

Structural Investigation through Digital Modelling of Two Domes by Ferdinando Crivelli

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Abstract – Domes were one of the features that made religious buildings grandiose and, with their imposing presence, often defined city skylines. However, before the development of modern construction science, building domes presented a significant challenge to builders, often resulting in numerous designs and revisions that delayed completion by decades, if not centuries.

The vulnerability of these structures means they remain one of the most delicate aspects of restoration and consolidation work. For this reason, it is particularly important to understand how they behave. The study of two 19th-century domes designed by Ferdinando Crivelli in Bergamo — the cathedral dome and the church of S. Andrea dome — demonstrates how three-dimensional digital modelling can be used as a valuable preliminary tool in assessing the behaviour of these structures.

I. INTRODUCTION

The significance of the information obtained from an accurate survey of the actual geometry of the dome was highlighted in the study of the Romanesque church of S. Tomè in Almenno San Bartolomeo [1]. The main idea is that the domes are built using regular geometry, in most cases based on a hemisphere; deviations from this initial shape are primarily due to the deformations that the dome has suffered over time.

In the analysis of S. Tomè, a method was developed that begins with acquiring a point cloud using a laser scanner. Then, a best-fitting algorithm, which has been specifically implemented in Grasshopper and volvox plugin [2], is employed to identify the hypothetical undeformed geometry of the dome.

In this way, deviations of the actual geometry from the initial configuration can be shown, allowing for the development of hypotheses regarding structural behaviour and potential failures. These hypotheses must then be verified through structural analysis.

The findings from S. Tomè indicate that the same investigative approach could be applied to further case studies as an initial analysis. In this discussion, we will focus on two domes designed by architect Ferdinando Crivelli in the mid-19th century, located in the historic centre of Bergamo: the Cathedral of S. Alessandro and the

Church of S. Andrea.



Fig. 1. Exterior view of the dome of S. Alessandro.



Fig. 2. Interior view of the dome of S. Alessandro.

Crivelli's solution for the dome of S. Alessandro (Fig. 1 and Fig. 2) resulted from a lengthy debate akin to the discussions surrounding the domes of Florence Cathedral and St. Peter's Basilica. Concerns about the feasibility and cost of Carlo Fontana's design, proposed in the late 17th century, led to a deadlock that persisted for more than one century. During this period, a large painted canvas by the Galliari brothers was displayed in the location intended for the dome [3].

In 1828, Giuseppe Cusi proposed the initial design for a hemispherical wooden dome. After some adjustments, the structure was completed in 1833. It consisted of wooden frame ribs covered with copper plates. Unfortunately, the structure deteriorated quickly, leading to the decision in 1847 to construct a new dome [3]. Architect and engineer Ferdinando Crivelli was tasked with reinforcing the drum that Cusi had built, as well as designing a new masonry dome while preserving the existing wooden frame [4]. The dome of S. Alessandro (Fig. 2) represents Ferdinando Crivelli's final work, completed before he died in 1855 at the age of 44 [3].



Fig. 3 Exterior view of the dome of S. Andrea.

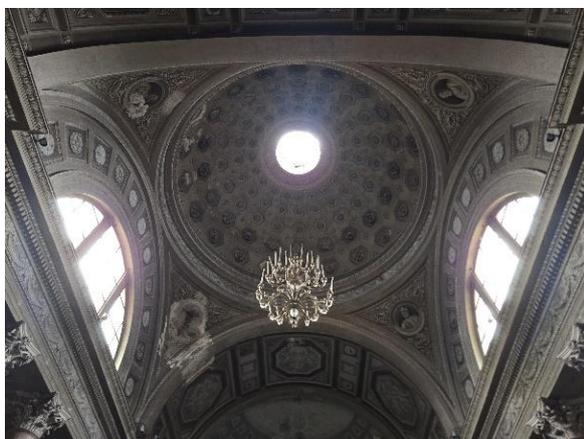


Fig. 4. Interior view of the dome of S. Andrea.

From 1837 to 1847, Crivelli also designed the neoclassical church of S. Andrea (Fig. 3 and Fig. 4). Although the project is often associated with the church for the Knights of Malta in St. Petersburg by architect Giacomo Quarenghi, who also hailed from Bergamo, the dome draws inspiration from the Pantheon in Rome [5].

II. ACQUISITION OF GEOMETRIC DATA FOR 3D MODELLING

A. Dome of S. Alessandro

In 2007, significant restoration efforts resulted in the complete replacement of the wooden ribs originally installed by Cusi and maintained by Crivelli. While this work addressed water infiltration issues, there are no known investigations into the condition of the masonry substructure [6]. For this reason, conducting a new laser scanner survey of the dome's intrados was deemed appropriate, positioning the instrument, a Faro Scan Focus 3D, along the drum's internal balustrade (Fig. 5). A series of eight scans with a resolution of 7.67 mm per 10 meters and a quality parameter of 4x were conducted, capturing over 26 million points per station. The alignment process, executed in targetless mode with more than 60% scan overlap, ensured a high level of precision and accuracy in the survey, yielding an average error of just 1.6 mm [4].



Fig. 5. Raw laser scanner point cloud of the dome of S. Alessandro.

B. Dome of S. Andrea

Although often overlooked by tourists, the Church of S. Andrea boasts remarkable architecture, making it a significant worship site for university students and a venue for various cultural events. In 2018, a preliminary metric survey using a laser scanner was conducted as part of the Architectural Surveying and Conservation course in the Building Construction Engineering programme at the University of Bergamo. The scanner acquisitions were performed to record only metric data, without colour information. Each scan's parameter was tailored to ensure compliance with the necessary Ground Sample Distance. The outcome of the laser scanning procedure is a point cloud with consistent point density, subsampled to 3 mm in grey tones based on reflectance values [7].

III. GEOMETRIC ANALYSIS

A. Dome of S. Alessandro

To analyse the geometric features and potential deformations of the dome, the point cloud underwent an editing process. Initially, isolated points were eliminated. Next, subsampling occurred at 1 cm intervals. After assessing the surface density of the remaining points, a uniform set was extracted at 5 cm intervals to avoid overload during quantitative analysis.

This uniform distribution enabled deriving the best fit to an ideal dome shape. Maintaining uniform density is essential to prevent biasing the least squares estimate, which could amplify regions with high point concentration while underrepresenting areas of lower survey quality, such as the base of the dome above the drum.

We can compare the edited point cloud with the ideal geometry and measure the distances between the actual points and their perpendicular projections on the surface. Based on these distances, points can be visualised using different colours, with red indicating the most outward points and blue representing the most inward ones (Fig. 6 and Fig. 7).

This representation indicates that the dome's geometry deviates from a perfect hemisphere and approaches a pointed arch. The apex of the dome, at 43.55 m above the level of the nave, is approximately 25 cm higher than the best-fit sphere. The sides of the dome are very close to the geometry of the sphere, with deviations ranging from -3 cm to +2 cm. However, the blue area in the north-western portion reveals an anomaly, as if the dome were leaning inwards. In contrast, the corresponding part in the south-east does not exhibit this deviation from the perfect sphere [4].

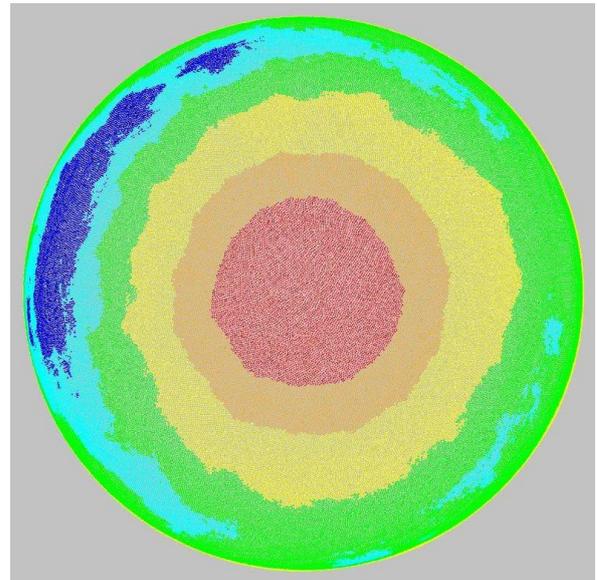


Fig. 6. Cloud to mesh comparison [3].

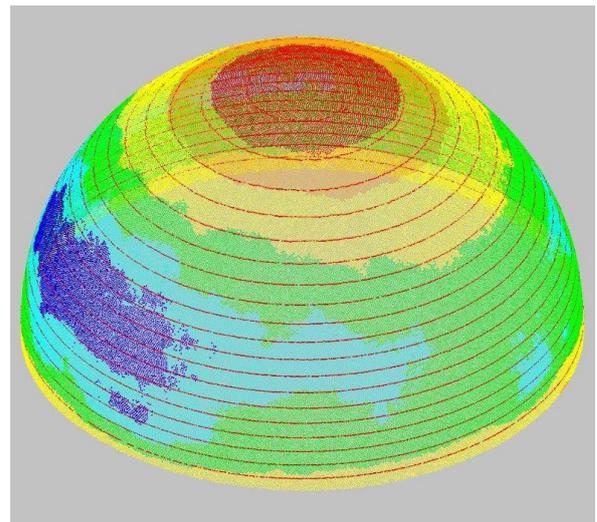


Fig. 7. Comparison between the cloud contour lines (red) and the isolines from the cloud-to-mesh comparison [3].

B. Dome of S. Andrea

A preliminary geometric analysis was carried out on the point cloud of the coffered dome of S. Andrea. The interpolation of the centres of the dome's contour lines indicates a slight tilt in its axis, which, alongside the cracks and deformations noted on the side vaults and floor, implies a possible rotation and downward movement of the building (Fig. 8 and Fig. 9) [7].

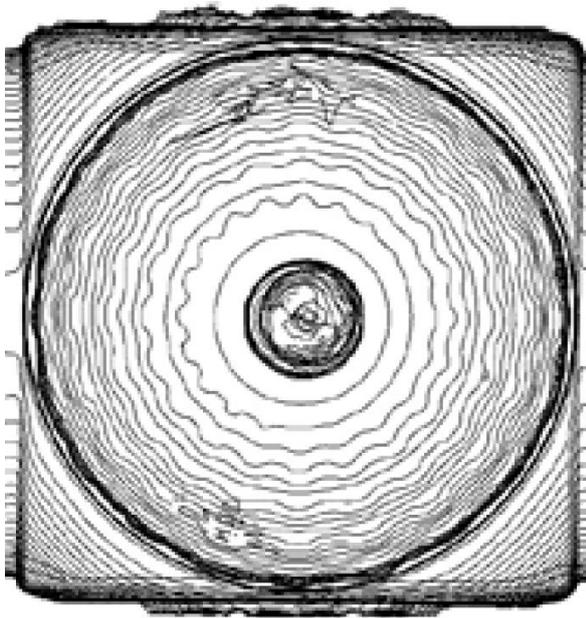


Fig. 8. Contour lines of the dome of S. Andrea [6].

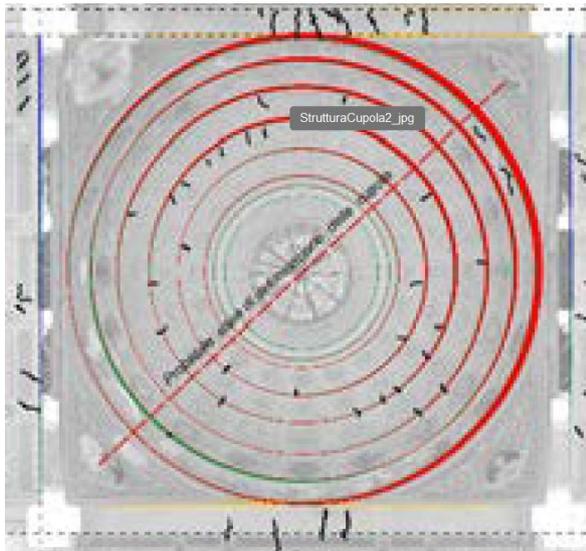


Fig. 9. Analysis of the deformations of the dome of S. Andrea [6].

IV. PRELIMINARY CONCLUSIONS

Similar to the church of S. Tomè, examining the geometric models of the domes of S. Alessandro and S. Andrea provided valuable insights into their structural conditions, highlighting the need for further investigations into their deformation.

For the dome of S. Alessandro, additional analysis is crucial to link the detected anomalies with either the construction methods used or the wear of the decorative surface.

In the case of S. Andrea, it is essential to establish the correct geometry, considering the lacunars, before proceeding with further investigations.

The application of three-dimensional digital modeling to Ferdinando Crivelli's two 19th-century domes has successfully demonstrated the value of geometric analysis as a preliminary assessment tool for heritage structures. Building upon the methodological foundation established in the study of S. Tomè in Almenno San Bartolomeo [1], this research confirms that systematic deviation analysis from ideal geometries can provide meaningful insights into structural behavior and historical construction processes.

For the dome of S. Alessandro, the identification of an apex elevation above the best-fit hemisphere, combined with the asymmetric north-western anomaly, presents clear evidence of either construction irregularities or subsequent structural deformation. The precision achieved provides confidence that these geometric features represent genuine structural characteristics rather than measurement artifacts. The proximity of the dome's sides to the ideal spherical geometry suggests that the identified anomalies are localized phenomena requiring focused investigation.

The preliminary analysis of S. Andrea's coffered dome, while less detailed than S. Alessandro, has revealed potentially significant axis tilting that correlates with observed floor deformations and vault cracking [6]. This correlation between geometric analysis results and visible structural damage indicators supports the hypothesis that digital modeling can serve as an effective screening tool for identifying areas requiring detailed structural investigation.

V. ONGOING ANALYSIS

The research highlights several critical aspects for ensuring reliable metrological results in heritage documentation projects. The necessity of maintaining uniform point density during analysis, as implemented through the 5cm subsampling for S. Alessandro, demonstrates the importance of preventing bias in least-squares geometric fitting procedures. This methodological consideration is particularly relevant for defining standardized heritage measurement protocols.

The geometric modeling approach demonstrated in this study should be considered as one component of a comprehensive heritage assessment methodology rather than a standalone diagnostic tool. The correlation observed between geometric anomalies and construction history (as in the case of S. Alessandro's complex construction sequence involving Cusi's wooden frame and Crivelli's masonry dome) confirms that digital analysis gains significant interpretive value when integrated with:

- Historical Construction Documentation: Archive research can distinguish between original construction variations and subsequent deformations, as evidenced

by the century-long design evolution of S. Alessandro's dome.

- Material Condition Assessment: The 2007 restoration work on S. Alessandro's wooden ribs, while addressing water infiltration, left questions about the masonry substructure condition that geometric analysis can help prioritize for investigation.
- Traditional Survey Validation: Strategic deployment of conventional surveying methods (total station measurements, manual geometric verification) can provide independent validation of critical geometric features identified through digital modeling.
- Structural Monitoring Integration: Where available, historical monitoring data can provide temporal context for geometric anomalies, distinguishing between stable construction irregularities and progressive deformation.

The applicability of similar methodologies to both Romanesque (S. Tomé) and neoclassical (Crivelli domes) structures suggests broader possibilities across different architectural periods and construction techniques. This transferability potential has significant implications for developing standardized approaches to heritage structure assessment.

VI. FUTURE DEVELOPMENTS

For the dome of S. Alessandro, the north-western geometric anomaly requires correlation with detailed material investigation to determine whether the deviation represents construction methodology artifacts, subsequent settling, or localized material degradation. Integration with the 2007 restoration documentation could provide valuable temporal reference points.

For the church of S. Andrea, a new and more accurate survey campaign, establishing precise geometry accounting for the coffered surface complexity is essential before proceeding with detailed deformation analysis. The observed axis tilting requires validation through independent measurement methods and correlation with the documented floor and vault damage patterns.

In parallel, there is a need for a multi-temporal Analysis. The Integration of current geometric models with historical survey data and archival documentation to enable quantitative assessment of structural change rates over extended time periods.

Furthermore, a predictive maintenance integration that correlates the geometric analysis results with structural health indicators could be pursued in order to develop predictive models for heritage structure maintenance scheduling and resource allocation.

These developments could eventually contribute to emerging international standards for heritage structure documentation, ensuring that geometric analysis methodologies align with broader conservation and management frameworks.

VII. CONCLUDING REMARKS

The investigation of Ferdinando Crivelli's domes demonstrates that three-dimensional digital modeling can effectively bridge the gap between advanced measurement technologies and the practical needs of heritage conservation. The methodology provides quantitative, reproducible assessment capabilities that complement traditional approaches while offering new insights into structural behavior and construction history.

This preliminary investigation opens pathways for more comprehensive structural assessment programs, where geometric analysis serves as an efficient screening method for identifying heritage structures requiring detailed intervention. As measurement technologies continue to advance and processing methods become more sophisticated, the integration of digital modeling with traditional conservation practices promises to enhance both the scientific rigor and practical effectiveness of heritage preservation efforts.

Future research should focus on developing the methodological frameworks necessary to ensure consistent, reliable application across diverse heritage contexts while maintaining the accessibility that makes this approach valuable for institutions with varying technical resources. The ultimate goal remains the preservation of our built heritage through improved understanding of structural behavior and more informed conservation decision-making.

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