddha. It is a spectacular Buddhist monument with its main function being to preserve relics and different religious objects, as well as offer to believers a place to meditate and pray.

In Sri Lanka, stupas have been an integral part of the country's religious and cultural heritage for over two thousand years. The country is home to many ancient and historically significant stupas, some of which are considered to be among the most important Buddhist sites in the world.

Typically, a Sri Lankan stupa consists of several main components and Figure 1 shows such main components in graphical form.

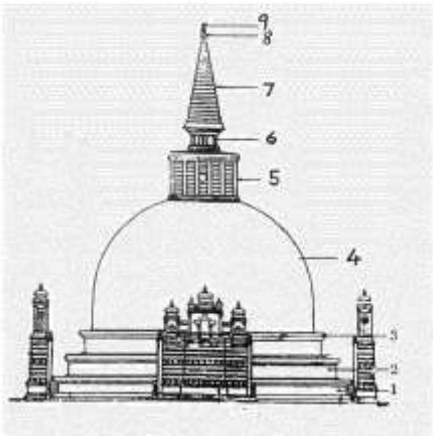

Figure 1: Main components of a Sri Lankan stupa (1,2,3-Basal rings, 4-Dome, 5-Square chamber, 6-Cylinder/s, 7-Spire, 8-Minaret, 9-Crystal).

Over time, different architectural shapes have been used for the stupas. The five main types of shapes used can be identified in the context of the ancient Sri Lankan stupas. Such main shapes are listed below.

1. Bubble shaped (Bubbulaakara)
2. Paddy heap (Dhaanyaakara)
3. Bell shaped (Ghantaakara)
4. Pot shaped (Ghataakara)
5. Lotus shaped (Padmaakara)
6. Nelli fruit shaped (Amlakara)

The typical shapes of the above types are shown in Figure 2. According to a publication of Ranaweera,(1998), the bell shape is the most common used for ancient stupas and for larger stupas like the Jathawanaramaya, while in the Abayagiriya, the paddy-heap shape was used. Some stupas have been changed in size and shape during re-constructions and restorations.

The last two types (Padmakara and Amlakara shapes) have been very rarely used and presently, there are no any fully surviving ancient stupas that have the Padmakara shape. However, it is believed that stupas like the Vijeyarama stupa (Anuradhapura), Indikatuseya (Mihintale), Demalamahaseya (Polonnaruwa) and Stuthigara chittya (Dedigama) may initially have had this shape.

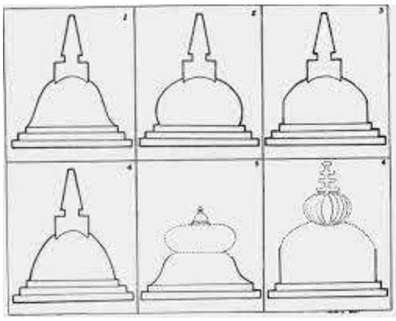

Figure 2: Stupa Shapes (Godakumbure, 1976):-1-Bell, 2-Pot, 3-Bubble, 4-Paddy-heap, 5-Lotus,6-Nelli fruit

Due to the non-availability of any physical structure or any ancient drawings explaining this shape, archaeologists and architects have suggested various imaginary shapes to define the "Padmakara" shape. Bandaranayake, (1990) suggested that the shape shown in Figure 3 as the "Padmakara" shape.

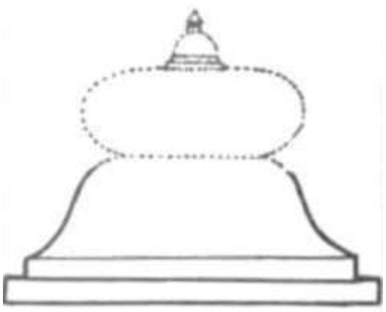

Figure 3: Architectural shape proposed by Bandaranayake (1990) of the Padmakara shape.

Karunaratne, (1998) has suggested a different shape to be the "Padmakara" shape in study on the design and development of Buddhist architecture. The sketch of that proposed shape is shown in Figure 4.

Figure 4: Architectural shape proposed by Bandaranayake (1990) of the Padmakara shape

These two are the commonly used shapes to define the "Padmakara" shape in archeological and architectural forums. Thus, this study focused on studying the structural performances under gravity loading of these proposed shapes and checking whether there were any links for discontinuing the usage of this shape by ancient Sri Lankans, in term of the structural engineering aspects of the shape. The Vijayarama stupa in Anuradhpura was selected as a case study as all its dimensional parameters were well documented in a study by Prematilleke and Silva, (1968).

METHODOLOGY

The study used 2D axisymmetric models to simulate the structural behaviour of the selected shapes using SAP 2000 software. Most previous research has also used SAP 2000 for their analytical studies. The Vijayarama stupa exists as a partially restored stupa with only a few meters in height, from basal ring level as shown in Figure 5(a), existing today. Figure 5(b) shows a typical scaled cross-section of the stupa at the time of restoration.

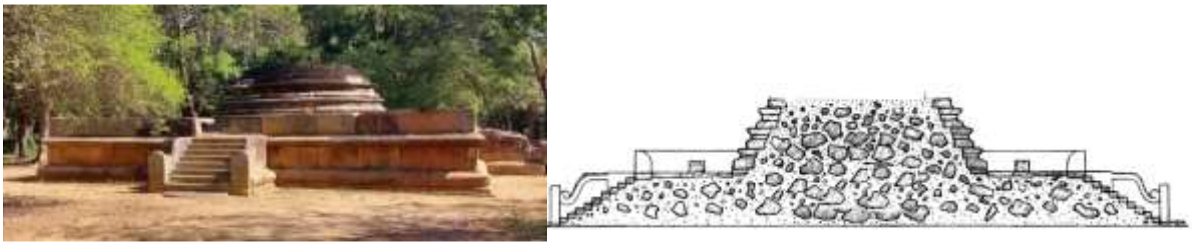

Figure 5: (a) Photograph of the restored Vijayarama stupa (b) A typical scaled cross section of the stupa

Based on the measurements of the Vijayarama stupa, two architectural models were prepared based on Bandaranayaka's (model 1) and Karunarthne's (model 2) proposals for a "Padmakara" stupa. These designs are presented in Figures 6(a) and 6(b).

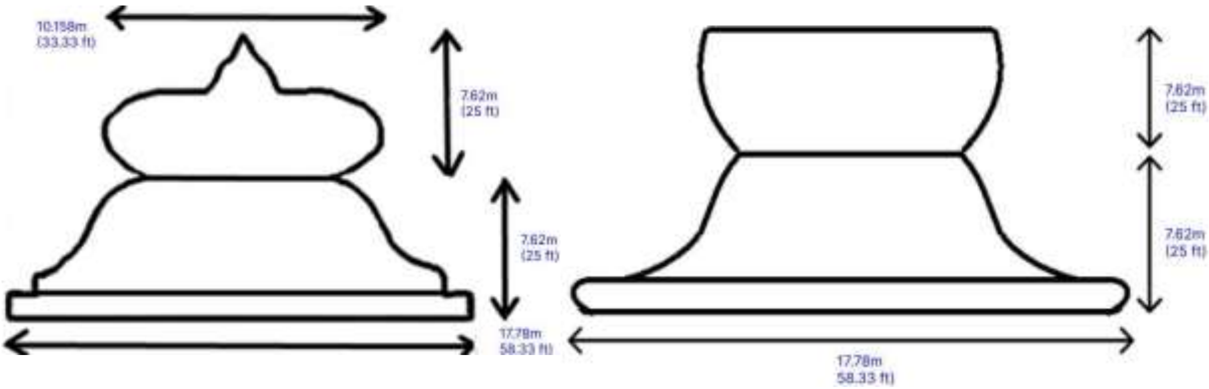

Figure 6: (a) Developed model for the Vijayarama stupa based on Bandaranayaka's proposal, (b) Developed model for the Vijayarama Stupa based on Karunarthne's proposal

Separate 2D axisymmetric models were prepared for each case using SAP 2000 software. The material properties for the analytical models were selected based on data published in relation to the Abayagiristupa (Ranaweera , 1998), which belongs to the same era. Accordingly, the Elastic modulus, density, and Poisson ratio are selected as 4.5 x 10^9 Pa, 17.48kN/m^3, and 0.25 respectively. The 4 Nodes quadrilateral elements with the auto meshing option were used to develop SAP 2000 models.

RESULTS AND DISCUSSION

The scope of the study, comprised two developed models that were analyzed under gravity loading. To verify the analytical accuracy of the prepared SAP 2000 models, static equilibrium checks (considering symmetry as well) of the prepared models were performed and acceptable results were observed.

The axial stresses as graphical outputs in vertical direction and horizontal direction of the two considered models under gravity loading is presented in Figures 7 and 8. All stress contours have units of kPa.
According to the reported vertical stresses, the highest compressive stresses were reported close to the bases of each model. The reported highest vertical compressive stress in model 1 and model 2 are 0.44N/mm^2 and 0.45N/mm^2, respectively. The reported maximum horizontal compressive stresses are 0.22N/mm^2 and 0.15N/mm^2 in model 1 and 2, respectively. These stresses are reported at the edges, where the upper dome and lower dome meet. In the comparison of these stresses with the typical compressive strength of the bricks used in same era, these reported stresses are far below the compressive strength of such bricks. (The reported compressive strength of the bricks of used in the Yudaganawa Stupa is 6.38N/mm^2 (Karunananda et al, 2018) while the reported compressive strength of the bricks used in the Abayagiri Stupa is 8.50N/mm^2 (Ranweera ,1998)).

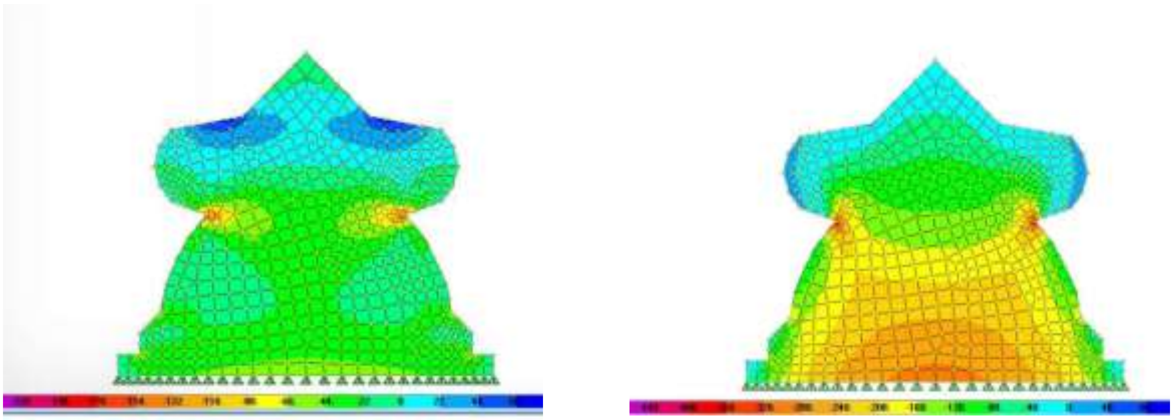

Figure 7: (a) Axial stresses of model 1 in horizontal direction (b) Axial stresses of model 1 in horizontal direction

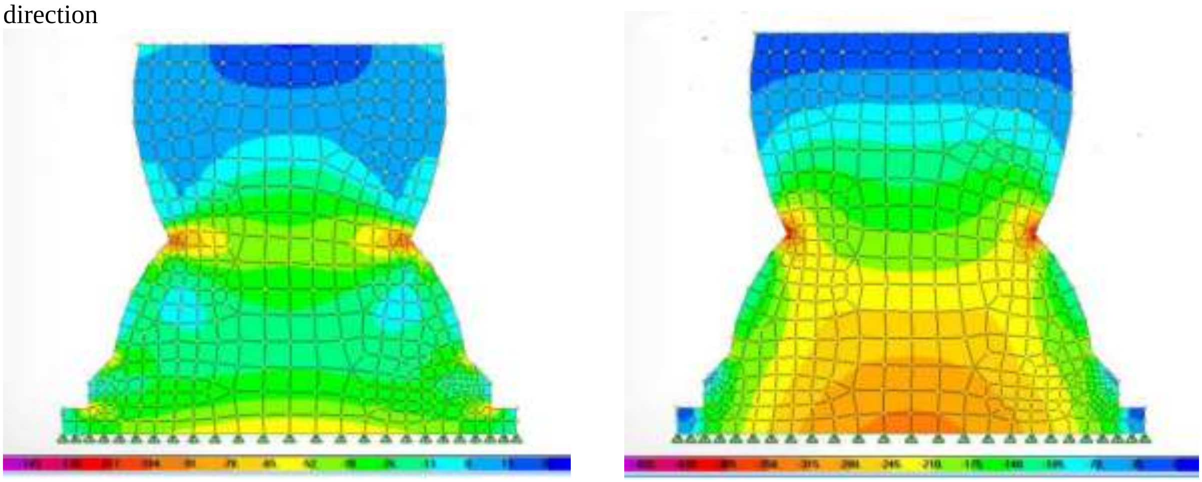

Figure 8: (a) Axial stresses of model 2 in horizontal direction (b) Axial stresses of model 2 in horizontal direction

The maximum horizontal and vertical tensile stresses reported in these models are tabulated in Table 1with reported locations. Accordingly, the tensile stresses of model 2 are considerably low when compared with model 1. However, these tensile stresses are lower than the reported tensile strengths of the bricks of same era (The reported tensile strength of the bricks used in the Yudaganawa Stupa being 0.55N/mm^2 (Karunananda et al, 2018) and the reported compressive strength of bricks of the Abayagiri Stupa being 0.85N/mm^2 (Ranaweera ,1998)). Even though the magnitudes of the reported tensile stresses in these models are comparatively lower than the reported tensile strengths of the old bricks from the same era, the tensile stresses have been distributed through considerably larger areas in both models (See Figure 7 and Figure 8).

Model	Maximum Horizontal stress	Maximum Vertical stress
Model 1	0.07N/mm^2 (In the area where the top dome and uppermost part are connected with each other)	0.08N/mm^2 (Edges of the overhanging parts of the upper dome)
Model 2	0.03N/mm^2 (Near the connection of the basal rings and the bottom dome)	0.03N/mm^2 (close to the top)

Table 1: Maximum and Minimum Horizontal, and Vertical stresses between Shape 1 and Shape 2

In other stupa types, tensile stresses have been reported in very limited areas under self-weights as reported by Ranaweera (1998). For example, in the Jathawanaramaya, which has used the paddy-heap shape dome, no tensile stresses are reported in the dome (Ranaweera, 1998). Figure 9 shows a vertical stress distribution of the Jethawanaramaya according to the analysis performed by Ranaweera (1998).

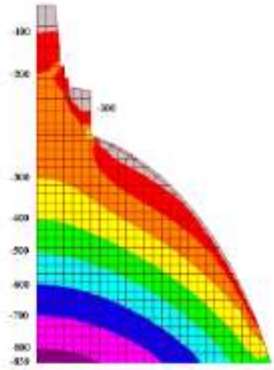

Figure 9: Vertical stress distribution of the Jethawanaramaya according to the analysis performed by Ranaweera (1998).

The existence of prolonged tensile stresses in the larger region (as these tensile stress regions occur under self-weight conditions) would have come to a structural concern as bricks are not usually expected to carry tension. It may lead to the collapse or partial collapse of a stupa that has a shape similar to either model 1 or model 2, with temperature and seismic loads possibly worsening the stress conditions in these tensile regions. Therefore, the structural feasibility of using the shapes of model 1 and model 2 for the construction of a stupa is not recommendable from a structural engineering perspective. Ancient Sri Lankans could have also become aware of the structural deficiency of this stupa shape, which may have led to the minimal usage of this shape in the construction of stupas.

CONCLUSIONS/RECOMMENDATIONS

As per the aim of this study, the studying of the structural engineering performance of the suggested architectural shapes of the "Padmakara" stupas, by archeologists and architects, under gravity loading was carried out. According to the findings of this study, the development of tensile stresses in considerably large areas of the stupa would occur if either of the shapes suggested for the "Padmakara" stupa by modern day archeologists and architects are adopted. Even though these tensile stresses are below the recorded tensile strengths of old bricks, the existence of prolonged tensile stresses in a larger area cannot be recommended as bricks are not usually used to withstand under tensile stresses.

Hence, the considered shapes for this analysis would not be feasible to construct a stupa from a structural engineering perspective and our ancestors may have also become aware of this concern. This may be the reason for the existence of the very small number of ancient "Padmakara" stupas in the country.

However, it is recommended to extend this study further by considering other types of loading (temperature , seismic, etc) and other alternative shapes (if any) that have been proposed for the "Padmakara" shape to further justify this conclusion.

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