STRUCTURAL ANALYSIS OF ANCIENT STUPA IN SRI LANKA

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Ancient stupas in Sri Lanka hold immense historical, archaeological, and religious significance. These monumental structures, dating back to ancient times, serve as tangible links to the country's rich cultural heritage. Therefore, it is imperative to restore and conserve these structures with great care so that future generations can witness the remarkable engineering technology of the past. However, it is essential to acknowledge that some restoration attempts in the past have resulted in catastrophic failures. These failures were mainly due to the complex structural behaviour of these massive structures due to complex geometries and different loading conditions. Consequently, these misguided restoration efforts have not only failed to preserve the historical value of the stupas but have also led to their degradation. The purpose of this research is to tackle the limitations found in current finite models and understand how they affect the restoration work. To achieve this aim, the study has two main objectives. Firstly, it investigates whether shifting from a 2D axisymmetric analysis to a more detailed 3D analysis is necessary. This change could significantly impact how successful restoration efforts are. Secondly, the research examines the lasting effects on stupas caused by moisture-induced expansion and the impact of temperature changes. Both of these factors play a crucial role in the restoration of stupas.

Deegawapi stupa was taken as the case study to achieve the objectives of the research. Then, 2D axisymmetric and 3D non-axisymmetric models of Deegawapi stupa were analysed under self-weight using the finite element package ABAQUS. Results indicated minimal divergence in maximum stress values between the two models. Notably, comparing full 3D analysis to partial (half and quarter) stupa analyses reveals negligible differences in outcomes, accompanied by significantly reduced computational time in wedge analyses. Accounting for material non-homogeneity between the original and new components of the stupa, there was stress variation in the structure compared to the homogeneous model. Notably, there was a high stress concentration between the interface of new and old material. However, stress concentrations at this interface were within material strength limits. Given that ancient stupas are predominantly constructed from clay bricks and a butter-like plaster, both of which are highly susceptible to moisture-induced expansion, this study conducted an analysis to assess the implications of this phenomenon. The analysis outcomes revealed a notable concentration of high stress at the interface between the new and old components, which exceeded the strength of both the new and old materials. Considering that these ancient structures are primarily situated in arid regions, they are subject to elevated thermal loads arising from intense solar radiation. To replicate the impact of such conditions, a thermal load ranging from 35°C to 65°C was applied to the stupa's exposed surface. The subsequent analysis of stress distribution revealed that the recorded stresses remained within the material strength.

Based on the findings of this research, it can be recommended to consider the non-linear properties of the stupa's materials for future studies in this field.

Keywords: Axisymmetric, 3D analysis, Material Non-homogeneity, Moisture expansion, Thermal effect

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PAST FAILURES

TISSAMAHARAMA STUPA

Cracks on the dome

Post stressing the dome using stainless steel cables

Post-tensioned dome

Present conservation guidelines, which prioritise minimal intervention and preservation of structures' historical and cultural value (Ranaweera 2001), conducting a highly accurate structural analysis is essential before undertaking any restoration process

ISSUES AND DRAWBACKS RELATED TO CURRENT FE MODELS

Material non-homogeneity

Old brick vs new brick

Non-axisymmetric nature of the stupa

2D vs 3D finite element analysis

Long term effects on the stupa

Shrinkage and expansion

Thermal effects

Primary Aim: Analysing how to restore stupas in Sri Lanka that ensures a successful restoration process without any failures while preserving their archaeological and architectural value.

The aim of this research will be achieved based on the following research objectives

1) Quantifying the effect of 2D and 3D analysis of stupa for restoration purpose

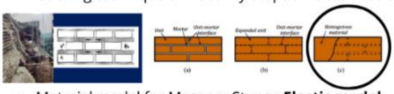
2) Analysing long-term effects on stupas

- **Moisture expansion of old stupa**
- **Thermal effects**

FINITE ELEMENT MODELLING OF STUPA

Main assumptions

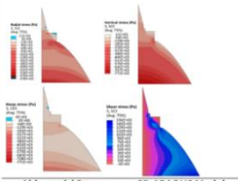
- Modelling technique of Masonry Stupa : **Macro modelling**



- Material model for Masonry Stupa : **Elastic model**
- Material and geometric non-linearity not considered

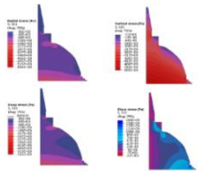
2D FEM ANALYSIS

ABHAYAGIRI STUPA



Abhayagiri Stupa	2D ABAQUS Model
Vertical Stress	
Maximum compression	-772 kPa (Bottom center)
Hoop stress	
Maximum compression	-253 kPa
Maximum tension	0 kPa
Radial stress	
	All compressive

DEEGAWAPI STUPA

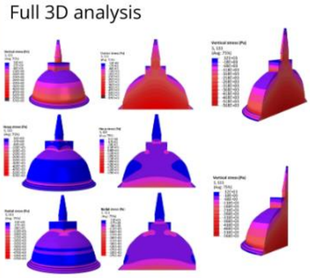


Deegawapi Stupa	2D ABAQUS Model
Vertical Stress	
Maximum compression	565 kPa (Bottom center)
Hoop stress	
Maximum tension	12 kPa (Dome)
	28 kPa (Spire)
Radial stress	
Maximum tension	Negligible tension (Dome)
	24 kPa (Spire)

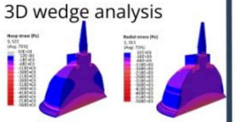
3D ANALYSIS OF STUPA - HOMOGENEOUS MODEL

DEEGAWAPI STUPA

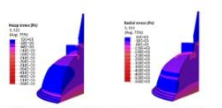
Full 3D analysis



3D wedge analysis



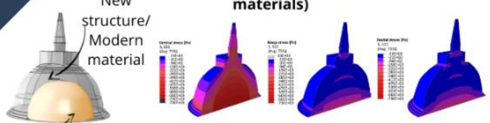
Half of the stupa model



Quarter of the stupa model

3D ANALYSIS OF STUPA NON-HOMOGENEOUS MODEL

(Material non-homogeneity between old and new materials)



Continuous connection between the two surfaces was considered

MOISTURE EXPANSION OF THE OLD STRUCTURE OF THE STUPA

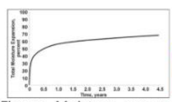
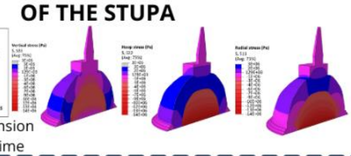
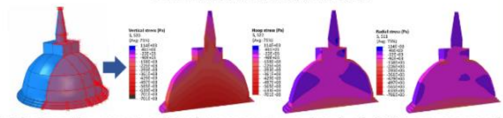


Figure- Moisture expansion of clay brickwork over time



THERMAL ANALYSIS



Considering the most critical temperature load of 65°C on exposed surface of stupa to direct solar radiation

CONCLUSION

- When analysing a stupa solely under its self-weight, 3D geometry modelling will not be essential
- Under the same conditions where a more detailed stress distribution of the structure is necessary, it is feasible to model a wedge of 3D geometry because there is no significant varation between full and wedge analysis

Model	Computational time
Half	0.35×Full 3D Model
Quarter	0.06×Full 3D Model (0.16×Half 3D Model)

- Other than self-weight, loading due to external environmental factors has a high effect on stress distribution of the structure. Therefore, if there is a chance of moisture leaking to the stupa core and high thermal loading on the stupa surface, it should be incorporated to the analysis