# Laser Scanning, Monitoring and Analysis of a Reconstructed Masonry Vault

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## 1 INTRODUCTION

Reconstruction of historic building elements is often necessary in adaptive re-use projects. Optimally this is performed with as much original material as can be salvaged. However, the use of hydraulic lime mortars in reconstructed masonry can lead to long curing time and excessive deformation under mechanical loads. Therefore, masonry reconstruction projects using historic materials should always be closely monitored. This paper focuses on the reconstruction of a masonry vault in such an adaptive re-use project.

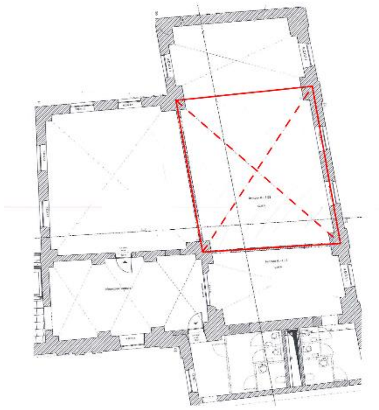

Figure 1: Floor plan with vault position indicated.

The vault was dismantled and reassembled using the original bricks and a newly made hydraulic lime mortar, the latter of which was mechanically characterized. New tie rods were installed before re-construction of the masonry vault. Existing cracks in the masonry walls supporting the vault were monitored for the detection of new damage. Detailed geometrical surveys were carried out using terrestrial laser scanning at two points in time after the reconstruction of the vault: a) before removal of the formwork and b) after the removal. These scans are able to not only register the geometry of the vault in great detail, but also to measure the deflection of the whole structure under its self-weight non-intrusively and with good accuracy.

### 1.1 *The vault structure*

The original vault was constructed using solid clay bricks and lime mortar. It horizontally spans roughly 9.66 m × 8.00 m and has a rise of 1.23 m (Figure 1). Its thickness in the mid-section of the span, measured manually through an opening in the vault, is 0.20 m.

### 1.2 *Material testing*

Samples of the new lime mortar were cast at the time of construction. These were cut in 40 mm cubic samples and tested in compression at the ages of 14 and 21 days. The results are presented in the following table:

Table 1: Compressive strength of mortar.

| Age [days] | $f_m$ [N/mm$^2$] | CoV [-] | # samples |
|---|---|---|---|
| 14 | 3.38 | 0.13 | 3 |
| 21 | 4.20 | 0.04 | 3 |

An increase of the compressive strength is registered for the samples aged 21 days. This age coincides with the time between finalization of the construction of the vault and removal of its formwork. It is therefore similar to the age of the on-site mortar when the vault's thrust line is activated.

### 1.3 *Monitoring*

The deflection of the vault during the gradual lowering and eventual removal of the formwork was measured at specific points by the contractor, amounting to roughly 3 cm at the center of the span.

A number of DEMEC displacement measurement points and crack meters were installed at visible cracks on the masonry walls supporting the vault, as well as on one of the old metallic ties. Measurements were registered before and after the removal of the formwork. The monitoring data did not indicate any major opening of cracks or additional displacements.

## 2 LASER SCANNING RESULTS

The deflection of the vault was determined by the use of point cloud data. A terrestrial laser scanner captured the geometry of the structure before and after the removal of the formwork. In this project, a Leica P30 was utilized, yielding a point cloud accurate up to 2 mm with a spatial resolution of 2 mm.

The deflection was established by evaluating the cloud-to-cloud distance between both point clouds. The results are shown in Figure 2. A maximum displacement of 0.030 m ±2 mm is observed.

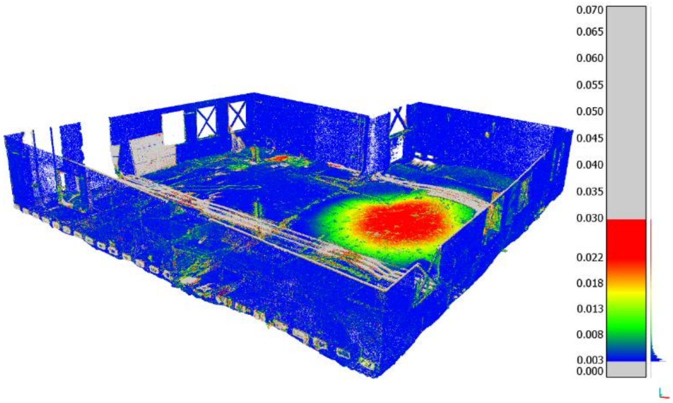


Figure 2: Cloud-to-cloud distance in vertical direction between two scanning campaigns [m].

Additionally, the acquired points were used to create a realistic mesh model of the vault. The top side of the structure was reconstructed using Poisson meshing after which the bottom side was determined by a fixed offset from the topside. The remaining holes were manually sealed, resulting in a watertight model that served as the basis for the numerical modeling.

## 3 NUMERICAL MODELING

### 3.1 *Model geometry*

The vault was numerically modeled using the software package DIANA FEA [1], adopting a linear elastic approach. It should be noted that this oversimplified approach was chosen as only the vault's instant deflection, not its ultimate limit, was investigated. Three different geometries were considered: a) an idealized curved shell, b) an idealized 3D solid and c) a scan-derived 3D solid. The first two geometries are determined by the fitting of simple shell or solid shapes to the actual geometry, while the third is derived directly from the high-precision scanning data.

### 3.2 *Loading and boundary conditions*

The models were loaded by their self-weight with no additional dead or live loads added. This is consistent with the state during and after construction, during which minimal service load was present, as well as with the projected use of the vault: the overlaying floor will rest on the surrounding masonry walls and not on the vault itself.

Boundary conditions were applied according to the horizontal translational restraint provided by the underlying masonry structural elements. Therefore, the ties were not explicitly considered in the model. Vertical restraint was provided at the four corners.

### 3.3 *Material properties*

From the determined compressive strength of the mortar $f_m$, and an estimated strength for the clay bricks $f_b$, the compressive strength of the masonry $f_k$ is calculated from the Eurocode 6 equation [2]:

$$f_k = K \cdot f_b^{\alpha} \cdot f_m^{\beta}$$

The Young's modulus of the masonry $E$ is calculated from the equation [3]:

$$E = 350 \cdot f_k$$

### 3.4 *Analysis Results*

All of the models give similar deflection shapes, which are in good agreement with the shape obtained from the scanning. Differences are noted in the volume and weight of the models, with the shell model being 314 kN, the solid model 307 kN and the scan model 352 kN.

The maximum deflection obtained by the shell model is 5.93 cm. The solid model produces a deflection of 6.07 cm. The scan model, despite being the heaviest, produces a deflection of 3.22 cm, both the lowest of the three and the closest to the actually obtained maximum deflection.

## 4 CONCLUSIONS

Several simple monitoring techniques were shown to be used efficiently during reconstruction of a masonry vault. Structural analysis of the vault has been carried out employing three approaches for representing its geometry. Differences in the approaches in terms of obtained deflection highlight the importance of detailed geometrical survey for the analysis of historic structures. Detailed geometric survey data is shown to be critical in achieving accurate analysis results in structures whose behavior is governed by their geometry.

## ACKNOWLEDGEMENTS

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