Study on the Cracks Developed in Dematamal Viharaya, Uva Province Sri Lanka

Abstract

Stupas of Sri Lanka stand as proud examples for the engineering Excellence of ancient Sri Lanka. Dematamal Viharaya at Butthala is one of the oldest Stupas in Sri Lanka built in the 2nd Century BC. It is a, 19m tall non-plastered brick structure.

This Stupa has developed since 1998. Cracks have initiated from the Pesawalalu and propagate to the top of the Dome. The width of these cracks varies from 0.2mm to 0.5mm.
The research covered in this report is aimed at the identification of the causes for the cracks and to propose corrective actions.

A comprehensive study was carried out to identify the possible causes for the cracks which may be due to self weight and shape of the stupa, expansive nature of soil, arch action induced due to separation of old and modern masonry. Experiments were done to assess the expansive nature of the soil and A Finite element analysis was carried out using the Finite element software SAP2000.

The results revealed that the possible cause can be the arch action induced due to separation of old and modern masonry. Increasing the bearing of the new brick work at the base and the installation of a tie beam around the *pesawalalu* are the two corrective actions suggested in this report.

Keywords: Cracks, Arch Action, Thermal loads

1. Introduction

Sri Lankans have excelled in the art of building for thousands of years. They built huge Stupas, Tanks and Temples with great skill and resourcefulness. The creation of Stupas has been one of their greatest achievements unmatched by anyone else in the world even after thousands of years.

Thuparama built by King Devanampiyatissa is the oldest Stupa of Sri Lanka. Jetavana Stupa which was the third largest structure at that time, only surpassed by the Pyramids at Giza, Mirisaveti and Ruwanvelisaya built by King Dutugamunu, Abayagiri Stupa and Tissamaharama are few of the examples of the great talents of our ancestors.

Normally a Stupa consists of a dome and has three cylindrical basal rings (*Pesawalalus*) at the bottom. The dome carries the square chamber called the *Hatharaskotuwa*, which is a solid structure. Then come one or more cylinders, the spire and the pinnacle. All these components are solids, and except the square chamber, are axisymmetric.

According to Ranaweera (2004) the ancient Stupa was mainly built with high quality burnt bricks and plaster. The outer surface of the Stupa was water proofed using a thick plaster layer. The bricks used in ancient Stupas were much larger than modern bricks and the mortar used in the brickwork of ancient Stupas was a clay slurry type - called "butter clay". This was spread between different courses of bricks in very thin layers, unlike the thick layers used in modern brickwork, basically to fill the cavities between bricks and make them almost touch each other.

Conservation is an important part of any ancient monument and has been followed to a great and satisfying extent in Sri Lanka. During the colonial era, the English rulers took a great interest in these ancient monuments. Most sites have been surveyed, recorded, and declared as archaeological sites.

With the Buddhist revival which came in the latter half of the 19th century, different religious organizations undertook restoration works of many historically important Stupas. During the last three decades of the 20th century, some major conservation works on Stupas as well as other temples were undertaken by the Central Cultural Fund as well as the Department of Archaeology.

1.1 Dematamal Viharaya - Buttala

The Ruhuna region in the deep South of Sri Lanka has many Buddhist Stupas scattered throughout the entire area. Dematamal Viharaya is one such Stupa, located at Helagama on the Buttala-Okkampitiya road. The Stupa lies about 4km from the Buttala town. It is one of the oldest Stupas in Sri Lanka. This is a, 19m tall non-plastered brick structure built by King Mahanaga of Ruhuna who was also the brother of King Devanampiyatissa. Restoration of the Stupa started in 1975 and was completed in 1990. It was repaired again for the last time in 1992 for the *Gamudawa* held in the region.

This Stupa has developed some cracks in the recent past. The cracks started to appear in 1998 and they were shorter and thin in the beginning but have increased in length and width in the past 13 years. Expansive nature of soil, Shape and self weight of the structure, the discontinuity between the old and new parts of the Stupa, and the creep in masonry due to thermal loads are few of the suspected reasons for the cracks. In this paper these suspected reasons have been analysed in detail.

2. Methodology

Expansive nature of soil in the area had to be analysed, for this samples were collected in the area and they were tested for many soil parameters. They were compared with standard values to measure the expansiveness of the soil.

Geometric data of the Stupa were obtained from the Department of Archeology. Brick samples were collected at the site and tested for its material properties. Properties of the ancient bricks were taken from associated literature.

SAP2000 was used to create models of the Stupa to check for effects due to self weight and shape of the Stupa, creep in masonry and the discontinuity between the old and modern structures.

3. Results and Discussion

As mentioned above four of the suspected reasons namely the Expansive nature of the soil, Self Weight and shape of the Structure, Creep in masonry due to thermal loads and the discontinuity between the ancient and modern parts of the structure have been analysed and the results are discussed below.

3.1 Expansive nature of Soil

One of the common causes for foundation problems is the expansive nature of soil. These soils are capable of absorbing water and they increase in volume. Due to the volume increase in soil, it will heave and that will in turn lift the building and initiate cracks on it which could happen the other way around given the circumstances. When the moisture content is low expansive soil might collapse and this might cause settlements causing cracks in the buildings.

Expansive nature of soil was one of the suspected reasons for the cracks in Dematamal Viharaya. It was decided to test samples for certain parameters and check whether the soil was expansive enough to cause cracks in the structure.

Samples were taken at two locations, near the Bo tree which was 10m away from the Stupa and from the surrounding paddy field. Tests such as Atterberg Limits, free swell index, swelling pressure test and hydrometer test were conducted on the soil samples. The following results were obtained from the tests.

Table 1: Soil test results, conducted on soil samples collected in Dematamal Viharaya, Buttala

	Sample 1[1]	**Sample2**
Dry Method		
Liquid Limit	19.0%	21.5%
Plastic Limit	12.6%	12.6%
Plasticity Index	6.4%	8.9%
Wet Method		
Liquid Limit	24.8%	25.3%
Plastic Limit	23.0%	23.4%
Plasticity Index	1.8%	1.9%
Clay percentage	18.0%*	21.0%*
Activity		
Dry Method	0.36	0.42
Wet Method	0.1	0.09
Free swell Index	NIL*	9%*
Swelling Pressure	NIL*	14.6kg/cm^{2}* [2]

Expansive nature of soil can be categorised in to four, according to its severity, namely Non critical, Marginal, Critical and Severe. The results obtained from the tests were compared against limiting values for expansive soil and it was categorised in to a certain group. The limiting values were obtained from IS 1498.

The LL obtained from the dry and wet methods were less than 25% for both locations. According to the standard the range of LL for non critical expansiveness was 25%-35%. The PL is 12.6% for the dry method and close to 23% for the wet method. The range of PL for marginally expansive soil was 12%-3%. Activity for both samples for both dry and wet method were less than 0.75. According to Skempton a normal clay has an activity less than 0.75. The Swelling index and Swelling pressure of the sample taken near the Bo tree was NIL and the values were 9 and 14.6kgcm^{-3} for the other location. The value obtained for the swelling pressure in the paddy field has a very high value and can

[1] Sample 1 - Near the Bo Tree

Sample 2 - In the Paddy field

[2] Tests done by the NBRO

be considered as an outlier when comparing to other results so it was considered an experimental error and was not taken into account while interpreting the results. The rest of the values for Swelling Index and Swelling Pressure correspond to moderately expansive clay.

Even though it is not possible to assess the expansive nature of a clay with few samples, these results give a fair idea of the expansiveness of the soil found in Dematamal Viharaya. Expansive nature of soil can be ruled out when deciding on a possible reason for the cracks developed in Dematamal Viharaya.

3.2 Self weight and Shape of the Stupa

The shape and Self weight of the Stupa was another suspected reason for the cracks formed in Dematamal Viharaya. A SAP2000 model was used to analyse the effects of self weight and shape.

The geometry of the Stupa was obtained from the drawings given by the Department of Archaeology. According to Ranaweera (2000) it was decided to analyse the Stupa using ASOLID elements and the base of the Stupa was to be fixed. A computer generated mesh was used in the model.

According to the drawings given by the Department of Archaeology it can be seen that the restored Stupa had been built on the remains of the ancient Stupa. So it was decided to create model of the Stupa according to the drawings, with the ancient bricks in the bottom part and the modern bricks above.

Literature on the ancient Stupa materials was used to obtain the properties of the old bricks. The used values are given in the table below. The values had been obtained from the tests done on samples collected from Sandagiri Stupa which was built at the same period as Dematamal Viharaya and which is approximately of the same size.

Few modern bricks were collected from the site and tested for their compressive strength whereas the wet and dry densities were also obtained. Since it was not possible to get values for Poisson's ratio, Young's Modulus and the Tensile strength, values taken from associated literature (Ranaweera 2004) has been used for the modelling. The following table shows the values used in the model done with modern bricks.

Table 2: Material Properties of Ancient Bricks found at Sandagiri Stupa, Tissamaharama (Ranaweera 2004)

Density	18.4 kNm^{-3}
Young's Modulus	9790000 kNm^{-2}
Poisson's Ratio	0.27
Compressive Strength	11.6 Nmm^{-2}

Tensile Strength	1.54 Nmm-^{2}

Table 3: Material Properties of Modern Bricks

Density	19.1 kNm^{-3}
Young's Modulus	1920000 kNm^{-2}
Poisson's Ratio	0.21
Compressive Strength	3.71 Nmm^{-2}
Tensile Strength	0.55 Nmm-^{2}

SAP2000 Models were created using the above material properties and the stress contours are given in the figures below.

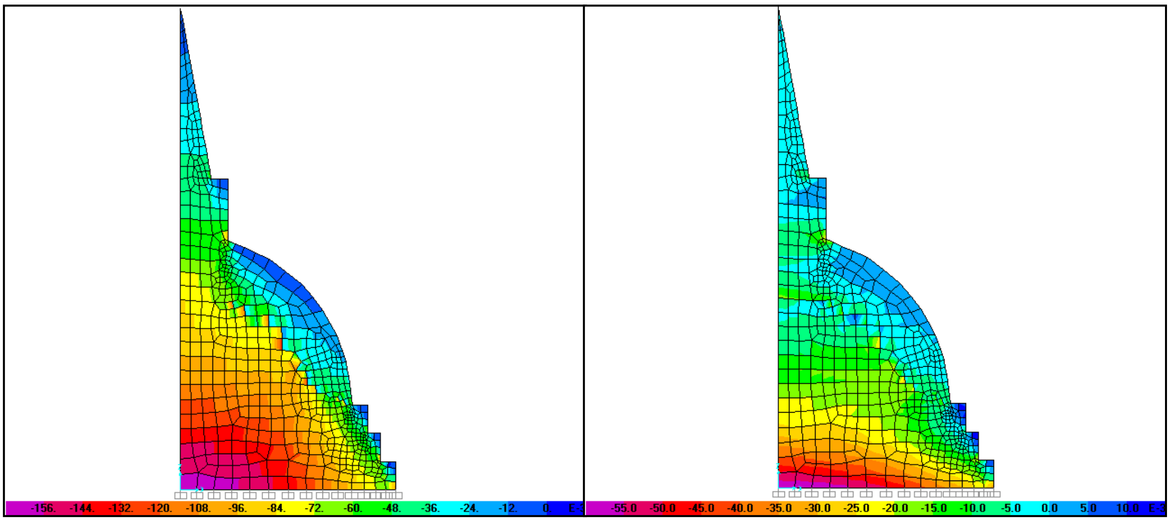


Figure : Vertical and Hoop Stresses due to Self weight of the Stupa modelled with modern brick properties

Figure 1 shows the Vertical and Hoop stresses in the Stupa. The Vertical Stresses are wholly compressive in the range of 0.156Nmm^{-2} to 0.003Nmm^{-2} and steadily increase from top to bottom. Maximum Compressive stresses can be noticed at the base. As for the Hoop stress it is mainly compressive and has a variation similar to the vertical stress, but tensile stresses also can be seen at the outer edge of the dome and in the edge of the *Pesawalalus*, where cracks have appeared in the Stupa. But the tensile stresses are less than 0.01 Nmm^{-2} which is approximately one fifth of the tensile strength of the modern bricks. So it can be concluded that the self weight had not been the reason for the cracks.

3.3 Creep in masonry due to thermal loads

The Stupa is a solid structure completely built with masonry. One of the anticipated reasons for the crack on the Stupa was the creep occurring on the Stupa due to Thermal Loads. To confirm this the ASOLID model of the Stupa was given temperatures from 20^{o}C to 35^{o}C at 5^{o}C intervals. Since it was not possible to find out the co-efficient of thermal expansion for the different materials, similar values were used for both materials. The Resulting Stress Contours are shown below.

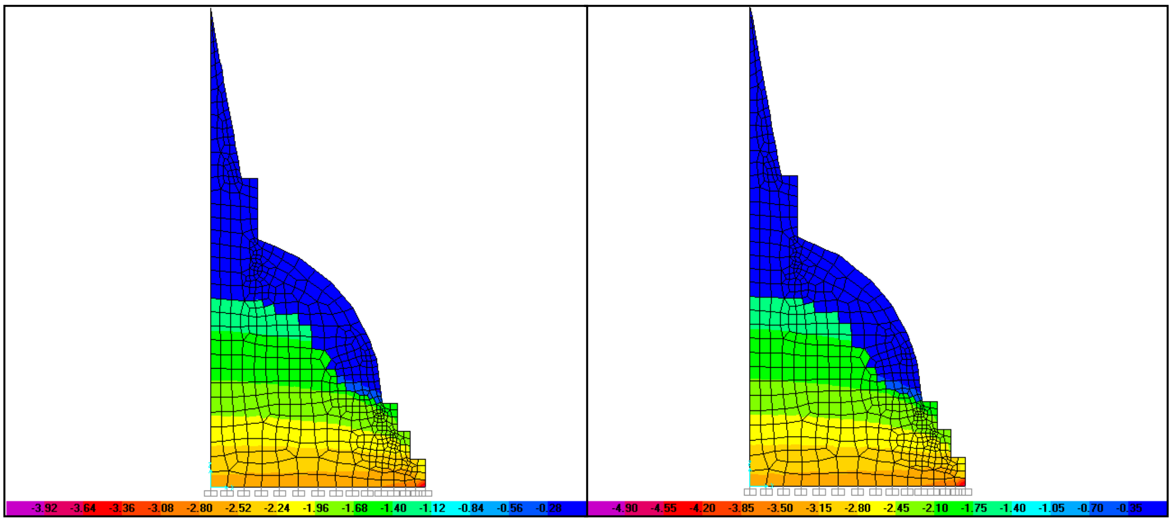
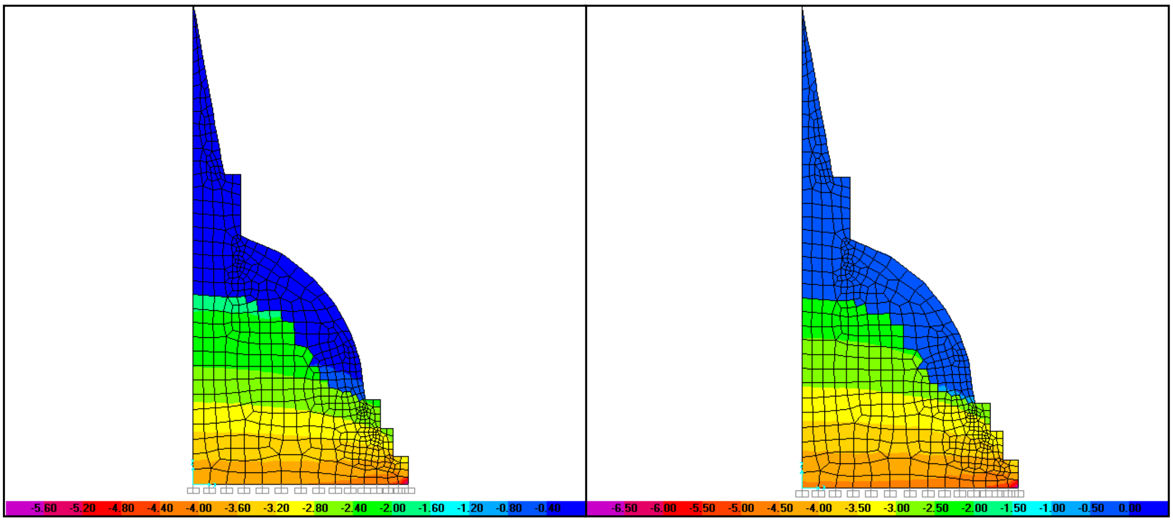


Figure 3: Hoop Stresses at 20^{o}C and 25^{o}C



From the above models it can be concluded that the hoop stresses are compressive and they increase while the temperature is increased. But the highest compressive stress obtained is $6.5 Nmm^{-2}$ in the base of the Stupa constructed with ancient bricks. This value does not exceed the strength ($11.6 Nmm^{-2}$)of the material.

3.4 Discontinuity between the old and new parts of the Stupa

The drawings obtained from the Department of Archaeology and the relevant literature, shows that before restoration Dematamal Viharaya had been a ruin of ancient brickwork with *Navanita* (Butter clay) as the binding element, which was about 12.5 m in height and consisted of the three *Pesawalalus*. The drawings of the Stupa show a profile of this mound. The new Stupa had been constructed on top of this mound using modern bricks and mortar.

Reports on the collapse of Stupas such as Mirisiwatiya and Snadagiri Stupa reveal, that the same method of construction had been employed in those Stupas prior to collapse. According to Silva WNG (2002) it was the opinion of the engineers that the main reason for the failure of Mirisaveti in 1987 was the crushing of the new brickwork at the base of the dome, which was only 2-3 feet wide. These findings helped to the development for the hypothesis described below.

Inadequate cleaning of decayed surface of the old brick work, improper keying of bricks between old and new and ingress of water into old brick work during and before construction leads to the separation of the new brick work from the old brick work. The fact that no proper measures such as reinforcement were taken to strengthen the bonding would ensure that separation of brick work was inevitable. This could result in the new brickwork acting like an arch. The arch action may lead to the increase in the hoop tension in the pesawalalu which might lead to cracks. These two ways are explained below.

I. Development of High Compressive stress at base.

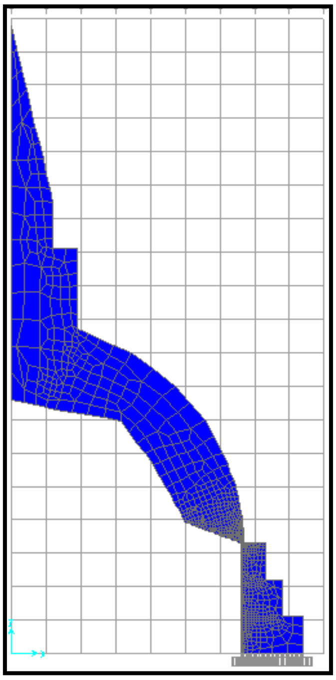
Since the new brick work acts like an arch and the whole of the modern brick work will be made to bear on the base of the arch. This will develop high compressive stresses at the base. If these stresses exceed the compressive strength of the brick then the bricks will crush. When the inadequate base crushes the arch will tend to slide out. This sliding out action will cause the arch to push out the *pesawalalu* which would in turn develop hoop tensile stresses and will initiate cracks in the *Pesawalalu* and the dome.

II. Thrust at the base due to Arch Action inducing Hoop tensile stresses in the Pesawalalu.

The arch action in the new brick work will create a horizontal thrust outwards at the base which is connected to the *Pesawalalu*, this thrust will push the circular *pesawalalu* outwards. Since this action will be resisted by the *Pesawalalu* hoop tensile stresses will be developed in the *Pesawalalu*.

These two actions would lead to the initiation of cracks in the *Pesawalalu* and lead to propagation.

The drawings give one cross section of the ancient brick work. A SAP2000 model for only the new brickwork and the Pesawalalus was created using the obtained geometry. Since it was assumed that the complete separation takes place, ancient brick work was not included in the model. The model was created with ASOLIDs. The following figure shows the vertical stress contours.



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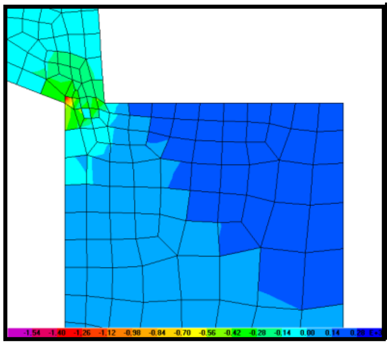

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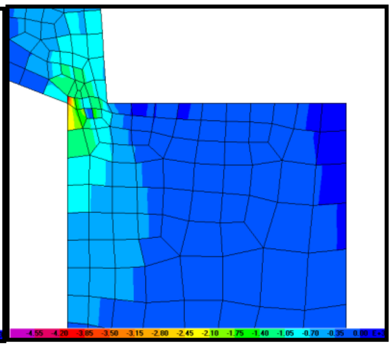

4c

Figure 4 : (a) Model used to analyse arch action (b) Hoop stresses at the base of the arch (c) Vertical stresses at the base of the arch

It can be clearly noted that a increase in compressive stress occurs at the base, whether it be Vertical, Radial or Hoop Stress. In the case of Vertical stress the increase compared to the model with both materials is forty times higher where as it is 400 times an 90 times higher in the radial stress and Hoop stress respectively.

It also shows the development of high hoop tensile stresses in the *pesawalalu* edges thus proving the second part of the hypothesis to be true. The general range of the Hoop stress at the pesawalalu is 0.14-0.28 Nmm^{-2}, an increase of 250 times compared to the self weight model.

4. Concluding Remarks

From all the work done for this research it could be concluded that the expansive nature of soil and the self weight do not contribute to the formation of cracks. The work done on creep on masonry does not reveal any conclusive evidence.

The work on arch action seems to reveal some promising results. Even though the results do not definitely lead us to a conclusion the results obtained point to a solution in this direction.

A notable point is that only one profile was available for the new and old brick work interface. A meeting with Mr. Gamunu Silva who was a key party in the restoration of Mirisivatiya stupa revealed that 18 profiles were considered and modelled to assess the Mirisivatiya collapse.

Besides only 3 brick samples were used to assess the strength of the new brick material, and the old material was not assessed at all and the values for comparison and modelling were taken from literature. Proper results could be obtained if more representative material properties could be used.

All of the above should be taken into account while arriving at a conclusion. The analysis done helps to come to a conclusion that if the separation of materials result in arch action then it would lead to the development and increase of vertical compressive and hoop tensile stresses which would in turn lead to the formation of cracks. Remedial actions have been proposed for the stupa to overcome the problem.

Apart from these there are possible reasons which have not been explored and analysed. The roots of the Bo tree, which is just 10m away from the stupa, could be the inducing factor for the cracks. Settlement of foundation could also be a contributory factor for the formation of cracks. Foundation details, bed rock dept are required to do further analysis on this.

Assuming the arch action has in fact induced the formation of cracks, two types of remedial action are proposed. Both methods have been used in conservation works in other stupas which experienced similar kind of failure.

High compressive stresses develop at the base of the new material. This is because the area of the bearing is very small, thus not able to carry the stresses induced by the arch action. By increasing the bearing this problem could be solved. A tie beam around the pesawalalu will be able to compensate for the hoop tensile stresses developing at the pesawalalu.

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