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# Environmental Loading on Lalibela's Biete Giorgis Church: A CFD Study of Wind-Driven Rain

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**SUMMARY**

Cyclic ingress of moisture across the walls of historic structures may cause material deterioration, surface cracking and erosion with a compounded effect on the durability of exposed structural elements. Such moisture loading is one of the most probable causes for the structural distress observed on the Rock-Hewn Churches of Lalibela in Ethiopia. As a part of an ongoing study to develop resilient conservation strategy for these historic sites, CFD model was developed to quantify the wind pressure and wind driven rain (WDR) loads. Results for Biete Giorgis (the church of St. George), a cruciform shaped building standing in the middle of an open cavity, is presented. The CFD simulations allow to reveal the unique microclimate around the church that has a clear contrast from that of surface mounted buildings. The study will be extended to identify and design climate resilient measures towards the conservation these historic heritages.

***Keywords:*** *Wind driven rain (WDR), CFD, Aerodynamics, historic structures of Lalibela church buildings*

## 1. INTRODUCTION

The eleven Rock-Hewn Churches of Lalibela, registered on the world heritage list by UNESCO in 1978, are considered as the most prestigious structural complexes found in Ethiopia, Figure 1. They were carved out of a living rock in the 13th century by king Lalibela, and they have been used as centres of spiritual service by Ethiopian Orthodox Church. Biete Giorgis church, one of these historic churches with the cross shape, is shown Figure 1a. The rock material of these churches experienced serious deterioration, and hence protective shelters were constructed over some of the churches in 2008 (UNESCO 2008), for example Biete Amanuel shown in Figure 1b. However, because the sheds change the microclimate and their structural supports induce stress on the bases of the churches, the cracking of the walls and the rock material deterioration worsens for some of the sheltered churches. Hence, a detailed study of the microclimate, the hygrothermal and mechanical behaviour of the rock is sought before taking any further intervention.

The 2018 advisory report by UNESCO states that "A preliminary study was realized on all the churches and water infiltration through the roof was identified as the primary environmental destructive agent." This implies wind driven rain load plays a key role for the rock deterioration problems and surface erosion, and cracks observed on the roofs and facades of the churches. Similar observations are also made in other surface mounted historic structures, for example see the study of Bourcet et al, 2021 and Frost et al., 2023. Wind driven rain is one of the primary causes of surface wetting, moisture ingress and facade deterioration in building envelopes (Juras and Jakubcik, 2016) and wind driven rain analysis allows to define moisture boundary conditions for hygrothermal analysis of building envelopes (Tariku and Kumaran, 2006). Unlike ordinary structures, the Lalibela churches have unique geometric shape and are below the ground surface with complex terrain conditions. This makes CFD based analysis a viable alternative for evaluating the micro wind climate around the churches, the wind pressure load and the wind driven rain load on the envelopes of the churches. Thus, this paper presents an ongoing CFD study for the aerodynamic and wind driven rain analysis of Biete Georgis (Figure 1a).


Figure 1: Rock-hewn Churches of Lalibela, Ethiopia (a) Biete Giorgis (b) Shelter over Biete Amanuel constructed in 2008. Source: UNESCO 2018.

## 2. METHOD

The 3D CAD of the church building is modeled using SOLIDWORKS and the CFD simulation is carried out using Siemens STAR-CCM+ version 2306. The church has a plinth length of 12.36m and about 13m height; it is embedded in a trapezoidal cavity of approximated top dimensions 25.6m, 25.6m, 23.6m, 19.6m and bottom dimension of 22.2m, 22.72m, 18m and 17.8m in four sides by almost 13 m depth. Door and windows of the church are assumed to be closed during wind and rain simulation. The surface wind is simulated by defining a computational domain size of about 20H x 10H x 5H, where H =13m. The computational domain was discretized into millions polyhedral cells by applying various stages of grid refinement resulting a finer mesh around the building (Geleta and Bitsuamlak, 2022). Atmospheric boundary layer wind speed of 10 m/s at 10 m height and turbulence profiles, consistent with open flat exposure with aerodynamic roughness of 0.05 m, were specified at inlet of the computational domain. The wind and the wind driven rain around the model building is resolved by running simulations in two stages (Blocken and Carmeliet, 2004, Gholamalipour et al. 2024). In the first stage, the local 3D wind profile is computed by solving the Reynolds Average Navier Stokes (RANS) Equations together with k-ε turbulence model equations. Once a converged solution is obtained for the wind, the wind driven rain is simulated by running a Lagrangian two-phase simulation. The trajectory of raindrops and their flow rate is computed by injecting rain drops from horizontal plane of 60 m by 40m located at 10 m above the natural ground surface. The rain phase at the injector plane has mass flow rate corresponding to rainfall intensity of 6mm/h, and raindrops having diameter of 5mm, horizontal velocity of 10m/s, and terminal velocity of 10m/s.

## 3. RESULTS AND DISCUSSION

Since the church is standing in an open cavity, it is subjected to a unique microclimate different from that of surface mounted buildings. Figure 2 shows the vertical wind profile in the cavity, and the wind pressure on the church. The wind speed is normalized by the wind speed at the reference height z = 10 m above the ground, and the pressure coefficient is computed by dividing the computed surface pressure with the velocity pressure at z =10m. The incident wind velocity is directed from left to right.

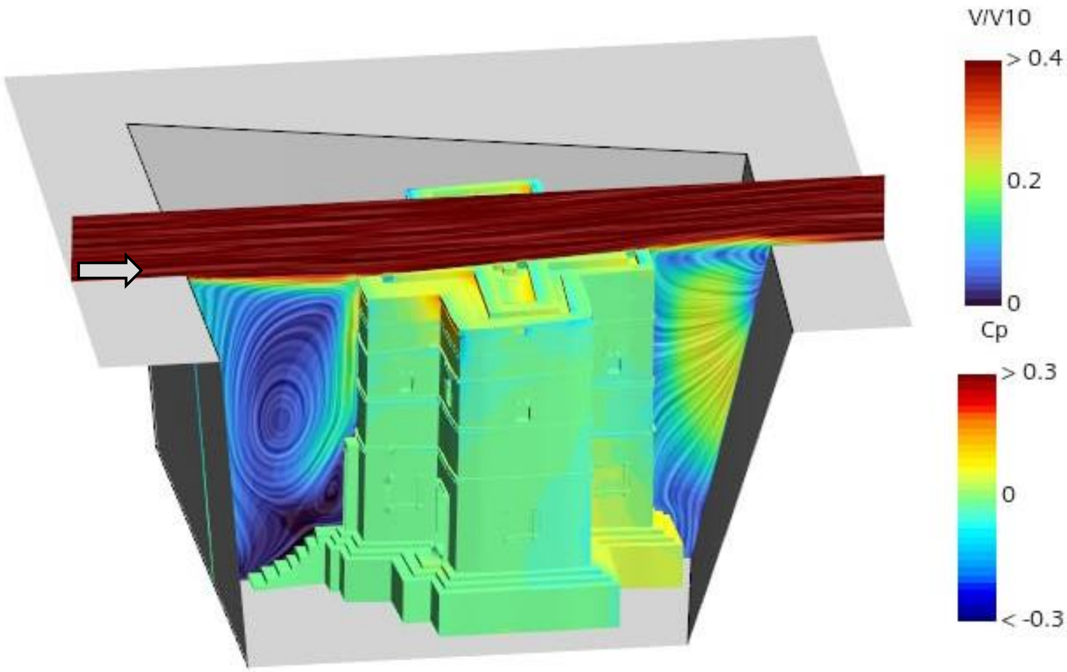


Figure 2: Aerodynamics of Biete Georgis of Lalibela, Ethiopia. Vertical velocity profile of the cavity flow - on a vertical plane through the center of the church and contour of building surface pressure coefficient.

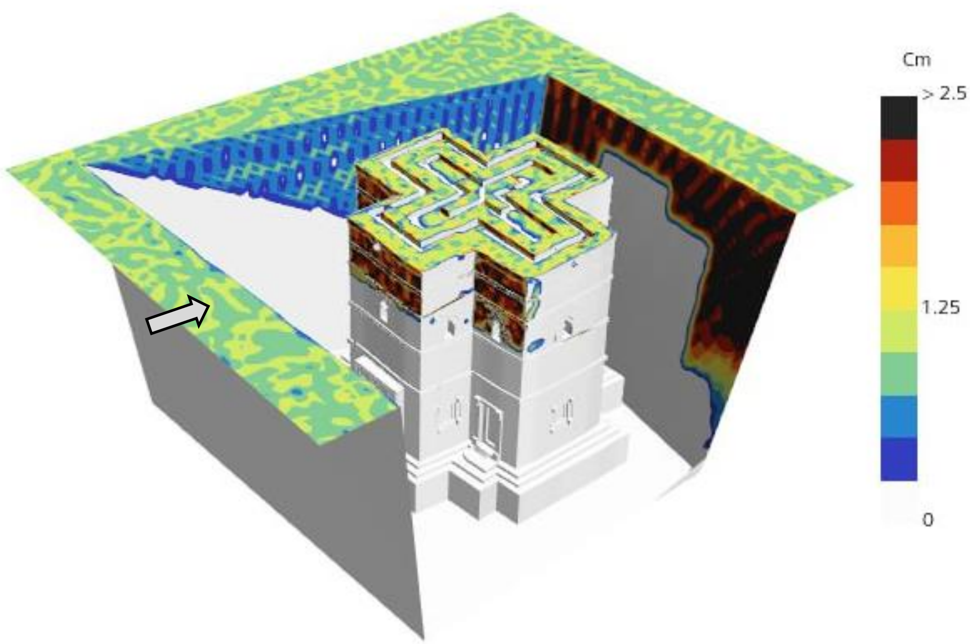


Figure 3: Wind driven rain load coefficient for the Biete Giorgis of Lalibela, Ethiopia. Reference wind speed $V_{10}$ = 10m/s, Rainfall intensity $I_h$ = 6mm/h, diameter of raindrops = 5mm.

Wind velocity profile within the cavity exhibits circulatory flow that induces impingement and downwash on the wind ward façade and upwash on the leeward facade and surface pressure on the church – relatively strong over pressure on the top wind ward façade and strong suction on windward roof zone.

Figure 3 shows the ratio of the incident mass flux of raindrops impinging the wall surfaces to the mass flux specified at the rain-drop injector plane. The wall surfaces bounding the downwash flow experience strong wind driven rain impingement. Stronger raindrop impingement is observed on upper wind ward surfaces of the building and the leeward cavity wall than the flat surrounding ground surface. The incident wind velocity is directed from left to right. Comparison of Figure 1(a) and Figure 3 may imply correlation between decolorization and weathering of the rock and the wind driven rain impingement pattern.

## 4. CONCLUSION

With primary objective of wind driven rain analysis, CFD model of Biete Giorgies, one of the eleven rock-hewn churches of Lalibela Ethiopia, was developed using STAR-CCM+ to compute the wind velocity and wind driven rain load. The wind field was resolved using RANS modeling with k-ε turbulence whereas the transport of raindrops was simulated using Lagrangian multiphase modeling. The non-dimensional wind velocity in the cavity, building external surface pressure coefficient, and the rain impinging the external surfaces of the church are presented. It is observed that the rain load intensity and distribution on the building and the cavity walls is strongly influenced by the wind pattern within the cavity. Further analysis is being carried out to study the variation of WDR load coefficient with (a) wind direction, (b) rain intensity and raindrop diameter, (c) unsteady wind conditions from LES turbulence model and transient inflow boundary (Geleta, and Bitsuamlak, 2022), (d) modeling schemes of the rain phase (Eulerian versus Lagrangian).

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