Information Modelling as a Support for Damage Interpretation: The Case of the Dome of Santa Maria del Fiore in Florence

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Abstract

This study presents a methodological framework for classifying and interpreting structural damage in masonry buildings through a Historic Building Information Modelling (HBIM) approach, with a particular emphasis on diagnosing crack patterns in domes. The approach was tested on the Dome of Santa Maria del Fiore in Florence (Italy). The first step involves identifying key parameters for systematically describing cracks within the HBIM environment, focusing on their morphology, position, and related deformation. A Diagnostic Support Tool was developed to semi-automate the identification of failure mechanisms, while final interpretation – particularly of contributing causes – remains reliant on expert judgment. The geometric model of the case study was developed and two levels of crack representation – realistic and simplified – were implemented to ensure both interpretative clarity and interoperability with structural analysis software. The Santa Maria del Fiore case study demonstrates the effectiveness of the protocol in capturing the complex behaviour of masonry domes, offering a replicable workflow. The HBIM model was then enriched with data acquired from the structural monitoring system installed on the Dome, one of the most comprehensive ever installed on a historical monument. This integration enabled 3D visualization of crack evolution over time. Key indicators for monitoring data reliability and damage evolution are proposed and applied to the case study.

1. Introduction

Historic Building Information Modelling (HBIM) is becoming an increasingly valuable tool for supporting the conservation process of heritage buildings, driven by ongoing advancements in related research domains. However, current information models of historical architecture still present notable limitations, leaving several open research questions. Among these, the representation of structural damage remain particularly critical, given its importance for conservation processes. Although only partially addressed to date, the HBIM management of cracks holds clear and considerable advantages: HBIM enables spatial localization for a better understanding of the damage, facilitates the association of related information, and allows for possible correlations with other influencing factors, such as construction features, deformations, and transformations undergone by the building.
To address this shortcoming regarding the informative representation of damage, this paper proposes an HBIM-based protocol for crack patterns mapping and classification, as well as for the assessment of their evolution in time thanks to the integration of structural monitoring data. The aim is to develop a semi-automated yet expert-guided workflow that supports damage diagnosis while preserving the irreplaceable role of specialist judgement in crack interpretation. The proposed BIM-based operational methodology addresses multiple aspects related to damage informative representation and, more broadly, to the comprehension of the structural behaviour of the building. Specifically, this study aims to investigate the following aspects:
- The development of the HBIM model from a geometric perspective, with a focus on the modelling of cracks. The model is designed to meet the dual requirements of faithfully representing both the building and its damage, while also ensuring potential interoperability with structural analysis software;
- The identification of the information to be associated with the cracks, to enable accurate structured and critical documentation of damage;
- The definition of a classification protocol based on the data embedded in the HBIM, capable of guiding the interpretation of failure mechanisms. This protocol is intended to be generalisable and fully integrated with the HBIM environment;
- The integration of monitoring data to validate diagnostic hypotheses and contribute to the risk assessment.

The proposed methodology serves as an operational guide to support the data collection phase of the survey process, with the primary goal of gathering the information necessary for developing an information model that supports the interpretation of damage mechanisms. The proposed approach has been validated through its application to several case studies that differ in type, complexity, failure mechanism and monitoring systems (Parente et al., in press). This article focuses on the application of the proposed methodology to masonry domes, and in particular to the Dome of Santa Maria del Fiore in Florence. This case is particularly emblematic, as it provides an opportunity to address and investigate the various issues related to the topic. Moreover, the extensive body of research on the Dome provides a solid foundation for the development and validation of the proposed system. Finally, the Dome is equipped with one of the most comprehensive structural monitoring systems ever installed on a historic building.

2. State of the art: damage classification and crack representation in HBIM environment

Despite the undisputed importance of interpreting crack patterns for assessing the stability of historical buildings, there is a notable lack of standardized protocols for classifying damage, particularly that associated with static failures. While the literature on seismic damage is extensive and continuously updated, research on static failures remains largely confined to foundational contributions that shaped the history of the discipline (Mastrodicasa, 1943; Di Stefano, 1990). Crack patterns in masonry structures exhibit recurring morphologies directly correlated with the underlying kinematic behaviour. Consequently, Mastrodicasa, 1943 and similar studies illustrate the recurring crack patterns for each type of failure (settlement, crushing, damage due to thrusting structures, etc.), primarily focusing on vertical structural elements, walls and pillars.

The failure mechanisms of arches, vaults, and domes have been the subject of other research (Huerta, 2001). Although the mechanisms of bending and sliding in arches had long been recognized, it is through the work of Heyman that a comprehensive understanding of the structural behaviour of masonry, and of arches in particular, was achieved (Heyman, 1995). Subsequent studies further analysed recurrent crack patterns, based on the empirical observation of damage encountered in real-world cases.

Moreover, Italian regulation "Evaluation and reduction of seismic risk for Cultural Heritage" (D.P.C.M. 9 February 2011, chapter 4.1.4) provides a reference methodology for documenting damage patterns, beginning with crack classification. These guidelines stress the relevance of construction techniques, geometrical configuration, and historical context for interpreting damage mechanisms. However, despite underlining the significance of this process, the regulation does not explicitly formalize the methods for its implementation. This study seeks to address this gap.

HBIM offers a valuable tool for visualizing and classifying damage. However, mapping cracks within HBIM remains challenging due to the absence of suitable tools and standardized methodologies. Current approaches vary considerably depending on the intended use of the model and the required level of detail. In some cases, a simplified geometric representation is employed, and compensated by the integration of a rich set of descriptive attributes (Barontini et al., 2022). Other studies choose a geometrically accurate modelling, which faithfully reproduces the actual shape of the damage (De Falco et al., 2024). Cracks are thus represented through specific customized objects, to which appropriate properties can be assigned. An alternative lies in the development of dedicated software tools, specifically designed to integrate damage mapping functionalities within HBIM workflows. These tools enable the simultaneous achievement of both a faithful representation and a critical description of damage, supported by a specifically designed data framework (Lanzara et al., 2021).

3. An HBIM for the Dome of Santa Maria del Fiore

3.1 Geometric modelling for damage interpretation

The Dome of Santa Maria del Fiore presents considerable geometric complexity. When its construction commenced in 1420, the cathedral was already largely completed, including the octagonal drum that would support the dome. As a result, any irregularities in the pre-existing structure were inevitably incorporated into the dome's geometry. The dome is composed of two concentric shells, structurally interconnected by a system of ribs, eight at the corners and sixteen intermediate ones.

In the development of the HBIM, the first issue concerns the level of geometric detail that the model must achieve depending on the intended objectives. The balance between geometric accuracy and model manageability is a widely debated topic (Attenni et al., 2022; Delpozzo et al., 2022): on the one hand, the conservation of historic buildings requires detailed representations; on the other hand, an excessive level of detail can be burdensome or even counterproductive, especially when one of the model's objectives is interoperability with structural analysis software (Ottoni et al., 2017).

In light of these considerations, the modelling strategy adopted in this study is guided by three main objectives: first, to accurately identify the structural components of the Dome and their geometries, thus enabling a detailed investigation and clarification of specific historical-construction aspects; second, to establish a reliable reference model for the precise representation of the crack pattern and monitoring system, which are central to this research; and third, to enable potential interoperability with structural analysis software platforms.

The geometric modelling has been performed in a pure 3D modelling software (Rhinoceros), starting from 2D drawings resulting from a former published survey (Dalla Negra, 2004) and adopting a "direct modelling" process (Tommasi et al., 2016) (Figure 1). Then, the geometric model was imported in Archicad for data enrichment. The chosen level of detail is sufficient to incorporate the main irregularities of the Dome, such as the dimensional variations between the sides of the octagonal base. Indeed, the discrepancy of approximately 60 cm between the longest and shortest sides reflects the geometric deviations present in the previously built tambour. Only those irregularities that would have hindered the export and meshing processes within structural analysis software have been simplified, such as the small receding parts on both inner and outer shell.

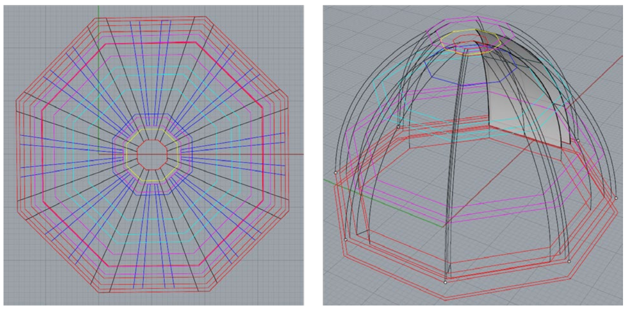


Figure 1. Geometric model construction procedure: profiles are generated by interpolating the points corresponding to the edges; surfaces are then modelled starting from the resulting profile curves.

From a semantic point of view, the construction elements of the Dome have been identified and modelled following the classification previously proposed in (Celli and Ottoni, 2023). The main structural components – tambour, inner and outer shell, corner and intermediate ribs – were modelled and compared with their ideal geometries. The geometric modelling process also facilitated a more detailed investigation of specific construction features that remain either unresolved in the literature or subject to conflicting interpretations. One notable example is the *serraglio* (the Dome's closing ring), which was modelled based on information drawn from archival documents concerning the supply of *macigno* stone beams (Haines and Battista, 2015). Archival documentation was also consulted for modelling the *macigno* chains (Saalman, 1980). The aforementioned photogrammetric survey made it possible to locate and model several additional architectural details, including *buche pontaie* (scaffolding holes), walkways and passages between the ribs, as well as the *oculi* facing the Dome's intrados. For elements not fully described in the mentioned survey, such as the sub-horizontal arches connecting the ribs, geometries were integrated based on data from other studies (Giorgi and Matracchi, 2008). The wooden chain was incorporated as modelled in (Celli and Ottoni, 2023).

Regarding the crack pattern of the Dome, it generally aligns with the well-known collapse mechanism of masonry domes, typically characterized by meridian cracks. However, the Dome's sophisticated geometry and construction features resulted in a more complex crack morphology, which can be classified into four main types, in line with the widely accepted classification (Petrini, 1984): A. Major vertical passing cracks (through inner and outer shell), up to 5-6 cm wide, located at the center of even webs (considering web 1 that on the nave); B. Cracks on the tambour, starting from the oculi, inclined at 60° and 1-2 cm wide; C. Non-passing cracks at the eight edges between the webs; D. Minor vertical cracks in odd webs (Bartoli et al., 2016).

Cracks were modelled as linear paths in the case of non-passing cracks, and as surfaces for passing ones, faithfully replicating the damage pattern (Figure 2).

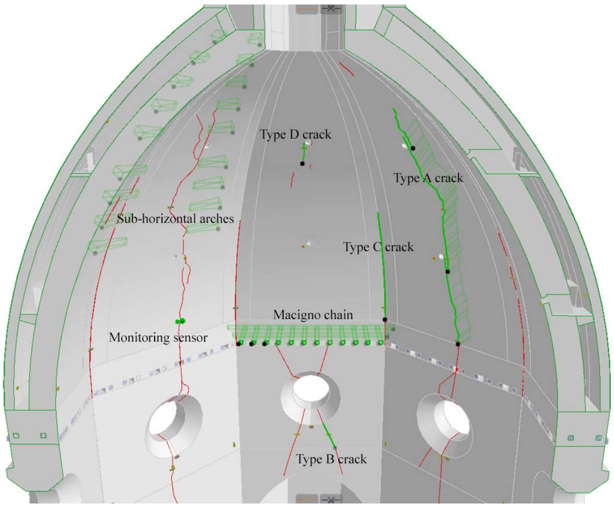


Figure 2. HBIM model of the Dome. Some structural elements investigated in detail during the study, along with the four types of cracks, are highlighted.

The layout of the cracks on the intrados was reconstructed for each web using the internal elevations generated from the photogrammetric survey (Dalla Negra, 2004). The crack mapping on the tambour and pillars was completed with the aid of the comprehensive damage survey conducted in the 1980s (Petrini, 1984). The distribution of type A cracks on the external dome shell was obtained from G. Padelli's survey (Opera di Santa Maria del Fiore, 1939).

As mentioned before, the Dome of Santa Maria del Fiore is equipped with one of the most comprehensive and complex monitoring systems installed on a historical building, both in terms of the number of instruments (72 deformometers, 60 thermometers, 8 leveling sensors, 8 plumb-lines, and acelerometers) and the duration of data acquisition. This began in 1988, limiting the analysis to the automatic system installed by ISMES, although it can be traced back to 1955 when considering manually collected seasonal crack opening data. The results of this extensive monitoring campaign have been discussed in previous studies (Marafini et al., 2024; Ottoni and Blasi, 2015).

To integrate this monitoring system into the HBIM environment, symbolic objects, modelled as simple parallelepipeds, were placed along the previously reconstructed cracks (Banfi et al., 2017). These objects indicate the position and differ in shape and color depending on the type of monitoring sensor. Each sensor object is connected to an external Excel spreadsheet containing the monitoring data, allowing for the visualization of key indicators related to damage evolution directly within the 3D model. In addition to the textual display of data, the system supports 'graphical alerts': the symbolic object changes colour dynamically based on the value of a specific property (e.g., displacement trend), enabling a more intuitive interpretation of the ongoing structural behaviour.

Several strategies were adopted to enhance interoperability of the geometric model to structural analysis software (Figure 3). Each type of construction element corresponds to a specific layer, which can be turned on or off for export purposes. This allows the structural engineer to choose whether or not to include certain detailed elements, such as the sub-horizontal arches between the ribs. In contrast, detailed features corresponding to voids – such as the scaffolding holes, *oculi*, or passages between the ribs – which could cause anomalous stress concentrations in the structural model, are handled in the geometric model using Boolean operations. These can be temporarily removed in order to restore the complete, solid geometry. The *macigno* stone chains, inserted by Brunelleschi, are also managed through Boolean operations, allowing the user to choose whether to include this material, which has different mechanical properties, in the structural model. Moreover, as it is well known, the Dome's masonry is composed of stone at the base – up to approximately 5,5 meters from the springing – and continues in brick above that height. This transition between the two materials has been incorporated into the model, separating the webs and ribs in two parts corresponding to the two materials, enabling the assignment of different mechanical properties.

Finally, a simplified representation of passing-through cracks was added. These are modelled as simple cuts, voids with a maximum width corresponding to that of the actual crack and tapered towards both ends, as in reality. This representation can be incorporated into the finite element model when adopting the discrete crack approach, in which cracks are treated as discontinuities within the geometry (Bartoli et al., 2015). This approach enables the use of two complementary representations of the cracks: a detailed and realistic one, suitable for accurate sensor placement and damage interpretation, and a simplified version optimized for data export and integration with external tools for structural analysis.

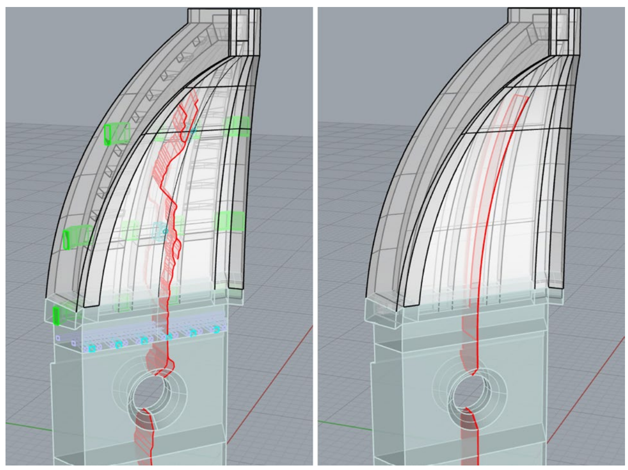


Figure 3. On the left, the complete model of Web 6 displays detailed cracks along with key architectural elements, including sub-horizontal arches, the *macigno* stone chain, *buche pontaie, oculi*, and passages in ribs. On the right, the simplified version - exportable for structural analysis - represents through-cracks as vertical cuts, with layers related to voids and secondary details deactivated. The two colors differentiate the stone base from the brick masonry portion.

3.2 Informative description of cracks

Customized properties are introduced and associated with the objects in the model corresponding to the cracks to incorporate the essential information for a critical survey of damage. To ensure a systematic and guided analysis, most of these customized properties are structured to accept only predefined values within a specific domain, using single- or multiple-choice drop-down menus. Other properties, however, are free-entry fields, allowing the manual input of text strings or numerical values.
The descriptive parameters are categorized into groups, each serving a specific role in the diagnostic process: *ID data, Affected element, Morphology*, *Location*, *Related cracks*, and *Geometry.* A unique code is assigned to each object in the model corresponding to a crack. Indeed, it is essential that each entity within the model is identified by an ID, which serves as the primary key in the database forming the information model. In case of cracks with multiple branches, a sequential number is added to the overall crack code to identify individual branches.
Some parameters provide general information about the affected structural element. These include the type of constructive element (e.g. wall, column, vault, dome), the material (specifically whether the crack affects the mortar joints or the load-bearing elements), and the visibility conditions of the inspection, which influence its accuracy and, consequently, its reliability.
The first key set of parameters describes the *Morphology* of the crack. Among the most significant data is the damage *Configuration,* which distinguishes between single-branch cracks, multi-branch cracks, and diffuse cracks (typically associated with crushing phenomena). This parameter is important for correlating cracks that may initially appear unrelated but should be considered part of (and symptoms of) the same collapse mechanism. Another key parameter is the *Direction* of each crack branch, which may differ from the overall crack orientation and can be associated with existing stresses with a good degree of approximation. The *Relative displacement over crack* refers to the three failure modes of fracture mechanics, while *Variation of crack width over length* is closely connected to the in-plane or out-of-plane type of movement (rotation, translation, bending). Whether the crack traverses the entire thickness of the element is not only indicative of the severity of the damage but also provides insight into its morphology. For example, a crack observed on only one face could suggest the presence of a cylindrical hinge, implying out-of-plane rotation. Moreover, for vaulted structure it is also important to assess whether there is a hinge at the intrados or extrados. Additionally, the associated *Deformation* helps to confirm the movement, although certain types of damage may not produce detectable deformation.
Regarding *Position*, a qualitative description of the location of the cracks within the structural element is provided, and is essential for conducting search queries in the diagnostic-support database, as later explained. This relative position is further supported, in the 3D model of the building, by the absolute position of the crack's tips (with coordinates of both ending points in the reference system of the spatially localized model), which can be updated over time to track the evolution of damage. Both the *location* and the *direction* of *Related cracks* are recorded.
Finally, other data are for evaluating the damage's *Geometry*, starting from the length of the crack. The width is measured according to the three types of movement identified in the *Relative displacement over crack* parameter. The position of the maximum width depends on the *Variation of crack width over length* (e.g., if the crack has a hinge at the bottom, the maximum width will be at the top and vice versa). For cracks with overlapping branches (belonging to the same mechanism), it may also be useful to evaluate the overall width.

4. Application of damage classification protocol

4.1 Diagnostic support tool

Once the cracks are described, the values assigned to the key parameters constitute the input data required for querying the *Diagnostic Support Tool,* which is structured as a database external to the HBIM model (Figure 4).
For masonry walls, the database is divided into three sections (Parente et al., in press). Section A utilizes crack *Morphology* data from the HBIM to identify the *Kinematics* or *actions* associated with the observed damage. Section B, queried using parameters about *Position* and *Related cracks* extracted from the HBIM, facilitates the identification of the affected *Macro-element*. Up to this stage, the *Diagnostic Support Tool* enables partial automation in determining both the kinematic mechanism and the damaged macro-element. However, the subsequent determination of the *Collapse mechanism* and its underlying causes necessitates expert assessment, as this process cannot be fully automated. To assist in this evaluation, Section C of the tool provides a checklist of potential contributing factors derived from information associated to HBIM objects corresponding to construction elements. The protocol was applied to several case studies involving vertical masonry structures, with damage attributed variously to foundation settlements, past earthquakes, or thrusting structures. This application allowed for the refinement of certain limitations of the tool, including, for example, the diagnosis of cracks where multiple types of movements coexist.

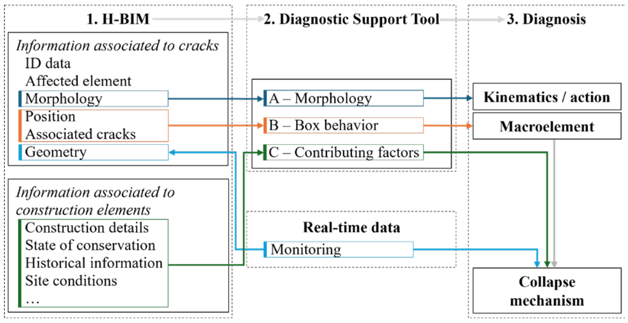


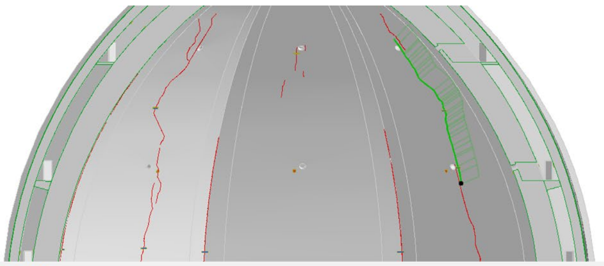
Figure 4. Diagram illustrating the workflow of the proposed protocol for damage classification.

The focus of this contribution, however, is on damage diagnosis in vaulted structures, for which a single section is sufficient, as the macroelement is identified a priori. Therefore, one sheet that simultaneously encompasses both morphological and positional data has been developed for each type of vaulted structure: arch or barrel vault, cross and cloister vault, dome. Of course, the morphology of damage changes according to the geometry of the structure.
In each sheet the fields represent the parameters to describe cracks. The records correspond to the various possible crack morphologies, which arise from assigning and combining different values to the aforementioned parameters. Each distinct crack morphology can be traced back to a specific type of *Kinematics.*
In arches and vaults the collapse mechanisms are mainly of two types: bending mechanisms, with formation of plastic hinges; shear mechanisms, with mutual sliding of ashlars. For each type of mechanism, multiple crack morphologies may occur, influenced by the element's geometry and construction details.

Correspondingly, for each damage morphology, the construction features that promote the activation of that specific failure mechanism are identified: presence and arrangement of ribs or *frenelli* (stiffening walls at the extrados), texture with flat-laid bricks, position of tie rods, etc.

4.2 Application to domes: the case of Santa Maria del Fiore

The cracks in the Dome of Santa Maria del Fiore were described and classified according to the parameters explained above (Figure 5). The values assigned to these parameters were used as input data for querying the *Diagnostic Support tool.* First, the analysis focused on Type A cracks, which are those with the greatest width. These have meridian direction, are located at the center of even webs, tapered towards both ends (also including the portion on the tambour), and passing through the whole thickness of both inner and outer shell.
By querying the diagnostic sheet concerning structural failures in domes (Figure 6), it emerges that the mechanism currently active corresponds to the classical behavior of masonry domes (Heyman, 1995), which is characterized by the rising of compressive stresses at the top and of tensile stresses at the base of the dome. These tensile stresses are incompatible with masonry material, which has almost no tensile strength, and consequently cause cracks along the meridians. In almost all real masonry domes, meridian cracks are the result of the structure’s self-weight and are typically accompanied by a slight opening of the tambour and a downward displacement of the apex.



ID DATA	
ID crack branch	FE-S4-1-CI-1
ID crack	FE-S4-1
ID element affected	S4-CI
Survey source	Photogrammetric survey (1999)
Type of affected element	interior shell
Affected material	in joints
Visibility	mainly plastered
MORPHOLOGY	
Type of crack	A (passing crack in the middle of even web)
Configuration	multiple segments
Branch arrangement	consecutive
Direction of crack branch	meridian
Direction of crack	meridian
Relative displacement over crack	in-plane opening
Overall variation of crack width over length	tapered towards both ends
Variation of width over length of branch	hinge at top
Depth	passing
Deformation	downward displacement of the top
POSITION	
Crack position	between second and third walkway
Coordinates of tip 1	28.50; 0.65; 25.26
Coordinates of tip 2	33.82; -5.06; 11.47
RELATED CRACKS	
Location	parallel cracks on even webs
ID of related cracks	FE-S2-1; FE-S6-1; FE-S8-1
GEOMETRY	
Lenght [m]	15,800
Maximum width [cm]	6,000

Figure 6. Informative representation of Type A crack of Web 4.

In polygonal domes, as illustrated in the diagnostic protocol, meridian cracks may develop either along the edges or at the center of the webs. If the dome behaves predominantly as a cloister vault, each web tends to detach from the others, resulting in cracking along the structural corners. Conversely, when the structure behaves as a rotational dome, cracks typically develop at the midpoints of each web. This behavior is exemplified by the Dome of Santa Maria del Fiore, where the construction techniques of the herringbone pattern (*spinapesce*) and the arrangement of bricks along conical courses (*corda blanda*), successfully induced the structural response characteristic of a rotational dome (Como et al., 2019).

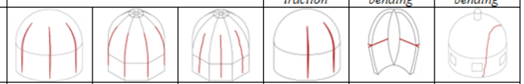
	Damage	*Symmetric traction*			*Asymmetric traction*	*Symmetric bending*	*Asymmetric bending*
	Schema						
	Affected element	Dome	Polygonal dome	Polygonal dome	Dome	Dome	Dome
Morphology	**Direction**	meridian	meridian	meridian	meridian	on parallels	parabolic
Morphology	**Relative displacement**	in plane opening	in plane opening	in plane opening	in plane opening	in plane opening	in plane opening
Morphology	**Variation of crack width over lenght**	- tapered towards both ends	- tapered towards both ends	- tapered towards both ends	- tapered towards both ends	costant	- tapered towards both ends
Morphology	**Variation of crack width in depth**	costant	costant	costant	costant	hinge at intrados	hinge at extrados
Morphology	**Depth**	passing	passing	passing	passing	non-passing /passing with major width at extrados	passing
Morphology	**Associated deformation**	- out of plumb of tambour - lowering of top	- out of plumb of tambour - lowering of top	- out of plumb of tambour - lowering of top	- asymmetric out of plumb of tambour	- out of plumb of tambour - lowering of top	- asymmetric out of plumb of tambour
	Position	-	at edgest	in the middle of webs	asymmetric	-	asymmetric
	Associate cracks	similar cracks other sectors	similar cracks other sectors	similar cracks other sectors	-	meridian cracks	-
	Contributing factors and construction features	(physiological, always occurring)	- bad interlocking at edges, behavior as cloister vault prevails	- good interlocking at edges, behavior as rotation dome prevails	- asymmetry of thrust-contrasting elements - different stiffness of the sectors of the tambour - differential settlements	(severe damage, leading to collapse)	- differential settlements - seismic action

Figure 5. Diagnostic support tool. Part concerning damage mechanisms of masonry Domes.

Moreover, the *Diagnostic Support Tool* assists in the interpretation of potential asymmetries in the crack pattern. In the Dome of Santa Maria del Fiore, the widest meridian cracks are found only in the even-numbered webs. Among these, cracks in segments 4 and 6 are wider and are historically documented to have appeared earlier (Blasi, 2023). Several possible causes of asymmetries in the crack pattern are identified and illustrated within the diagnostic tool: asymmetry in the thrust-resisting elements (such as aisles, apses, chapels, or adjacent buildings), since the dome naturally tends to open in the direction offering the least resistance; variation in stiffness among the sectors of the supporting structure (i.e., the tambour); potential differential settlements at foundation level.
Several studies confirmed that the causes of asymmetry in the crack pattern of Brunelleschi’s Dome are the first two previously mentioned, while foundation settlements have been excluded, also based on monitoring data (Ottoni and Blasi, 2015). In particular, the tambour exhibits different stiffness characteristics between the even webs, which rest on piers, and the odd webs, which rest on arches. This explains the presence of the main cracks exclusively in the even webs (Chiarugi et al., 1983). Indeed, the tambour behaves as a continuous beam: the sectors supported by piers act as the beam’s supports, and tensile stresses develop in the upper fibers with maximum at the

midspan, near the springing of the dome. Conversely, in the sectors supported by arches, tension occurs in the lower fibers, below the oculi (where type B cracks are in fact observed). The local tensile stresses that arise are the combined result of two effects: the physiological tension along the parallels at the base of the dome and the continuous beam behavior of the tambour. As a consequence, cracking inevitably initiated at the midpoints of the even webs of the dome (Fanelli and Fanelli, 2004). Then, the main nave provides greater resistance to the outward thrust compared to the apse. This difference may explain the greater width of the cracks in webs 4 and 6 on the apse side, compared to those in webs 2 and 8 facing the nave (Blasi, 2023).
However, as previously mentioned, the identification of these *Contributing Factors* – both geometric and construction-related – is not automatic and requires in-depth analysis by experts.
Generally, not in the case of Santa Maria del Fiore, once the dome has been subdivided into independent arches due to the development of meridional cracks, the failure mechanism involves each individual arch being subjected to bending. This, in turn, results in the formation of horizontal cracks along the parallels of the dome (Como, 2013).
The diagnosis of the other crack types of Santa Maria del Fiore dome, classified as type C and type D, is more complex, as it can only be explained through an analysis of the dome's static behavior in the presence of pre-existing type A cracks (Fanelli and Fanelli, 2004). In this case, the diagnostic support database proves insufficient, as it is confined to standard and recurring mechanisms and does not encompass cracks that arise from particular conditions and pre-existing damage.

5. Structural Health Monitoring: HBIM integration for damage interpretation and evolution assessment

Structural Health Monitoring (SHM) plays a critical role in the assessment and conservation of masonry structures. As stated in the Italian D.P.C.M. 9 February 2011, 'the periodic monitoring of the building represents the main tool for a conscious conservation', as it enables interventions to be planned and executed only when strictly necessary.
Beyond tracking damage evolution over time, SHM can also serve as a tool for validating diagnostic hypotheses. By focusing specifically on the monitoring of crack width, SHM can help to confirm crack morphology and the associated movement.
Additionally, following the identification of the kinematics, SHM can contribute to determining the underlying causes of damage. In particular, correlating environmental parameters – such as temperature and rainfall – with variations in crack width provides valuable diagnostic insights (Ceravolo et al., 2021).
Once the damage mechanisms are properly understood, monitoring enables the assessment of their evolution over time. However, interpreting monitoring data remains a complex and open issue, primarily due to the significant variability of hazard thresholds depending on the specific failure mechanism and case study.

5.1 Dataset reliability

Even before assessing the damage evolution, the reliability of the data set should be evaluated (Makoond et al., 2021). For this purpose and with specific reference to the monitoring of crack width, several parameters can be assessed, regarding respectively *Monitoring system design* and *Data analysis*. This information is received in the model as custom properties associated with the symbolic objects corresponding to sensors.
It should be noted that the following information refers to the individual sensor, and that the overall system completeness – in terms of the number of instruments and monitored variables – is not yet taken into account.
The parameters related to *System design* are as follows:
- *Duration:* of course, the longer the duration, the higher the reliability (Makoond et al., 2021). Long-term monitoring allows the cyclical component due to seasonal variations to be comprehended and extracted.
- *Sampling frequency:* seasonal (1/3 month), daily, or also recording daily variations (1/6 hours).
- *Resolution:* specification of the monitoring instrument.
- *Data reading:* on-site or via remote connection. The second allows any system errors to be highlighted immediately.

With regard to *Data analysis*:
- *Percentage and distribution of missing data*: it is not only the amount of missing samples, but also their distribution, that determines the reliability of the dataset. Missing values concentrated in blocks – resulting in large gaps or even entire missing time series – are considerably more detrimental than sporadic losses spread over a longer period, which tend to have a limited impact on the overall assessment. Of course, it gets even worse if the missing data are recent.
- *Coefficient of determination (R^2):* indicates the correctness of the statistical model used and thus concerns the reliability of the analysis (Makoond et al., 2020). R^2 is assumed to be evaluated with respect to a sinusoidal regression. A low R^2 means that it is necessary to deepen the analysis in order to better explain fluctuations in the dataset that cannot be attributed to cyclical variations.
- *Trend stability:* this parameter is particularly significant in the case of monitoring with a long duration and indicates whether the trend is stable or not over the observation period (Ottoni and Blasi, 2015). The presence of periods with different trends indicates that, reasonably, there may have been an event that changed the damage evolution and that needs to be further investigated. For example, an earthquake that led to a more rapid evolution, but also a strengthening that stopped the damage from worsening.

Reliability assessment was applied to some of the sensors on the Dome of Santa Maria del Fiore, particularly those located on webs 4 and 6 (Marafini et al., 2024) (Figure 7). System reliability is very high, especially because of the very long monitoring duration. However, some sensors have a substantial amount of missing data or show significant changes in the trend throughout the observation period, as already noted in (Ottoni and Blasi, 2015), which lower the overall reliability.

5.2 Damage evolution

Regarding the evolution of the damage, synthetic indices are proposed to be associated with each sensor. Again, the proposal is limited to the evaluation of data about crack width.
- *Trend [mm/century]:* it is the slope of the linear regression and is the main representative data of the pathological behavior of the crack. The sign of the trend indicates whether the crack is opening or closing.
- *Recent trend (2-5 years) [mm/century]:* in the case of long-term monitoring, it is useful to highlight the most recent trend and assess its consistency with the overall period one.
- *Average annual excursion [mm]:* the average of the differences between the highest and lowest values recorded in each year. It provides information on physiological behavior (annual cyclical variation due to thermal fluctuations).
- *Maximum jump [mm]:* this is the maximum difference between two consecutive data points. It highlights anomalies or responses to events.
- *Relevant events during the observation period:* earthquakes, periods of heavy rainfall, or excessive drought may have influenced the monitoring. Recording them and identifying their

dates help in understanding apparent anomalies in the dataset.
- *Correlation with temperature:* in case of systems that include a thermometer, correlation coefficient between crack width and temperature can be evaluated. The sign of the coefficient indicates whether the two variables are in phase or in antiphase (Ceravolo et al., 2021).
These parameters were associated with the sensors located on the Dome of Santa Maria del Fiore (Figure 7). The spatial localization and analysis (Barazzetti, 2024) of such a complex monitoring system enabled a clearer visualization of the damage and facilitated the prompt identification of the specific dome webs and height levels where the crack width progresses most rapidly. Indeed, by setting a "graphic override", the sensors in the model are automatically color-coded based on the values assigned to these parameters, such as the observed trend. This also supports the validation of the underlying mechanism diagnosis. For instance, it is evident that in type A cracks, the highest opening trend occurs near the springing of the dome, which aligns with both the understanding of the mechanism and the "tapered towards both ends" morphology of the entire crack.
The values assigned to other parameters can be visualized as well. For example, by graphically displaying the correlation with temperature, the "breathing" of the Dome becomes apparent: during summer, as the masonry expands, the passing-through cracks tend to close.

ID DATA - MONITORING	
ID sensor	DF4-10
ID crack branch	FE-S4-1-T-1
Type of sensor	Deformometer
Dome sector	4
Position	Intrados of interior shel
Height	2° galleria (occhi)
Measured quantity	Variation in crack width
DATASET RELIABILITY	
Duration	36 years
Acquisition mode	automatic
Resolution [mm]	0,020
Data reading	via remote connection
Percentage of missing data	10-20%
Distribution of missing data	in blocks
Dating of missing samples	recent (last 5 years)
Coefficient of determination (R2)	>80%
Trend stability	stable
DAMAGE EVOLUTION	
Trend [mm/century]	3,020
Recent trend (2-5 years) [mm/cent...	stable
Average annual excursion [mm]	1,981
Maximum jump [mm]	0,759
Relevant events during the observ...	earthquake, Mw 4,8, 18
Correlation with temperature	0,900
LINK	
Report	https://drive.google.con
Raw data	https://drive.google.con
Graphs	https://drive.google.con

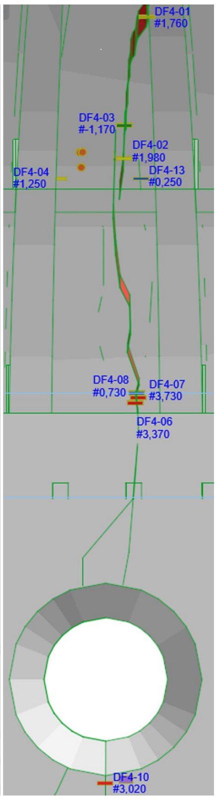


Figure 7. Informative representation of monitoring sensors. Sensors with a higher trend are automatically coloured in red.

6. Conclusions

The main aim of this study is the proposal of a protocol that serves as a structured guide for the critical survey of crack patterns, addressing a gap in the existing literature regarding the classification and interpretation of cracks in masonry structures. Specifically, this contribution focuses in detail on the section of the protocol dedicated to the diagnosis of damage in masonry domes, with an application to a case study: the Dome of Santa Maria del Fiore.
The development of the model for the case study facilitated a comprehensive exploration of multiple aspects related to the management of structural damage within the HBIM framework, encompassing both geometric modelling and the incorporation of crack monitoring data. Notably, specific synthetic indices were proposed to quantitatively evaluate the reliability of the data and to assess the progression of damage over time.
Future research should aim to address more specifically the technical implementation challenges behind HBIM damage management and monitoring data reception. This includes enhancing the interoperability of damage representation, as explored by (Zanni et al., 2024), and investigating the potential – yet unrealized – real-time integration of monitoring data into the information system. From the perspective of damage diagnosis, a broader validation is currently underway on several case studies, beyond those presented in (Parente et al., in press). This will lead to increased robustness of the protocol and, with regard to monitoring, will allow for the assignment of scores and weights to the indices for quantifying data reliability.

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