CHALMERS
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TRM Strengthening of Historic Masonry Vaults

Evaluation of use in the Church of Saint Bassiano in Italy and possibilities for Skörstorp's Church in Sweden

Master thesis in the Master's Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Master's thesis ACEX30

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Cover:
Exteriors of both Churches, the Church of Saint Bassiano to the left and Skörstorp's Church to the right.
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ABSTRACT

There is a growing need for reliable, minimally invasive methods to strengthen older buildings such as historic masonry structures, yet limited data exist on the long-term, real-world performance of such interventions. In this thesis the effectiveness of Textile Reinforced Mortar (TRM) in stabilizing historic masonry vaults is investigated through the case study of the Church of Saint Bassiano in Italy, where TRM was applied to the extrados of the vaults in the main nave over a decade ago. This is then applied to a Swedish context through the case study of Skörstorps's Church; a Swedish round church with similar structural concerns. The goal is to assess the effectiveness of the TRM application in St. Bassiano and evaluate if it is a suitable intervention for the case of Skörstorp's Church. In St. Bassiano, documentation and visual surveys indicate that TRM effectively stabilized the main nave vaults. However, cracking has since appeared in unstrengthened areas, such as the side aisles and vertical supports, suggesting a redistribution of stress due to localized stiffening. In the Swedish church, long-term cracking has persisted despite earlier repair efforts. Recently, cracks have worsened. The issues appear to have been affected by continuing soil settlement in combination with irregular load from roof and an increased outward thrust from the vaults resulting in increased damage to the round perimeter walls. A preliminary suggested solution informed by the observed hinge settlement mechanism would be to first strengthen the vault with TRM. Should the damage persist, further intervention might be necessary targeting the foundation.

Key words:
Textile Reinforced Mortar, Historic Masonry, Vault Strengthening, Heritage Conservation, Structural Assessment, Case Study

TRM som förstärkningsmetod av historiska murverksvalv
Utvärdering av användning i St. Bassiano kyrkan i Italien och möjligheter för Skörstorps kyrka i Sverige

Examensarbete inom masterprogrammet Konstruktionsteknik och Byggnadsteknologi

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SAMMANFATTNING

Det finns ett växande behov av tillförlitliga och minimalt invasiva metoder för att förstärka äldre byggnader, såsom historiska murverkskonstruktioner. Trots detta är kunskapen begränsad kring hur sådana förstärkningsåtgärder presterar i verkliga tillämpningar över längre tid. Detta examensarbete undersöker effektiviteten hos textilarmerat murbruk för att stabilisera murverksvalv genom två fallstudier: St. Bassiano kyrkan i Italien, där textilarmerat murbruk applicerades på valvens extrados i mittskeppet för över ett decennium sedan, samt Skörstorps kyrka; en svensk rundkyrka med liknande strukturella problem. Syftet är att utvärdera effekten av textilarmerat murbruk använt som förstärkning i St. Bassiano och bedöma om det är en lämplig metod även för Skörstorps kyrka. I St. Bassiano visar dokumentation och visuella undersökningar att textilarmerat murbruk effektivt stabiliserade valven i mittskeppet. Dock har sprickbildning senare uppstått i delar som inte förstärkts, såsom sidoskepp och vertikala bärande element, vilket tyder på en omfördelning av laster till följd av lokal styvhet. I den svenska kyrkan har långvariga sprickor kvarstått trots tidigare reparationsförsök, och på senare tid har sprickbildningen förvärrats. Problemen verkar ha förvärrats av fortsatt sättning i marken i kombination med ojämn last från taket och ett ökat utåtverkande tryck från valven, vilket lett till ökade skador i de runda omgivande väggarna. Ett preliminärt förslag till lösning, baserat på den observerade sättningsmekanismen, är att först förstärka valvet med textilarmerat murbruk. Om skadorna fortgår kommer ytterliggare åtgärder som riktar sig mot grunden att vara nödvändiga.

Nyckelord:
Textilarmerat murbruk, Historiskt murverk, Valvförstärkning, Byggnadsvård, Strukturell Bedömning, Fallstudie

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Preface

In this study I investigate the application of Textile Reinforced Mortar (TRM) as a strengthening method for historic masonry vaults. The research includes case studies of Saint Bassiano in Pizzighettone, Italy, and Skörstorp's Church in Sweden. The work was carried out between January 2025 and June 2025 as part of my Master's thesis at Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Structural Engineering and Building Technology.

A part of this work was conducted during a research stay at Politecnico di Milano from February 20 to March 21, 2025. The stay was hosted by the Department of Civil and Environmental Engineering, with Professor Dario Coronelli and Associate Professor Giuliana Cardani serving as academic supervisors. I am grateful to Dario, Giuliana, and the welcoming office at Politecnico di Milano for their warm hospitality and support during my stay.

I would also like to express my sincere gratitude to my examinator at Chalmers, Professor Karin Lundgren, and my supervisors Dario and Guiliana, for their valuable guidance throughout the project. Special thanks are extended to Giuliana for kindly providing original drawings of Saint Bassiano, as well as to Carl Thelin and Tyréns AB for sharing information on Skörstorp Church. I also want to thank my opponents Vendela Örndal and Linn Vernersson.

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Annie Skeppstedt

Notations

This section lists the abbreviations, technical terms, and architectural vocabulary used throughout the thesis. It is intended to aid the reader in understanding key concepts related to structural engineering and historical masonry.

Abbreviations

TRM	Textile Reinforced Mortar
FRCM	Fiber Reinforced Cementitious Matrix
SHM	Structural Health Monitoring
FEM	Finite Element Method
CRM	Composite Reinforced Mortar
SRG	Steel Reinforced Grout
EPS	Expanded Polystyrene
FRP	Fiber Reinforced Polymer
GFRP	Glass Fiber Reinforced Polymer
BTRM	Basalt Textile Reinforced Mortar
LDPM	Lattice Discrete Particle Model

Technical Terms

Extrados	Outer surface of an arch or vault
Intrados	Inner surface of an arch or vault
Groin Vault	Vault formed by intersection of barrel vaults
Rib Vault	Vault formed by diagonal or crossed arched ribs
Haunch	Part of the arch between crown and support
Hinge Mechanism	Structural failure mode in arches
Abutment	End support resisting arch or vault thrust
Apse	Semicircular space behind the altar
Main nave	Central, main hall of a church
Side aisle	Narrow passage alongside the nave
Spring line	Line where an arch or vault begins to curve
Pozzolanic Mortar	Mortar with pozzolanic additives
Carbon Mesh	Reinforcing textile used in TRM
C-joint Connector	Connector in TRM strengthening system

1 Introduction

1.1 Background

Historical buildings are often subject to structural issues caused by centuries of environmental exposure, design modifications, changing load distributions, soil settlements, and additional vibrations from external factors such as nearby traffic or seismic activity. These challenges are particularly acute in masonry vaults, which are vulnerable to cracking, deformation, and instability.

The church of Saint Bassiano in Pizzighettone, Italy, exemplifies these issues. The church has since its construction evolved through numerous changes and additions, as well as having experienced significant structural degradation over time. Problems such as foundation instability, widespread cracking in its masonry vaults, and deformations have been worsened by soil settlement, poor roof renovations that caused uneven loading on the structure, and external vibrations from both seismic events in 2012 and ongoing traffic activity. In response, Textile Reinforcement Mortar (TRM) was employed as an intervention technique in the cross-vaults and main masonry arches of the nave. The type of TRM used in this case was a bidirectional mesh of carbon fibers and pozzolanic hydraulic mortar (Cardani and Massetti, 2017).

This thesis takes the church of St. Bassiano as a detailed case study to evaluate the effects of TRM interventions on historic masonry vaults. By analyzing the effectiveness of TRM in this context, the study will explore the potential for applying similar techniques to a Swedish historical structure with comparable challenges, such as soil-induced settlement and load imbalances. The church chosen as a case study for the Swedish structure is Skörstorp's Church in Falköping, which has experienced cracking in vaults and walls for a considerably long time. The research aims to contribute to the targeted application of advanced reinforcement methods in heritage conservation by providing insights into their performance and adaptability in different contexts.

1.2 Aim

The aim of this Master's thesis is to analyze the effectiveness of Textile Reinforcement Mortar (TRM) as a targeted intervention technique for stabilizing historic masonry vaults. Using the church of St. Bassiano in Italy as a case study, the research will assess the impact TRM has had during a 10-year period on mitigating structural issues such as cracking, deformation, and foundation instability. A secondary objective is to evaluate the feasibility and adaptability of applying TRM techniques to a Swedish historical structure; Skörstorp's Church, which had similar structural and environmental challenges.

The main question to be answered through this study is:

- How effective is the use of TRM in strengthening and preserving masonry vaults in (historic) buildings, and what lessons can be drawn from the case of the church of St. Bassiano for possible application to Skörstorp's Church?

1.3 Limitations

This study focuses specifically on Textile Reinforcement Mortar (TRM) as an intervention technique on a historic masonry structure, limiting the scope of the research to the performance and adaptability of this method. Other reinforcement techniques, such as tie rods or injections, will only be mentioned where relevant to understanding the context of the use of TRM but will not be evaluated in detail.

The analysis is centered on two case studies; the church of St. Bassiano in Italy and Skörstorp's Church in Sweden. As a result, the findings are case-specific and may not be generalized to all heritage structures. Furthermore, the research relies on the availability of historical and technical data for both case studies. Any gaps in the data could restrict the depth of the evaluation or limit the scope of the conclusions.

Lastly, although cultural and environmental differences between Italy and Sweden will be considered, it may not be possible to account for all regional variations in construction materials, practices, and site conditions.

1.4 Methodology

This study employs a case-study-based methodology to evaluate the effectiveness of textile reinforcement mortar (TRM) as an intervention technique for historic masonry vaults. The research was divided into 4 main phases: planning and literature review, analysis of the intervention at the church of St. Bassiano, intervention applicability to the Swedish heritage structure, Skörstorp's Church, and final writing phase.

In the first phase, a thorough research planning was carried out, including an extensive literature review on TRM, masonry structures, and conservation principles.

In the second phase, technical documentation, historical records, and on-site data from the church of St. Bassiano were analyzed to assess the specific conditions of the masonry vaults prior to the intervention. The mechanical and structural effects of the TRM intervention, including its impact on load capacity, deformation behavior, and long-term durability, were evaluated.

The third phase involved a comparative analysis, where lessons from St. Bassiano were adapted to a Swedish heritage structure; Skörstorp's Church. Differences between the churches such as material and environmental conditions were considered keeping in mind the different conservation priorities. This phase involved a site visit and structural assessments to explore the feasibility of TRM in the Swedish context.

The findings were then compiled and revised into the final report. Throughout the study, the research has been guided by principles of heritage conservation, focusing on the balance between structural stabilization and the preservation of historical and cultural integrity.

1.5 Societal, ethical and ecological aspects

Preserving historical structures holds significant societal value, as these buildings are vital cultural assets that reflect a region's identity and heritage. The thesis contributes to society by exploring effective methods for maintaining these structures, ensuring they can be appreciated by future generations. The use of techniques like TRM promotes preservation while allowing buildings to remain functional and accessible, thereby supporting their continued role in society.

Ethical considerations are central to conservation work. Conservation should aim to preserve and, where possible, enhance the significance and values of cultural heritage (Feilden, 2003). TRM, as a modern material, must be evaluated in terms of its compatibility with original construction materials to avoid irreversible changes or unintended damage to the structure's integrity. Although interventions almost always involve some loss of value in cultural property, it is worth discussing to which degree it is justified (Feilden, 2003). Additionally, the research must respect the cultural significance of both the Italian and Swedish heritage sites, ensuring that any proposed solutions honor their historical and architectural authenticity.

The ecological implications of restoration techniques must be considered. The best way of preserving buildings is to keep them in use (Feilden, 2003). Reusing or keeping already existing buildings in use is also often the best way of taking advantage of already existing material and thus reducing the ecological footprint of tearing down and rebuilding. The study slightly touches on the subject of how the application of TRM can be optimized to minimize resource consumption and waste, ensuring that the interventions are sustainable.

Artificial intelligence (AI) has been used sparingly throughout this project, primarily as a support tool during the early stages of development, assisting in outlining ideas and sometimes structuring sections. However, all major analysis, interpretation, and final writing decisions were made independently.

2 Technical Context: Historical Conservation, Masonry Structures and Textile Reinforced Mortar

2.1 Historical Conservation

The first page of the book Conservation of Historical Buildings (Feilden, 2003), introduces the concept of a historic building quite well:

> *"An historic building is one that gives us a sense of wonder and makes us want to know more about the people and culture that produced it. It has architectural, aesthetic, historic, documentary, archeological, economic, social and even political and spiritual values; but the first impact is always emotional, for it is a symbol of our cultural identity and continuity - a part of our heritage."*

The notion that the initial impact a building has is always emotional, also gives an understanding of the values that guides us through conservation efforts. Conservation should uphold and, when possible, strengthen the values of cultural property. While interventions usually involve some loss of original value, they are often deemed necessary to protect the property for the future (Feilden, 2003).

2.1.1 Conservation Guidelines

Historical conservation has evolved from past practices of demolition and reconstruction to a more responsible approach that prioritizes minimal intervention, protection against deterioration, and compatibility with original materials. Regulating bodies, such as local heritage authorities, oversee conservation efforts, ensuring that interventions align with these principles before any project begins (Lourenco, 2018). These modern approaches are also grounded in international charters such as those developed by ICOMOS, n.d. (International Council on Monuments and Sites), which emphasize the importance of a multidisciplinary strategy, respect for the cultural context, and the preservation of both the material and intangible values of architectural heritage. According to ICOMOS, interventions should be formed after careful diagnosis, prioritize reversibility and compatibility, and avoid irreversible harm. Conservation is not viewed as an end in itself, but as a means to preserve the integrity and authenticity of the entire structure, including its original construction techniques and historical layers (ICOMOS, 2003).

Current conservation policies, mentioned by both Lourenco and ICOMOS, emphasize:

- Minimal intervention.
- Protection against disaster and neglect.
- Using identical or the best available replacement materials.
- Additions designed to be in keeping with the style of the original building or alternatively clearly distinguishable from it.
- Recording all changes in a detailed log for historical documentation.
- Ensuring interventions are compatible with original materials and, where possi-

ble, reversible.

- Conducting thorough preliminary analysis, including structural diagnosis and safety evaluation, before intervention.
- Integrating an interdisciplinary approach that incorporates historical, architectural, and engineering perspectives.

Recently, modern technologies have been more incorporated into conservation efforts, improving both assessment and intervention processes. Techniques such as reconstruction methods for surveying, structural health monitoring systems, and numerical simulations for analyzing load scenarios allow engineers to evaluate structural behavior with greater accuracy and predict responses to external forces (Lourenco, 2018).

2.1.2 Intervention Techniques

When intervention is necessary, replacement materials must be chosen carefully to maintain historical integrity. When selecting replacement materials they should be compatible from a chemical, physical and mechanical point of view. Furthermore, the following principles apply (Lourenco, 2018):

1. Use unweathered identical materials when available.
2. For new additions, slightly stronger materials may be acceptable.
3. For patching, use slightly softer materials to prevent the original masonry from deteriorating faster than the replacement material.
4. Avoid mixing chemically incompatible materials, as differences in moisture absorption, thermal expansion, or strength can significantly accelerate weathering and structural damage.

The historical compatibility of mortar is crucial. It must closely resemble the original material while remaining removable for future interventions. This compatibility must be ensured across multiple dimensions: (i) chemical compatibility between the new repointing mortar and the existing materials, such as stone or brick, along with their original bedding mortar; (ii) physical compatibility, particularly concerning solubility and moisture transport processes; and (iii) structural and mechanical compatibility, meaning that the strength of the repair mortar should closely match that of the historic materials (Lanas and Alvarez, 2003). Repointing mortar, in particular, should never be stronger than the masonry units it binds, as this could lead to cracking and long-term structural damage (Lourenco, 2018). The analysis of mortar composition includes identifying:

- Binder type
- Aggregate composition
- Additional ingredients such as plasticizers, pozzolans, or pigments
- Hydraulicity of the mixture
- Porosity and grading of the aggregates

As historic buildings are continually subjected to varying loads and environmental conditions, conservation efforts must focus on preserving their capacity to adapt rather than trying to restore them to an unchanging state. Common strengthening techniques include:

- Filling internal voids in stone masonry to improve cohesion.
- Using transversal connectors and tie-rods to enhance stability.
- Applying reinforced plaster systems, where steel or fibre reinforced polymer (FRP) meshes, or more recently TRM, are attached to walls for additional load resistance.

When strengthening vaults, restoration techniques involves rebuilding damaged sections, prestressing ribs with hydraulic jacks, or using metal ties across vault springings (Feilden, 2003). The durability of vaults is further influenced by the materials used in construction, with lime-based mortars offering greater elasticity and absorbtivity than modern Portland cement, which while stronger, offers less flexibility.

2.1.3 Challenges in Historical Conservation

Strengthening masonry structures, especially in seismic zones, presents unique challenges. Selecting an appropriate technique requires balancing conservation principles (compatibility, reversibility, minimal intervention) with technical feasibility and cost considerations (Lourenco, 2018). The "least bad" solution is often preferable. The solution that preserves the structure's integrity while allowing for future interventions. Considerations such as cost efficiency and regulatory approval, although important, should not outweigh the need to preserve the building's historical and structural integrity (Feilden, 2003).

2.2 Masonry Structures

Masonry is an ancient construction material that has been widely used because of its strength in compression and durability. However, it is significantly weaker in tension and shear, which influences its structural behavior and failure patterns. Understanding these principles is essential when analyzing masonry structures, particularly historic ones, which often exhibit complex patterns of stress redistribution and deformation.

2.2.1 Structural Behavior

Masonry structures are inherently anisotropic due to their layered composition, meaning their strength and behavior vary depending on the direction of applied forces. Much of their stability is derived from their self-weight, which helps resist bending and collapse. The high density of masonry, typically ranging from 500-2500 kg/m^3, contributes to this stability (Lourenco, 2018).

Ancient structures were often built with relatively weak materials, resulting in massive and statically indeterminate forms. A statically indeterminate structure has the capacity to undergo multiple internal adjustments, allowing it to accommodate new loads, settlements, and distortions. As deformations occur, the structure naturally establishes one of several possible equilibrium states. However, with continued deformation, the range of possible adjustments diminishes, gradually making the structure more determinate over time. Each structural form exhibits distinct weaknesses, constraints, and characteristic behavioral patterns (Feilden, 2003). The typical Romanesque structure, for example, was designed to disperse forces through thick walls, limited openings, and vaulted ceilings, ensuring stability despite the relative weakness of the materials used.

2.2.2 Compression, Shear, and Tension Resistance

Masonry resists axial compressive loads most effectively when applied normal to the bedding plane, as in load-bearing walls. Arches similarly carry loads through radial compression. In a stretcher-bonded wall, a point load spreads outward, transferring force downward through each unit. In a half-bond wall, stress disperses at about 45 degrees but remains concentrated along the load axis. This compression causes elastic shortening, while Poisson's ratio effects generate lateral tensile strain and stress. The bond between units plays a critical role in inhibiting crack growth, particularly in bonded masonry, where overlapping units help control vertical joint cracks. However, masonry performs poorly when subjected to compression parallel to the bedding plane, as bed joints are more prone to failure (Lourenco, 2018).

Shear failure in masonry structures can occur due to lateral forces such as wind, impact, or seismic activity. Shear behavior depends on wall geometry, mechanical properties, and boundary conditions. Common failure modes include shear sliding, which occurs along weak mortar joints when compressive loads are low, and diagonal tension shear, which manifests as stepped or direct cracking through masonry units and joints (Lourenco, 2018).

Historic masonry buildings often display visible patterns of cracking, which indicate internal stress distributions. Cracks typically form perpendicular to tensile stress directions, revealing the paths of principal compressive forces. Many historic structures develop cracks over time due to thermal changes, moisture content variations, and foundation settlements. Some cracks may close when loads are adjusted, while others indicate ongoing structural adjustments (Feilden, 2003). Such movements contribute to the continual evolution of structural equilibrium in historic buildings, which must be accounted for in any conservation effort.

Masonry has limited tensile resistance, especially in traditional unreinforced forms. While some tensile strength exists parallel to bed joints, in design calculations, it is often considered negligible. Reinforcing mortars can enhance tensile resistance, improving the out-of-plane bending strength of masonry walls (Lourenco, 2018). In historic structures, reinforcement is often introduced not to eliminate cracking but to manage and keep them under control, ensuring that the structure remains stable while accommodating natural movements (Feilden, 2003).

2.2.3 Arches and Vaults

Arches and vaults exemplify masonry's ability to carry loads primarily through compression. The principle behind their structural integrity lies in the way inward forces on the external surfaces generate radial compression, keeping the structure stable. Groined vaults, in particular, develop stiff geometries due to the intersection of arches along their diagonals. These intersecting arches guide thrust toward the vault's corners, where supports (abutments) must resist both vertical and lateral components of the load (Feilden, 2003).

Arches must be analyzed in the context of their surrounding walls or arcades, as their stability depends significantly on the condition and resistance of their abutments. If these supports shift, settle, or rotate, the structural integrity of the arch is compromised (Feilden, 2003). This interdependence between the arch and its abutments is a central concept in the work of Jacques Heyman, whose theory in *The Stone Skeleton* formalizes the behavior of masonry through three foundational assumptions: no tension, infinite compressive strength, and stability through equilibrium (Heyman, 1995).

According to Heyman's static theorem, also called the safe theorem or the lower bound theorem, of a masonry arch can be idealized as a system that remains stable as long as one state of equilibrium can be found. Thus, as long as the line of thrust, the path along which compression travels, remains within the thickness of the masonry, the arch will not collapse. Similarly, but from the other end, the upper bound theorem or kinematic theorem states that once the thrust line moves outside the masonry body, i.e. when the load path can no longer be contained within the structure, that load will be the collapse load. This leads to the formation of cracks which acts as hinges. The way these hinges forms describes the collapse mechanism of the arch or vault. See Figure 2.1, for a schematic drawing of a possible collapse mechanism in a vault under uniform load. This theoretical framework explains why local cracking in arches often signifies a redistribution of forces rather than immediate failure. However, it also identifies a critical threshold: when three hinges form, the structure becomes statically determinate and unstable. In pointed arches, the apex frequently acts as one of these hinges due to geometric sharpness, reducing the margin for additional hinge formations (Heyman, 1995).

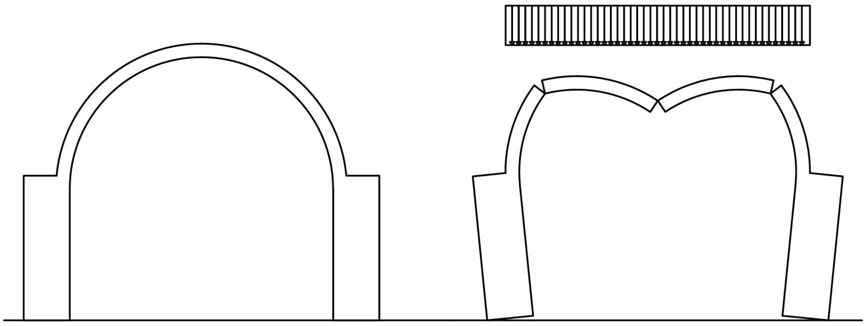


Figure 2.1: Schematic of hinge formation resulting in collapse of vault under uniform load

2.2.4 Cracking Behavior According to Mario Como's Theory - Force Transmission

In line with Mario Como's theory, as elaborated in *Statics of Historic Masonry Constructions* (Como, 2017), the cracking patterns observed in cross-vaults can be interpreted through the no-tension model. This model presumes that masonry behaves primarily in compression and has negligible tensile resistance. Consequently, the vaults function similarly to a series of independent arches, each transferring load to longitudinal supports and ultimately to the foundations.

Como explains that in a groin or cross-vault, the intersecting webs behave analogously to barrel vaults sliced by the diagonals of the vault plan. Each slice operates as an arching band, where the load is directed along the compressive lines to the diagonals, acting essentially as the principal load-bearing elements. See Figure 2.2 for a schematic drawing of the plan view illustrating this effect. This structural behavior underpins the formation of characteristic cracking patterns, typically appearing perpendicular to the compressive thrust lines, and particularly manifesting in areas where tensile stresses develop due to geometric irregularities or support settlements.

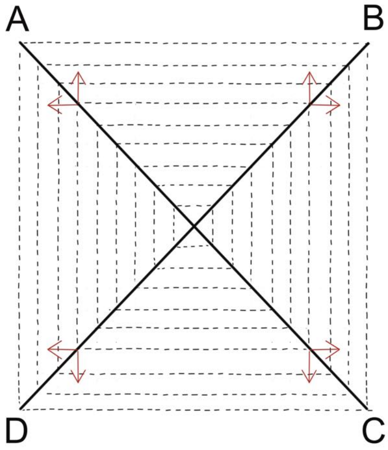


Figure 2.2: Webs of a groin-vault sliced into various spans of arching bands supported by the diagonals.

As illustrated in Figure 2.2, the square vault plan ABCD is subdivided into arching bands that radiate from the diagonals. The bounding edges AB, BC, CD, and DA represent the plane projections of the edge arches, or formerets. According to Como, the shape and curvature of these elements, whether rounded or pointed, can significantly influence the distribution of forces and hence, the resulting cracks. The diagonals act as the main sustaining arches (groins), concentrating the thrust and dictating the directional flow of forces.

Como's model thus provides a predictive framework for interpreting the location and orientation of cracks, which typically align with zones of tensile stress. His theory emphasizes that rather than being random, these patterns are indicative of the vault's structural logic and the inherent mechanics of load transmission in no-tension masonry systems.

Como also provides a theory on the crack formation on the extrados and follows a similar pattern to the arching bands in Figure 2.2. Two common cracking patterns tend to develop, see Figure 2.3. The first is an internal square pattern, formed by the more depressed (lower) arch bands that hinge at the springings, creating deformation closer to the center of the vault. The second is an external square frame pattern that involves arch bands that hinge along their haunches at a constant distance from the vault edges, indicating cracking that occurs closer to the outer edges. In addition to these patterns, Sabouret cracks may also form. these are deep, through-thickness cracks that appear in the transverse webs of vaults, typically running parallel to the nave's axis and extending from the extrados to the intrados. They usually as a result of structural shifts, such as foundation settlement or wall removal, as the vault deforms in search of a new equilibrium.

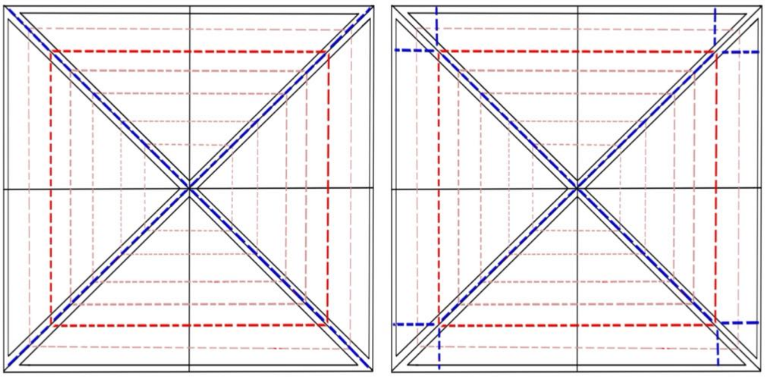


Figure 2.3: Possible cracking patterns on the extrados. Cracks forming along the groin on the extrados in dark blue and sabouret cracks in dark red.

2.3 Textile Reinforced Mortar

Textile reinforced mortar (TRM), is a system consisting of high-strength, open-mesh textiles embedded in an inorganic matrix, creating a composite material. The original nomenclature that was used for this material was fibre reinforced cementitious matrix (FRCM). However, considering that the matrix does not necessarily have to be cementitious, lead to the term being modified to be more inclusive for different materials used. The name textile reinforced mortar (TRM) or textile reinforced concrete (TRC) is now more commonly used. (Koutas et al., 2019). Like the name suggests, TRM is used as a structural reinforcement and was developed as a less invasive alternative for strengthening historic structures (Angiolilli et al., 2020).

In the previous studies made on the strengthening of the church of San Bassiano (Cardani and Massetti, 2017), the nomenclature fiber reinforced cementitious matrix (FRCM) has been used, since that is the term used by the company, Ruregold, which provided the specific strengthening material, as well as being the previous international nomenclature standard for the material. Ruregold's FRCM systems combine high-performance fibres, in this case made of synthetic fibres of carbon with an inorganic matrix as a bonding agent of pozzolanic material. For simplicity this report will refer to the strengthening system as TRM, since that is the term now more widely used in Europe and Sweden, although it is important to keep in mind that this refers to the same technique as the mentioned FRCM.

2.3.1 Early Developments of TRM for Masonry Structures

TRM can be considered a relatively new development in the field of structural reinforcement. In their State-of-the-Art review, Kouris and Triantafillou, 2018, mention that the general idea for TRM can be traced back to Josef-Louis Lambot in 1887, who gave the suggestion to use embedded iron wires in cement mortar, not unlike the concept of reinforced concrete. However, the idea was not fully realised until Pier Luigi Nervi, an Italian engineer and architect, who started to further research what he named "ferrocemento" which is a type of thin concrete composed of cement mortar reinforced with several layers of small size steel wire mesh. The idea developed into something called fibre reinforced polymers (FRP), which has been actively used for strengthening already existing structures. Although FRP has many favourable properties, there are also some drawbacks, mainly due to the use of epoxy resins which is quite expensive, performs bad in high temperatures and are incompatible with substrate materials like masonry and concrete. The drawbacks of FRP have led to the search for better techniques for strengthening structures. At first, the priority was to try replacing the epoxy resin, for example with an inorganic mortar matrix. However, it proved difficult for the large size of the granules in the mortar to penetrate and impregnate the fibre sheets in the same way the resins do. The solution was to replace the fibres with textiles (Koutas et al., 2019). The different types of textiles and mortars used can vary, still including the use of steel (De Santis, Roscini, and de Felice, 2019, Garcia-Ramonda et al., 2022a), but also a lot of different kinds of fibre meshes and mortars. The most common mortar to use is either cementitious mortar, or hydraulic lime mortar. However, in conjunction with historic masonry reinforcement, it is not uncommon that a pozzolanic mortar has been used. The adoption of inorganic matrix composites gained popularity due to their compatibility with historic masonry and their ability to replace epoxy resins (Angiolilli et al., 2020). The most common fibers are basalt-fibers, glass-fibers, carbon-fibers, or other types such as PBO which is a quite new addition, or even hemp fibers (Menna et al., 2015; Mercedes et al., 2020). This system achieves full composite action through mechanical interlocking between the fiber grid and the surrounding mortar, as the fibers protrude from the openings of the grid (Angiolilli et al., 2021).

Several studies confirm the numerous advantages of Textile Reinforced Mortar (TRM) over Fiber Reinforced Polymer (FRP), particularly in the context of historic masonry. TRM offers superior compatibility with traditional substrates, higher breathability, and easier reversibility, making it more suitable for heritage conservation (Angiolilli et al., 2020, Casacci et al., 2019). Additionally, TRM provides better fire resistance and reduced sensitivity to environmental degradation compared to FRP (Angiolilli et al., 2021). Unlike FRP, which relies on adhesive bonding, TRM utilizes a mechanical interlock for bonding, further enhancing its effectiveness in masonry applications (Kouris and Triantafillou, 2018). These benefits reinforce the growing preference for TRM in structural strengthening efforts.

Early developments in TRM include studies that compare the different types of fibers that can be used on smaller specimens. Ascione et al. (2015) did a study proposing a qualifying method for externally bonded TRM systems using tensile and shear bond tests. They studied basalt, carbon, glass and steel textiles with cement or lime mortar on bricks and tuff. The method qualifies the system based on the weakest failure mechanism that takes place under shear and should be able to be applied to TRM composites with different constituent materials and substrates. Although it is mentioned that further studies should be made due to the small number of tests conducted.

Some early research also studied different coatings for TRM, or similar such as studying glass-fibre reinforced polymer (GFRP) mesh. This was done by Corradi et al., 2014 (2014) and Gattesco et al. (2015). It is similar to TRM with a mesh inserted into an inorganic matrix. The biggest difference lays in the use of an epoxy resin coating of the fibres. The studies investigated the shear strength and behaviour (Corradi et al., 2014) and the diagonal compression (Gattesco et al., 2015). The studies found that the use of GFRP increased the strength of the masonry, with failure due to tensile rupture or failure of connectors.

Donnini et al. (2016) further studied the organic coatings applied to carbon fabric to see how they affected the bond between fabric and mortar. The purpose of their research was to study this effect, and its effectiveness was studied via direct tensile, pull-off, and shear-bond double-lap tests. The study found that polymer coatings improved the bond between fabric and matrix, increasing the TRM's mechanical performance. Increased fabric impregnation levels enhanced ultimate tensile strength. The use of flexible epoxy and sand coatings could result in fibre rupture due to improved adhesion. However, the coating process was manually applied, which led to potential variability in the results. Further exploring this Donnini and Corinaldesi, 2017 (2017), also studied the effect of polymer coatings on carbon and basalt fibres to improve adhesion with mortars. The research further explores the influence of the gripping system on tensile properties, the effect of different fibre types, the number of plies, and the type of mortar used.

2.3.2 Initial Applications of TRM on Masonry structures

Quite early on, studies were conducted on larger masonry structures. Some initial studies on the use of TRM involves the application of different combinations of fibre types and mortar types on masonry wall structures and panels (Menna et al., 2015, Marcari et al., 2017, Giaretton et al., 2018, D'Ambra et al., 2018, Benedetti, 2019, Casacci et al., 2019, D'Antino et al., 2019, Incerti et al., 2019, De Santis, De Canio, et al., 2019, Mercedes et al., 2020, Angiolilli et al., 2020, Del Zoppo et al., 2020).

Several initial studies explored the capacity of Textile Reinforced Mortar (TRM) systems to enhance the in-plane behaviour of masonry under shear and compression. Marcari et al. (2017), for example, applied basalt TRM (BTRM) to volcanic tuff masonry panels and reported clear gains in shear strength, along with a shift in failure mode from joint sliding to diagonal cracking. Panels reinforced on both sides also showed more stable deformation under load. In a similar vein, Giaretton et al. (2018) tested TRM on clay-brick and clay-block walls, noting improved displacement capacity and no early debonding even without mechanical anchorage. However, applying TRM on just one face introduced asymmetric stiffness, which led to some unwanted out-of-plane movement. D'Antino et al. (2019) explored a related system of glass fiber TRM embedded in a lime-based mortar on historic masonry. Their work showed that TRM can increase peak load and delay detachment, particularly when paired with steel anchors, producing a bilinear response with better ductility.

Recent efforts have also focused on irregular masonry, where strengthening can be especially complex. Del Zoppo et al. (2020) investigated how different inorganic composites affect the in-plane shear capacity of irregular masonry walls. All systems tested showed substantial improvements, with glass fiber reinforced polymer (GFRP) grids playing a particularly strong role in enhancing both strength and deformation. They also introduced analytical models to help estimate the shear contribution of TRM systems. Building on this, Angiolilli et al. (2020) studied glass-fiber TRM with hydraulic lime-based mortar applied to historic stone masonry made of irregular stones and weak joints. Their diagonal compression tests confirmed a notable boost in shear strength, stiffness, and ductility. The addition of fiber grids and anchors helped both in-plane and out-of-plane performance, and LDPM (lattice discrete particle model) simulations aligned well with observed damage patterns. A follow-up study by Angjeliu et al. (2021) conducted on-site cyclic diagonal compression tests on similar stone masonry panels retrofitted with TRM. Their work confirmed that the TRM coating, comprising a glass-fiber mesh embedded in a natural hydraulic lime mortar, significantly improved shear strength and modulus. The study also found that reinforcement effectiveness was influenced by the mortar's mechanical properties and wall thickness, with the fiber mesh mainly contributing to post-peak behavior while the mortar governed initial shear strength.

From a sustainability standpoint, alternatives to synthetic fibers have also gained attention. Mercedes et al. (2020) compared traditional glass-based TRMs with systems that used hemp and cotton textiles. Their results showed that these vegetal TRMs could match or even exceed the mechanical performance of glass-fiber TRM systems in terms of energy dissipation and shear strength, while offering environmental benefits like reduced cement use and biodegradable components. Finally, Garcia-Ramonda et al. (2022) explored the use of Steel Reinforced Grout (SRG) for in-plane strengthening. They emphasized the importance of textile density and layering in shaping failure behavior and energy dissipation. Low-density steel textiles showed better interlocking with the matrix and improved ductility, suggesting that finding the right reinforcement ratio is key to balancing strength and deformability.

Beyond in-plane behavior, TRM systems have also been employed to enhance the out-of-plane performance of masonry walls. D'Ambra et al. (2018) explored the out-of-plane performance of clay brick masonry retrofitted with basalt TRM (BTRM) using a pozzolanic mortar. Their experimental results revealed a significant increase in the ultimate load capacity and a transformation of the failure mechanism from brittle behavior to sliding at higher displacements. This demonstrated how TRM can both enhance strength and improve ductility under out-of-plane bending. Gkournelos et al. (2020) investigated how prior in-plane damage influences the out-of-plane behavior of masonry walls strengthened with TRM and thermal insulation. Their experimental campaign, combining diagonal compression and out-of-plane bending tests, found that the presence of prior in-plane damage did not significantly impair the out-of-plane capacity of TRM-strengthened walls. Moreover, walls retrofitted with TRM combined with expanded polystyrene (EPS) for insulation outperformed or matched those using TRM alone, without compromising in-plane performance. These findings support the viability of integrated TRM-insulation systems for enhancing both structural and thermal performance. A more holistic approach was presented by Donnini et al. (2021), who examined the behavior of masonry panels made from tuff and fired clay bricks under both in-plane and out-of-plane loads. Their tests showed that TRM reinforcement improved the in-plane shear strength of tuff masonry by approximately 170 percent and increased out-of-plane ductility and strength in both materials. However, compressive capacity was only minimally affected, and the diagonal shear performance was found to be highly dependent on the quality of the mortar matrix. The study also evaluated analytical methods for predicting TRM behavior, contributing valuable data for modeling efforts.

Beyond flat walls, TRM systems have also been effectively applied to curved geometries such as masonry vaults and arches. These structures are especially vulnerable to both vertical loads and seismic activity, making strengthening interventions essential. Ptaszkowska and Oliveira (2014) used numerical models to investigate the effect of extrados diaphragm reinforcement on vault stiffness. Their work was experimentally supported by Garmendia et al. (2014), who demonstrated increases in load-carrying capacity in TRM-reinforced arches. Research by De Santis et al. (2017) and Carozzi et al. (2018) involved full-scale masonry vaults strengthened with TRM, SRG, and FRP systems. TRM was found to increase vault capacity up to 5.5 times compared to unreinforced cases, with notable improvements in deformation behavior and collapse prevention. Kariou et al. (2019) further confirmed that reinforcement layout and textile type had a strong impact on the mechanical response, with extrados applications outperforming intrados ones. This focus on curved geometries continued with Boem and Gattesco (2023), who combined full-scale tests with numerical simulations to evaluate the effect of CRM and TRM systems on thin barrel vaults. They observed resistance gains of up to 20 times for extrados-reinforced vaults. The authors confirmed that both CRM and TRM systems significantly improved displacement capacity and overall strength, especially when strong connections were established at the abutments. They also noted that numerical predictions were less accurate for intrados-reinforced vaults, indicating areas for further modeling refinement.

The potential of TRM in seismic strengthening has been investigated through cyclic and dynamic testing. Ramaglia et al. (2017) performed shaking table tests on TRM-reinforced vaults and observed more than double the seismic resistance compared to unreinforced specimens. Failure modes were favorably altered, shifting from the vault to the abutments. De Santis, Roscini, and de Felice (2019a, 2019c) further tested full-scale vaults under cyclic loading. Their results confirmed TRM's ability to enhance strength and ductility while delaying key failure mechanisms. Proper detailing, particularly at connections and along the vault surface, was found to be critical to the effectiveness of the system. Research by Bayraktar and Hökelekli (2020) proposed a cost-effective TRM strengthening method for masonry and concrete minarets. The system demonstrated strong performance under combined vertical and horizontal seismic loads while maintaining the structure's historical and architectural features. Reductions in seismic drift ranged from 32 to 48 percent depending on the masonry type, and the intervention was minimally invasive. Garcia-Ramonda et al. (2022a) focused on reversed cyclic shear-compression tests of masonry walls retrofitted with basalt TRM. Their findings confirmed the system's capacity to enhance resistance, energy dissipation, and ductility. The study also highlighted TRMs ability to restore structural integrity to damaged walls, making it a suitable option for post-earthquake rehabilitation.

2.3.3 Recent research developments and future application

While earlier studies concentrated on improving strength and deformation capacity, more recent research has turned attention to the bond behavior between TRM systems and masonry substrates. Garcia-Ramonda et al. (2022b) examined Steel Reinforced Grout (SRG) for in-plane shear strengthening of masonry walls. Their results showed that a low-density steel textile provided better interlocking with the mortar matrix, minimizing slippage and debonding. However, adding too many textile layers led to toe-crushing, a sign of over-strengthening. These findings underline the need to balance reinforcement intensity and compatibility with substrate behavior. There have also been some concerns around the effect of alkaline environments on the bond behaviour of TRM. Particularly basalt showed to have decline in strength when exposed to alkaline environments. However this decline was not shared by the use of glass-fiber, instead showing an increase in peak strength (Azimi et al., 2025).

To model these effects more accurately, A. Sakr et al. (2020) developed a two-dimensional nonlinear finite element model to simulate de-bonding in TRM-strengthened RC beams. Based on experimental bond-slip data and surface roughness, their model accurately captured various failure modes, confirming the importance of simulating interface behavior for design reliability. The influence of textile type, mortar thickness, and layer number on load-bearing capacity was also confirmed.

Cucuzza et al. (2023) compiled an extensive review of experimental and numerical studies on TRM retrofitted masonry walls. They highlighted the growing importance of modeling textile-masonry interactions and presented original lab data to validate macro- and micro-modeling approaches. The research stressed the importance of harmonizing experimental results with simulation tools for design predictions.

Sciegaj et al. (2023) extended this modeling focus by incorporating calibrated bond-slip relations and efficiency factors into finite element analysis of textile-reinforced concrete (TRC) under multi-axial loads. Their approach accurately predicted stiffness, crack propagation, and ultimate capacity, validating the use of efficiency factors for yarn stiffness as essential parameters in advanced modeling.

Although previous research on TRM has deepened the understanding of its mechanical properties and laboratory-based performance, further investigation is needed into the specific bond behavior between TRM and masonry. This, along with several other key gaps, continues to limit the widespread adoption of TRM in heritage conservation. Most existing studies focus on short-term results from controlled environments, providing limited insight into how TRM performs over extended periods in real-world conditions. As a result, long-term evaluations of TRM applications on historic masonry structures are scarce, particularly those that account for environmental factors such as moisture variation, temperature changes, and continuous vibration exposure.

Another overlooked aspect in the literature is the impact of partial TRM application on the structural behavior of complex historic buildings. Although TRM has shown to enhance local stability, less is known about its influence on the global structural system, especially when only select parts of a building are reinforced. This raises concerns about potential load redistribution and unintended consequences in unreinforced areas, which are seldom addressed in existing studies.

3 Case Study: Church of St. Bassiano

The Church of Saint Bassiano in Pizzighettone, Italy, is a significant Lombard - Romanesque structure, see Figure 3.1 for the current state of the church, which has undergone various transformations and restorations over the centuries. The church suffered significant structural damage due to material degradation, past alterations, and external factors such as earthquakes and more prominently soil settlements, making strengthening interventions necessary. In response, a strengthening intervention incorporating Textile Reinforced Mortar (TRM) was implemented (Cardani and Massetti, 2017).

Due to its many alterations, the church has frequently been used as a case study in previous research (Angjeliu et al., 2019; Angjeliu et al., 2021; Cardani and Massetti, 2017; Cardani and Angjeliu, 2020). The numerous changes and transformations the church has undergone, both architecturally and structurally, makes it particularly well-suited for such analyses. Additionally, the extensive documentation, research, and recorded interventions on the church further establish it as an ideal subject for this report.

a) b)

Figure 3.1: a) Exterior of St. Bassiano seen from north-west and b) interior of the church from the west looking east towards the apse.

3.1 Historic and Architectural Background

The church layout spans 25 meters in width and 40 meters in length, with a central nave measuring 6.8 meters wide, flanked by two aisles that are each 3.4 meters wide. The columns within the church measure approximately 1.1 meters by 1.1 meters. See Figure 3.2 for top view of the structural layout. The church's vaulting system reflects these historical developments. Groin vaults cover the first six bays, while the apse area is distinguished by a barrel vault and a semi-dome. The masonry showcases evidence of multiple construction phases, as seen in the variations in brickwork patterns throughout the structure.

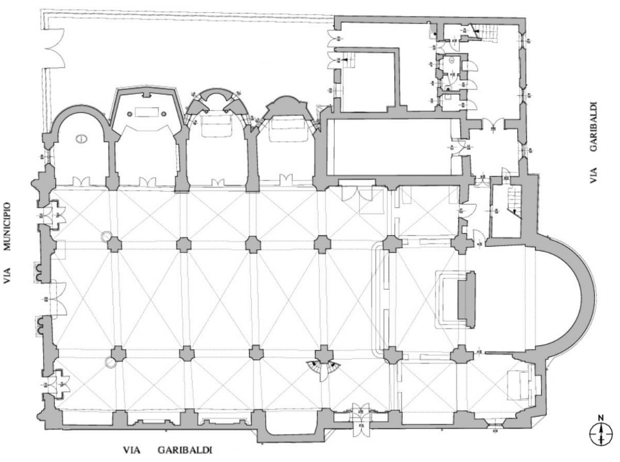


Figure 3.2: Plan view of the Church of St. Bassiano in its current state. Drawings provided by Giuliana Cardani and used with permission.

3.1.1 Changes from 1158 to 1300

The church of Saint Bassiano is estimated to have been built first in 1158, as part of the rebuilding of the city of Pizzeghettone after the Milanese forces had destroyed the city. The Lodi people reconstructed a preexisting church dedicated to Saint Bassiano, the patron saint of Lodi city. The original version of the church, see figure 3.3, had a simpler design compared to its current appearance, the façade was likely smaller, with remnants still visible today. The structure consisted of three naves and probably two towers positioned where the lateral apses now stand. The apses were all with a rounded end. The bell tower was located on the south side, while a second tower on the north side differed from the one visible today, as it bore traces of a demolished vault. The two towers were significantly shorter than the one standing today. At the end of the three naves, on either side of the main altar, the structure was enclosed by an external wall aligned with the choir (Cardani and Massetti, 2017).

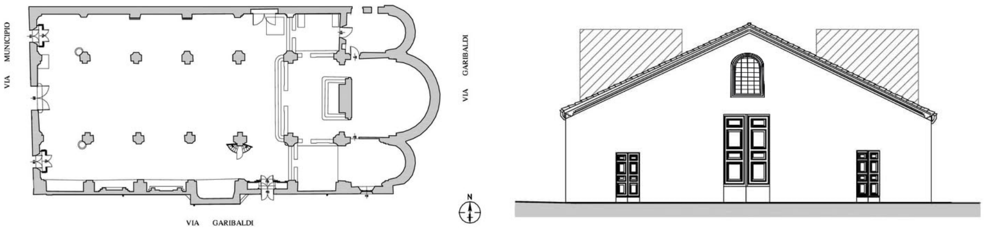


Figure 3.3: Top view and front view of church and the changes undergone from its first construction to 14th century.

3.1.2 Changes from around 1300 to 1750

Some important changes were made to the church between the 14th to the 18th century, see Figure 3.4. It is believed that the ribbed vaults were built during medieval times, 14th or 15th century, and later repaired during the 18th century. To accommodate the increased height of the central nave, the façade was elevated (Cardani and Massetti, 2017).

More known are some of the other important changes made from 1460 to 1750. A major transformation occurred in 1456 under the influence of the Milanese Sforza family, radically altering the architectural character of the church. The façade was elevated, incorporating decorative brick elements under the eaves, two brick arched windows above the lateral doors, and a prominent rose window featuring twisted columns and multifoil small arches. Surrounding this rose window were polychromatic tiles displaying the heraldic symbols of the Sforza family. This addition cut through a preexisting window. Furthermore, two rows of chapels were added along the external sides of the aisles. A new single-pitch roof was constructed northward, covering both the nave and chapels and concealing the single-lancet windows of the nave. It is believed that during this time, the high southern windows of the main nave were widened, replacing the single-lancet windows with divided windows, which are now only visible from inside the church (Cardani and Massetti, 2017).

Between 1525 and 1580, additional modifications were undertaken. The present sacristy was built in 1525 to the northwest of the church, and in 1533, the bell tower was relocated from the south to the north side of the apse, marking the beginning of the current bell tower. A significant fresco depicting the Crucifixion, created by Bernardino Campi between 1540 and 1543, was added to the counter-façade, internally covering the rose window. In 1578, the first elevation of the bell tower took place to accommodate a clock, and in 1720, the demolition of the old parish house led to the right tower of the church being taken down to a lower height (Cardani and Massetti, 2017).

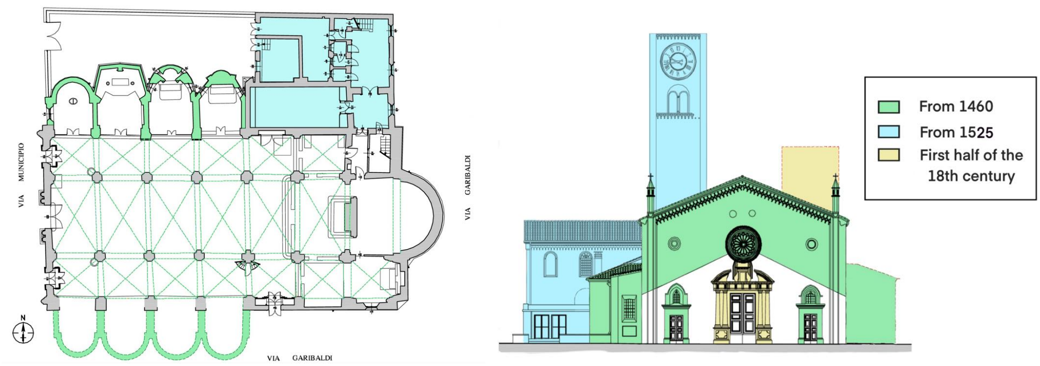


Figure 3.4: Top view and front view of church and the changes undergone from around 1460 to 1750.

3.1.3 Changes made after 1750

Some small changes were also made after 1750, see Figure 3.5 mainly in the bell towers. The old bell tower on the south side was demolished, and the entrance portal was likely added during this period. Moving into the 19th century, further structural changes were made, including the demolition of the south-facing chapels and the probable reformation of the south-facing windows of the main nave. To reinforce the building, iron tie rods were added to the masonry vaults. In 1820, the bell tower on the north side was further elevated, and in 1835, the church interior was fully decorated in the style still visible today (Cardani and Massetti, 2017).

The 20th century brought additional modifications, notably the last elevation of the bell tower, which gave it its current octagonal shape. In 1963, a restoration led by architect

A. Edallo altered the roof, replacing some sections with modern materials. The long single-pitch roof on the north side was removed, revealing the previously hidden single-lancet windows, which were then restored. Two chapels on the north side were also reconstructed in a modern style in 1964 (Cardani and Massetti, 2017).

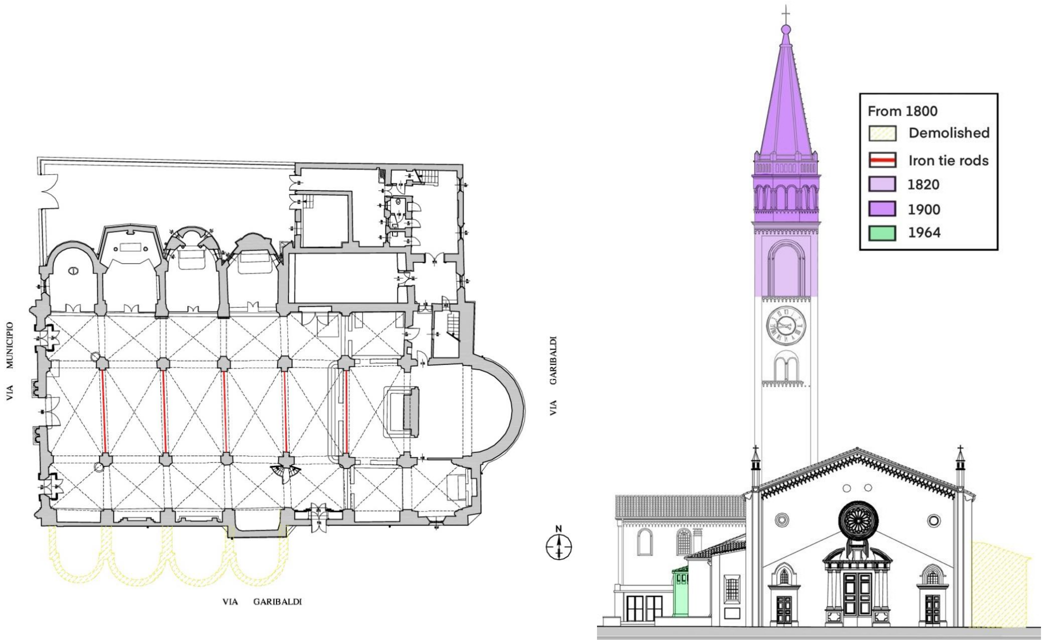


Figure 3.5: Top view and front view of church and the changes undergone after 1750.

3.2 Crack Survey and Intervention

A comprehensive survey, including the surveying of crack patterns, was conducted in 2013 to assess the structural condition of St. Bassiano Church, revealing extensive damage throughout the building (Cardani and Massetti, 2017). Already in 1989 it was reported that the church suffered extensive structural deterioration, including cracks and moisture penetration. Following the results of the survey, a major restoration effort was undertaken with the aim of strengthen the overall structure while enhancing its seismic resistance.

3.2.1 Previous survey

One of the most critical findings in previous survey was the effect of past alterations to the roof, which increased thrust forces on the nave vaults and subsequently on the aisles (Angjeliu et al., 2021). This led to widespread cracking and detachment between the arches and the vaults of the central nave, see Figure 3.6 where there are horisontal cracks along the walls. The primary arch between the apse and the nave exhibited significant displacement, sliding by more than 2 cm (Cardani and Massetti, 2017).

The northern bell tower, which underwent multiple height modifications over time, was found to have a poor foundation on a ground that appears to be sagging over time. This instability resulted in a substantial out-of-plumb deformation of approximately 12 cm towards the northeast. The imbalance led to localized crushing on one side and dragging forces on the other, which also contributed to structural damage to the sacristy (Cardani and Massetti, 2017).

Due to the severity of these findings, a full-scale diagnostic investigation campaign was carried out that included a) Soil penetration tests on the south and east sides, b) Groundwater level monitoring, c) Foundation inspections near the three apses, d) Sonic testing and tomography on internal pillars, e) Inclination measurements of the internal pillars, f) Flat jack tests (both single and double) on the west and east sides, g) Out-of-plumb analysis of the bell tower and h) Masonry coring and borescope inspections of the apse and bell tower.

The flat jack tests revealed that while the façade exhibited a relatively uniform load distribution, the bell tower showed significant structural imbalance, with stress concentrated towards the northeast. Sonic tomography results further indicated that the internal pillars were composed of non-homogeneous materials, showing to have been enlarged when the vaults were added(Cardani and Massetti, 2017).

The crack survey identified an extensive and well-defined pattern of damage running the length of the church, see Figure 3.6. The observed crack patterns suggest common failure mechanisms associated with vaulted structures. Several cracks appear near the intersections of vaults, particularly at the haunches and crowns, indicating excessive thrust and possible hinge formation. Additionally, diagonal cracking near piers and structural intersections suggests differential settlement or shifts in the supporting structures. Specific areas of the vaults exhibit concentrated cracking, which may be a result of stress accumulation due to inadequate load distribution or the previous structural modifications. Longitudinal cracks were particularly evident in the intrados of the arches and vaults, beginning at the façade and continuing towards the apse. However, disruptions in this pattern were observed near the apse, showing more diagonal cracks and cracks along the walls, likely influenced by structural changes such as the addition of the sacristy and modifications to the bell towers over time. Looking at the crack pattern in the apse, see both Figure 3.6 and Figure 3.7a, the crack pattern that can be seen in the semi-dome resembles the crack patterns previously discussed for failure mechanisms of domes. With the cracks forming from the crown down, in the form of slices with the widest part being at the base of the dome, indicating a widening of the base of the dome.

The sectional views, Figure 3.8, illustrate cracking in the main nave walls. Cracks in the upper masonry may indicate outward thrust caused by the vaults and roof structure. Additionally, the diagonal cracks in the lower sections of the walls could be the result of differential foundation settlement. If certain sections of the foundation are settling unevenly, tensile stresses may be developing in the masonry, leading to cracking. Looking at the crack pattern of the first and third arch in a) it suggests a settlement of the two middle pillars of these three arches. The same can be said for the second and fourth arch in b), indicating a settlement of the two middle pillars in conjunction with these arches.

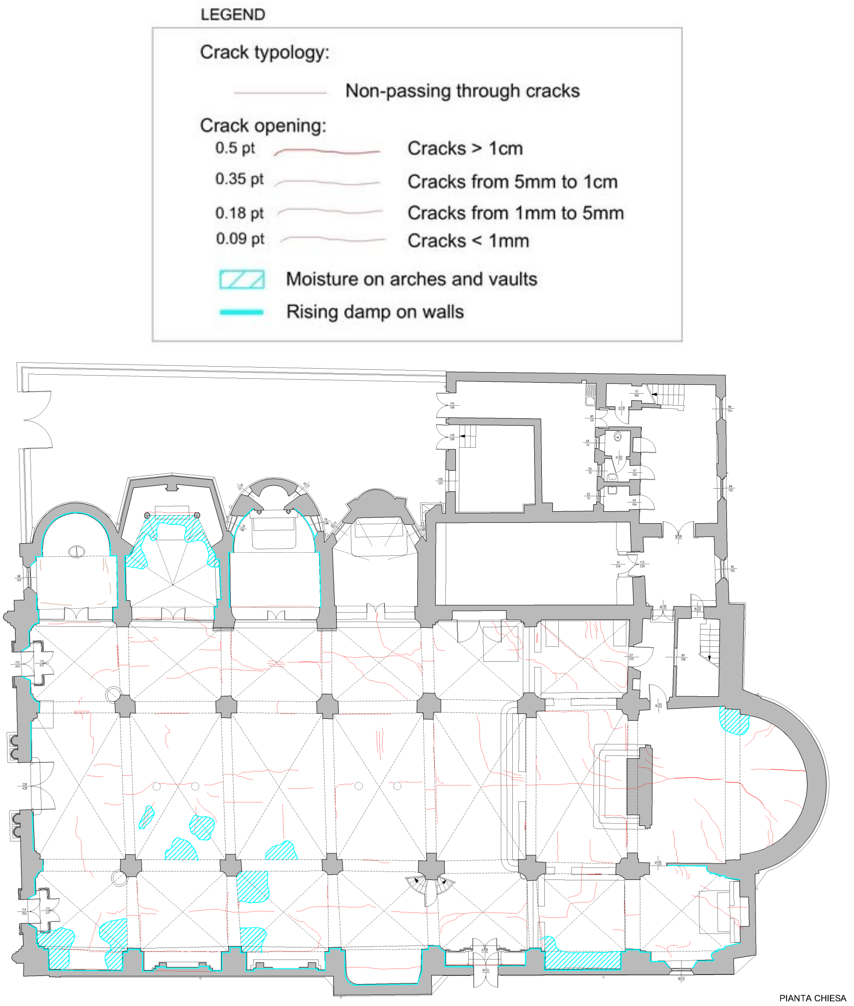
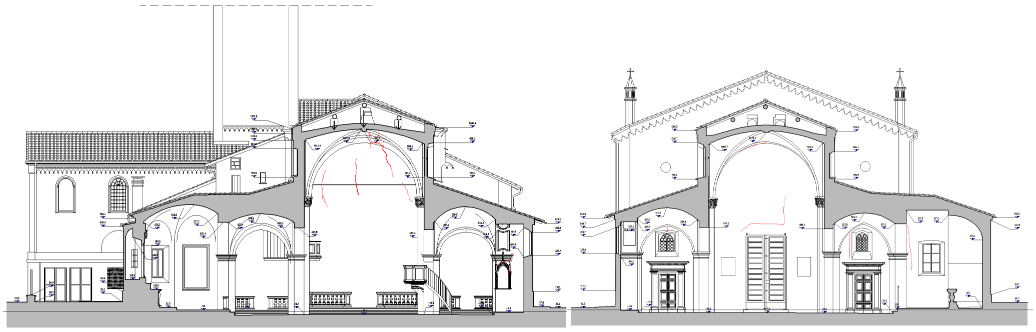
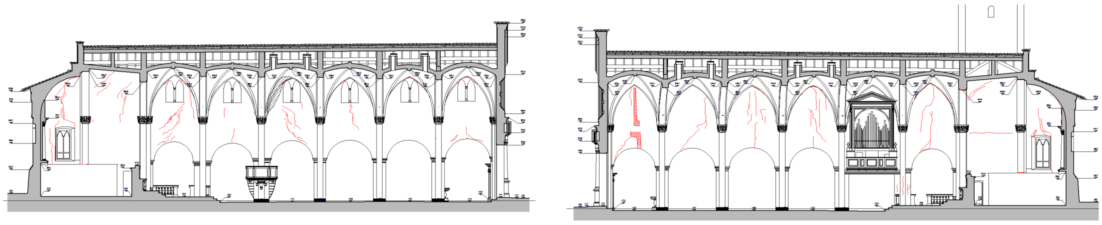


Figure 3.6: Plan view of St. Bassiano showing crack pattern survey from 2013 provided by Giuliana Cardani.



a) b)

Figure 3.7: Section view of St. Bassiano showing crack pattern of a) east wall including the apse and b) intrados of the west wall, i.e the front side of the church.



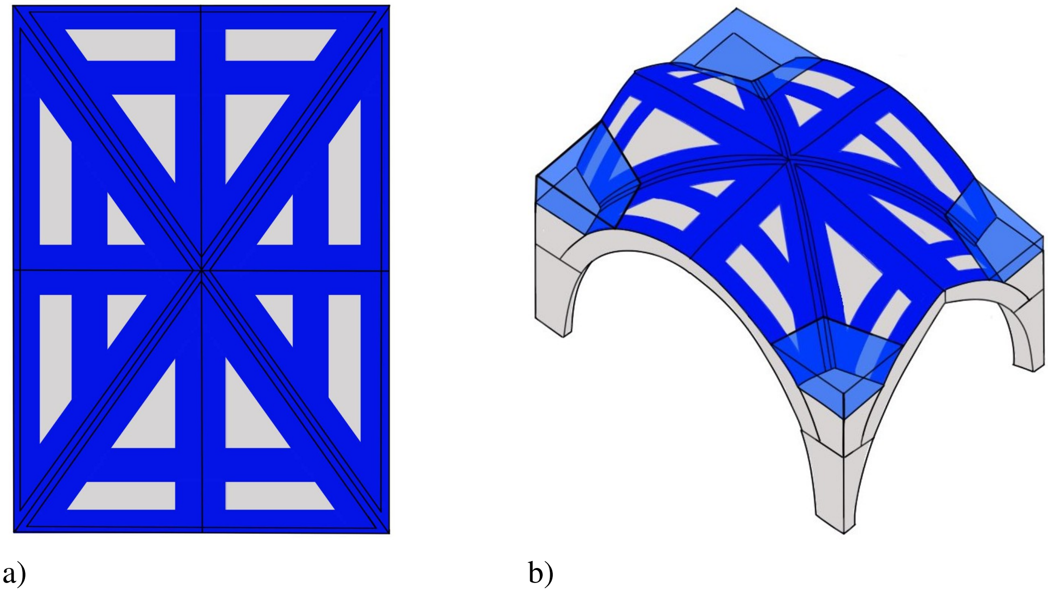
a) b)

Figure 3.8: Section view of St. Bassiano showing crack pattern of a) south wall of the main nave and b) north wall of the main nave.

One of the primary factors contributing to settlement-related damage was the high groundwater table, measured at approximately 0.5 meters below ground level. Seasonal variations in water levels intensified structural movement, necessitating past drainage interventions in 1990 and 1998. Despite these efforts, settlement remains an ongoing issue (Angjeliu et al., 2021). As can be seen in previous figures, the areas marked in blue indicate moisture-related deterioration, where moisture intrusion is evident in certain sections of the vaults, as shown in the plan view, Figure 3.6.

3.2.2 Intervention description

The intervention consisted of two more large-scale efforts; the replacement of the existing roof structure and the reinforcement of vaults and arches in the main nave and semi-dome in the apse using a TRM application. The original roof system was replaced with a truss-based structure, redistributing the loads on to the side walls and significantly reducing the stress on the nave's vaults and arches. The TRM used for this case was a system made up of a carbon mesh (X Mesh C10 from Ruregold, previously Ruredrill) and a pozzolanic based hydraulic mortar (X Mortar 25 from the same company) applied on the extrados of the masonry vaults. The pattern for the TRM application on the vaults can be seen in Figure 3.9, a) shows the pattern from planview and b) shows the pattern from a 3D point of view. Figure 3.10 shows the TRM pattern applied to the semidome. Figure 3.11 shows pictures of the TRM application more up-close in its current state taken during the survey made by author in march 2025.



a)

b)

Figure 3.9: Pattern of the TRM application in St. Bassiano a) from planview and b) showing 3D point of view.

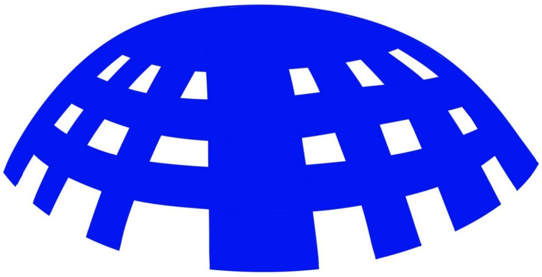
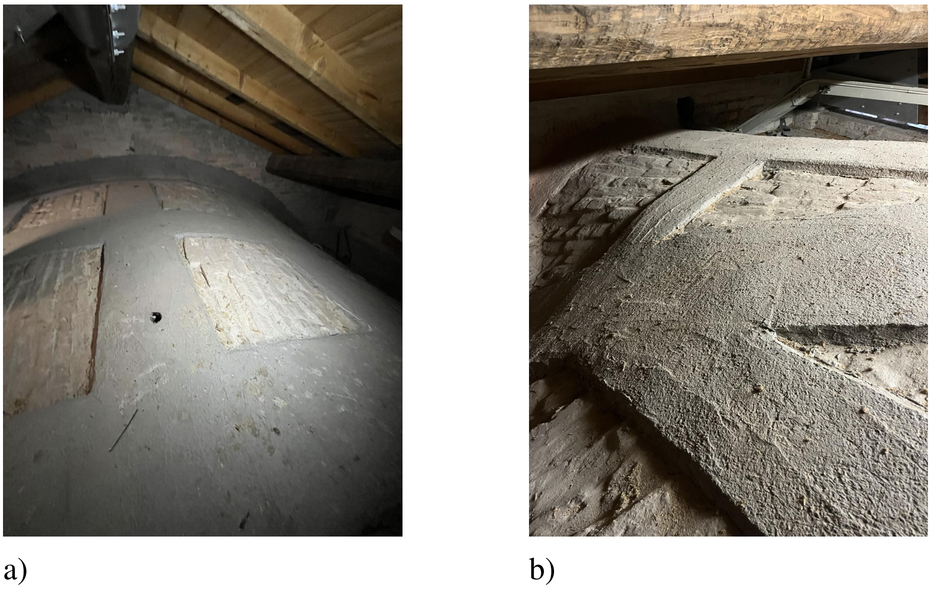


Figure 3.10: Pattern of the TRM application in St. Bassiano on the semi-dome. Schematic drawings made from pictures taken during intervention phase.



a)

b)

Figure 3.11: Pictures of current state of the TRM application on St. Bassiano, a) Barrel vault and b) Ribbed vault.

The intervention process began with the cleaning of the masonry vaults, followed by the removal of backfilling material and the repair of the cracks (extrados) using Rurewall R/Z mortar. Once the surface was prepared, the reinforcement system was applied in multiple layers. The surface was dampened before the first layer of inorganic matrix mortar was applied with a thickness of roughly 3-5 mm. The first layer of the carbon-mesh textile reinforcement is embedded in the fresh mortar, ensuring proper integration. A second layer of inorganic matrix mortar is then applied to cover the textile. In the case of st. Bassiano, a second layer of textile reinforcement is positioned and embedded following the same procedure, with a final layer of inorganic matrix mortar applied over the entire system. To ensure structural integration, the reinforced mortar system was connected to adjacent elements using C-joint connectors, see Figure 3.12. The TRM strips are connexted along the edges, see Figure 3.13a and in the corners of the vault, see Figures 3.13b and 3.12. For some structural purposes and a more level floor providing easier accessibility over the vault, corner fill was added, which can be seen as the light blue fill in b) Figure 3.9b and Figure 3.12. After the reinforcement layers were applied, the surface was smoothed and finished.

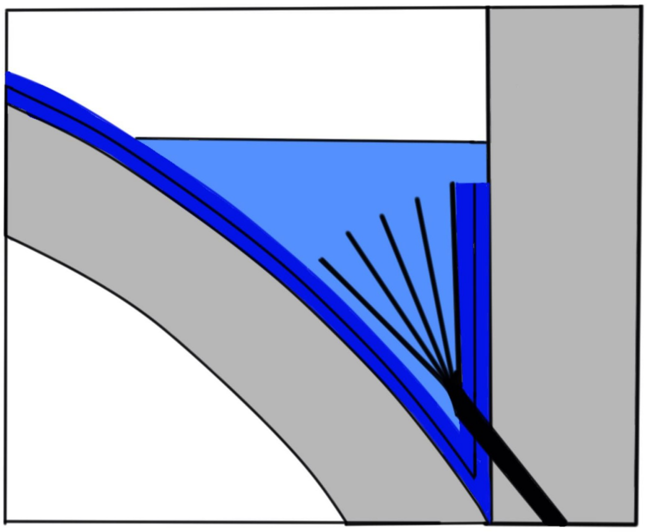


Figure 3.12: C-joint connector applied in vault corner.


a) b)

Figure 3.13: Pictures from the TRM application in St. Bassiano on the vault extrados a) connection to side-walls and b) corners of the walls filled up.

Additionally, the rebuilt walls between the groin vaults and the damaged ribbed walls above the vaults were reinforced. In cases where the ribbed walls exhibited severe deterioration, they were carefully dismantled and reconstructed using the original bricks, ensuring structural continuity with the longitudinal nave walls.

A particularly delicate aspect of the restoration involved the repair of the vertical sliding of the arch between the apse and the nave. To restore its original alignment, a dense system of adjustable props was employed to gradually reposition the arch. Once realigned, TRM was applied to the extrados, with regularly spaced joints ensuring strong adhesion and preventing future displacement.

3.2.3 Current crack survey

To evaluate the effectiveness of the undertaken interventions, in particular the TRM intervention on the vaults, another crack survey was carried out for this report on 27 february 2025 by the author. Mainly comparing the current state of the cracks in the church with the cracks measured in the previous survey.

In 2023 a renovation of the plasters of the main nave was carried out. Cracks were superficially closed and the walls were cleaned. This makes it slightly more difficult to evaluate the crack patterns detailed in the previous survey for this section of the church. Looking closely, it is possible to faintly see shadows where the cracks are, see Figure 3.14. What can be stated is that the cracks are still prevalent; however, they do not seem to have grown and they have not opened up again since then.

Figure 3.14: a) Picture of wall above fourth south arch in main nave of St. Bassiano in its current state and b) close up of crack pattern from previous survey.

From the plan view, it is possible to compare the crack pattern to the current one present in the side aisles. The crack pattern drawn shows the cracks on the vaults. In Figure 3.15, the cracks drawn in red marks the cracks that could be seen in the current state of the church. They can either signify a new crack taking form, or a continuation of an existing crack, having expanded in length or in width. Noticeable here is that the damage is quite extensive in both side aisles. Most prominent in the north side aisle is the damage in the 3rd bay, with more cracks forming and the middle crack in the centerpiece elongating. There is also added water damage which was not noted in the previous survey. In the south side aisle the first four bays (from the left) have the most new cracks with some added water damage to the second and fifth bays. The vaults in the side aisle now have cracks in the middle reaching almost through the entire length of the aisle. Although, on the contrary, no new cracks appear in the intrados of the main nave.

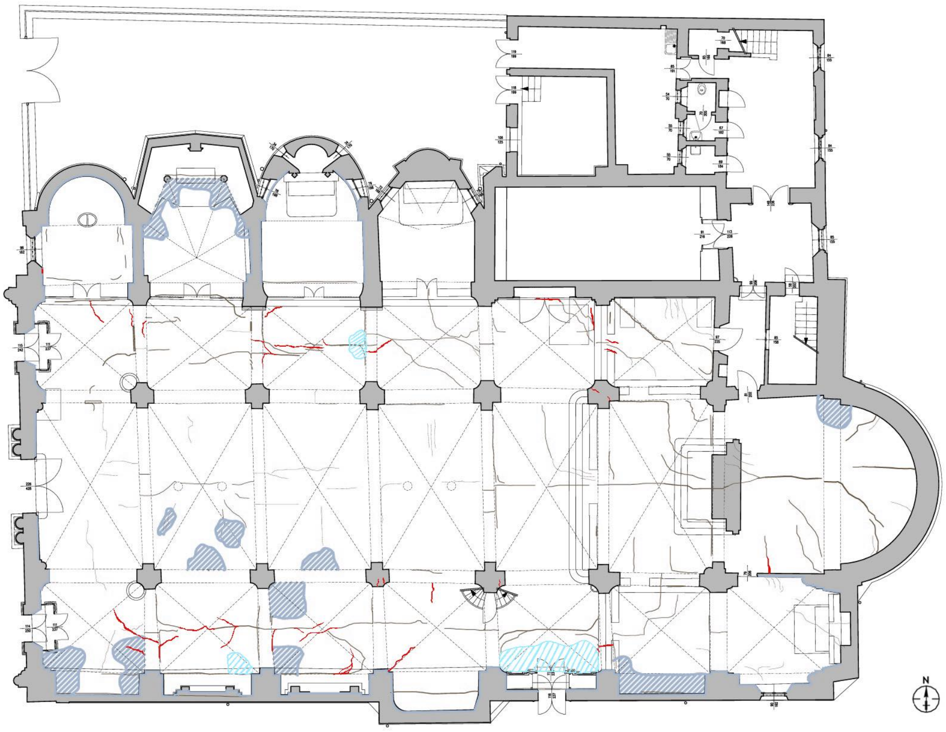


Figure 3.15: Plan view of crack pattern survey in St. Bassiano with new crack formations in red and new water damage in cyan blue.

3.3 Evaluation of TRM Strengthening Performance

3.3.1 Observations from Crack Survey

In the structural survey, it became evident that while the main nave remains relatively stable, the side aisles have experienced continued movement and deterioration. Since no reinforcement was applied to these areas, the difference in structural stiffness between the reinforced and unreinforced sections appears to have had possible unintended consequences. The main nave's strengthened vaults and walls likely altered the way loads are distributed throughout the structure, possibly contributing to the more pronounced damage observed in the side aisles.

A clear indicator of ongoing settlements can be seen in the south side aisle, where arches in the first three bays (from the left) show signs of separation from the adjacent walls. This suggests a differential settlement, likely influenced by the asymmetrical nature of the church, which could be causing an uneven distribution of loads. Additionally, certain pillars, particularly those near the pulpit, as well as the second and third pillar (from the left) on the opposite side, show signs of setting. This further supports the hypothesis that soil movements still affect the foundation of the church.

Comparing the newly mapped cracks to previous documentation, it is apparent that certain cracks have elongated or expanded, particularly in the side aisles. The most significant changes in the north aisle occur in the third bay, where a central crack in the vault's keystone has lengthened, accompanied by new cracks forming nearby. In the south side aisle, the first four bays exhibit the most significant new cracks, with additional water damage becoming apparent in the second and fifth bays. The presence of long, continuous cracks running through the center of the vaults in the side aisles raises concerns about the structural integrity of these sections, as they could indicate a weakening of the vaults' support mechanisms.

Water damage is another key factor in the ongoing deterioration of the side aisles. Unlike the main nave, where water infiltration was not visible, the side aisles exhibit worsening moisture-related deterioration. The first chapel, in particular, shows extensive water damage alongside cracking, suggesting persistent infiltration issues. These areas require further attention, as moisture infiltration can accelerate material degradation and contribute to crack propagation.

The extrados of the main nave vaults was carefully inspected to assess the performance of the TRM intervention. The condition of the intervention appears to be excellent, with no visible deterioration, damage, or signs of detachment. The vaults remain dry, indicating that the intervention successfully mitigated water infiltration, which was previously a significant concern. The stiffness of the reinforced vaults suggests that the TRM has effectively enhanced the structural integrity of the main nave, preventing further crack development and minimizing deformation.

However, while the TRM intervention has proven successful in stabilizing the vaults of the main nave, it is essential to consider the indirect effects on the rest of the structure. The increased rigidity of the main nave may have contributed to the worsening condition of the side aisles by redistributing forces in a way that places additional strain on the unreinforced sections.

TRM Performance Based on Hinge Mechanisms and Crack-Formation Theory

The application of TRM to a masonry vault, particularly on the extrados, modifies the structural behavior of the vault. TRM introduces tensile capacity where there previously was none (or very little). According to Heyman's assumptions, masonry cannot resist tension, but with TRM, limited tensile strength is added. This, in theory, means:

- **Delayed or reduced hinge formation:** The onset of plastic hinges is delayed or made more difficult due to the added tensile strength.
- **Increased stiffness:** The vault becomes stiffer, reducing deformations that could otherwise lead to hinge formation.
- **Greater flexibility of the thrust line:** The thrust line can deviate slightly outside the middle third without immediate failure, as TRM can carry some of the resulting tensile stresses.

Furthermore, based on Como's theory regarding crack patterns in masonry vaults, the presence of TRM could influence the cracking behavior in the following ways:

- **Crack bridging and arresting:** TRM can bridge developing cracks and may prevent them from propagating further.
- **Modified cracking patterns:** The crack formation may shift from a few large cracks to a more distributed network of finer microcracks.
- **Persistence of existing cracks:** If TRM is applied externally without prestressing or bonding across the crack plane, pre-existing cracks may remain open.

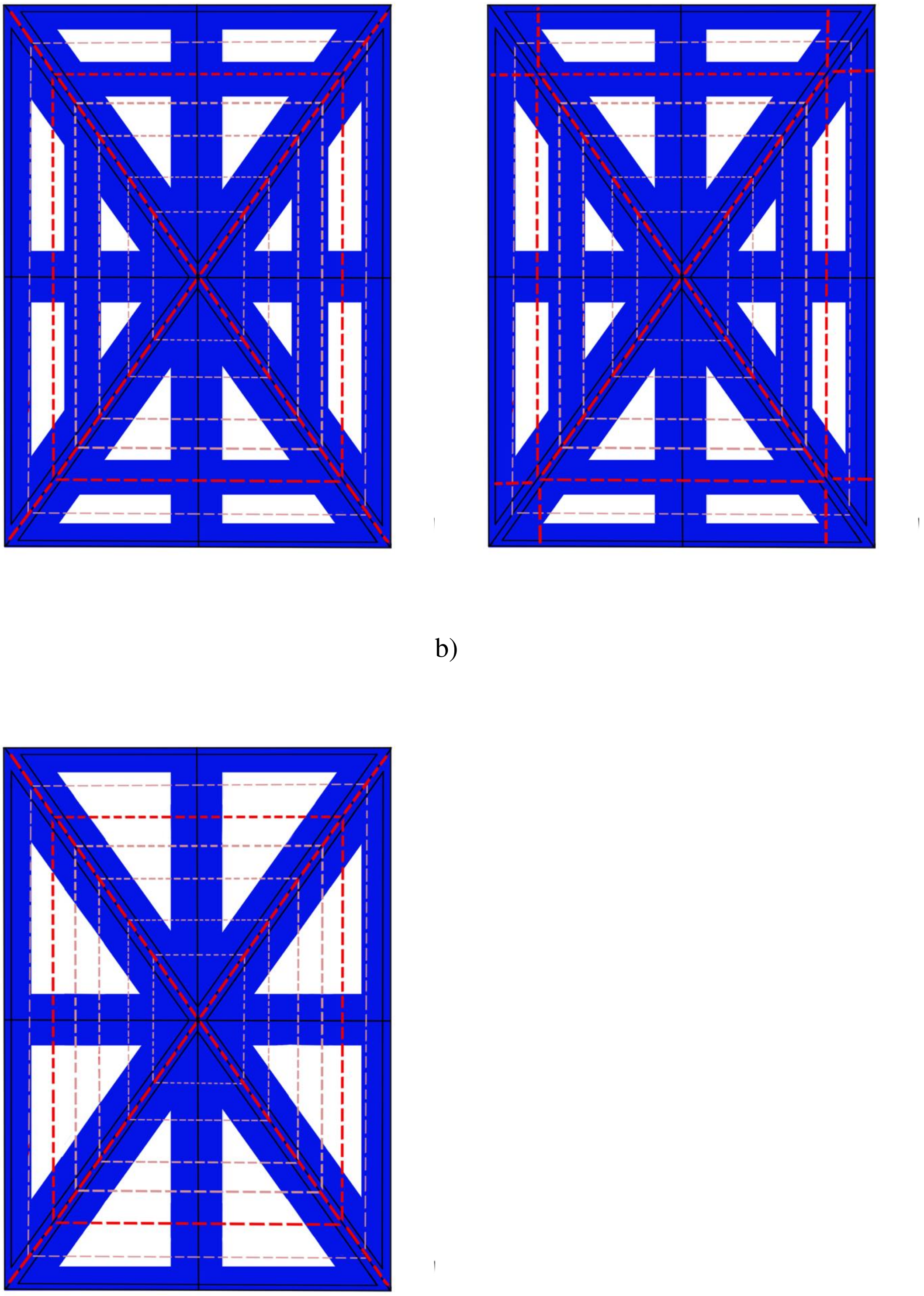
Thus, TRM on the extrados should act to reduce the development of collapse mechanisms by allowing some tensile stress at critical zones, arresting or controlling crack propagation and maintaining better structural integrity even after cracking begins. In an unreinforced vault, when the thrust line moves near the extrados at the crown or intrados near supports, hinges form. With TRM at the extrados this will change; Near the haunches the TRM will resist opening of extrados cracks.

Considering hinge formation more broadly, TRM applied solely on the extrados is particularly effective against outward thrust and horizontal displacement of the walls or buttresses. However, it offers limited benefit against intrados cracking, unless the vault would be sufficiently thin and flexible enough, allowing the reinforcement to confine and influence the intrados through indirect tension. As a result, new cracking patterns may emerge: instead of distinct, wide-open hinges, the vault is more likely to develop distributed micro-cracks in zones of peak tension, offering a more stable and ductile failure mode.

Looking further at the theory from Mario Como on possible crack-formation on the extrados of the vault, it is possible to compare this to the TRM layout used on the vaults of St. Bassiano. The TRM is applied to prevent these cracks from forming. Tension in the vault causes extrados-cracks to typically form across the diagonal, as well as along the transverse and longitudinal axes of the vault as previously mentioned in 2.2.4 and seen in Figure 2.3.

In Figure 3.16a and Figure 3.16b, these possible crack-patterns (red dashed lines) Como suggested are overlapped with the TRM layout in blue applied to the extrados of the vaults on St. Bassiano. The TRM has been strategically placed along the vault's arch bands, diagonal ribs, and perimeter zones, corresponding to areas where tensile stresses are expected to concentrate under load. This distribution of TRM is intended to counteract the development and propagation of cracks by providing additional tensile resistance along the main thrust lines of the vault. The reinforcement layout aligns with the load paths and acts to bridge potential discontinuities, thus enhancing the structural response and contributing to the overall stability of the vault system.

The TRM is providing the best counteraction to the crack-formation when applied perpendicular to the cracks. Therefore, one might suggest that the central square of TRM strips might be considered redundant in its application to prevent certain cracks. Although, they might still contribute to increasing the rigidity of the vault structure, providing a more conservative solution. This increased stiffness could prove beneficial in the context of seismic performance, where a more unified and continuous response may help mitigate damage during dynamic loading. Nevertheless, without considering the need for the vault to maintain stability during seismic actions, Figure 3.16c shows a possible TRM layout that might be a sufficent application to withstand the largest tensile forces in the vaults.



a)

b)

c)

Figure 3.16: Schematics of two possible crack-patterns (red) on the extrados, mentioned in 2.2.4, overlaid on the TRM layout (blue) for the vaults in St. Bassiano. Image a) and b) show the actual TRM-layout of the vaults in St. Bassiano with the two possible crack-patterns mentioned previously and c) shows one of these possible patterns overlaid on the suggested simplified TRM-layout.

Another possible effect of the reinforcement in St. Bassiano, observed in some of the vertical elements, is that they may be subjected to increased stresses causing further cracking. One possible explanation for this could be the result of a stiffer and stronger vault, which could cause the thrust at the abutments to increase as the vault can carry higher loads. The walls must now resist greater horizontal forces without collapsing or moving outward. Thus, walls may experience larger horizontal reactions, increasing the risk of increased structural vulnerability in vertical elements. This raises the question whether strengthening the vault without strengthening the abutments can transfer the problem from the vault to the walls, also highlighting the need for further investigation of the global structural response. It would therefore be beneficial to move beyond the vault in isolation to examine how TRM application may affect the behavior of adjacent elements and the overall stability of the building, particularly in complex structures such as churches, which is currently proving to be a gap in existing literature.

4 Case Study: Skörstorp’s Church

Skörstorp’s Church is is a unique and historically significant church located in the Diocese of Skara, Sweden, see Figure 4.1 for image of the exterior and interior of the church. It was built in the mid-12th century and is one of the few round churches in the Nordic countries and the only one of its kind still preserved in the Skara Diocese (Svenska Kyrkan Falköping, 2023). There have long been cracks in the church and it has historically suffered some extensive damage throughout its years, documented in this chapter. Recently, in the later half of the 2010s renovations of the roof structure were made due to Serpula lacrymans (true dry rot fungi) having caused severe deterioration of its structural integrity. Investigations conducted alongside this revealed some recent changes in the cracks, which has led to further crack measurements and investigations being carried out.

This chapter explores Skörstorp’s Church as a representative example of the challenges faced when preserving historic masonry structures subject to foundation instability and structural cracking. The church serves as a comparison to the case of the Church of Saint Bassiano, allowing for an analysis of damage mechanisms and potential interventions across different geographical settings and contexts.


a) b)

Figure 4.1: Skörstorp’s Church, a) exterior from South-west and b) interior of the Church towards the altar in the east.

4.1 Historic and Architectural Background

This section presents an overview of the architectural layout and material characteristics of Skörstorp’s Church, followed by a summary of its historical developments and documented restoration efforts.

4.1.1 Architectural Description

The main nave of Skörstorp’s Church is circular and features a vaulted ceiling, supported by four corner piers and surrounded by thick perimeter walls. The diameter of the round main nave is approximately 10 m from inside the walls and 12 m from outside the walls, making the walls roughly 1 m thick. See Figure 4.2 for the plan view of the church. The sectional views in Figure 4.3 and Figure 4.4 shows both the interior layout of the church, as well as the cross section of the roof structure on top of the round main nave. The sectional views were produced to illustrate the general layout and vertical crack patterns in the walls; these are schematic in nature, only rough measurements were made, and should therefore not be considered precise.

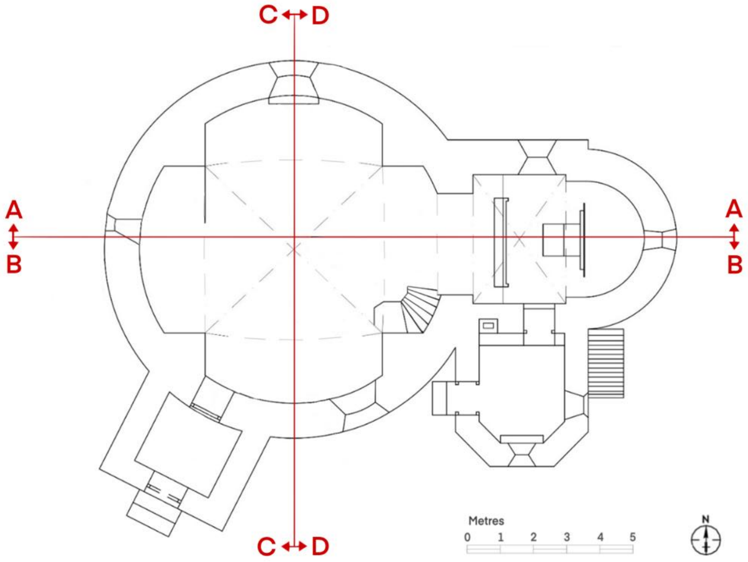


Figure 4.2: Plan view of the church layout showing sections A (north), B (south), C (west) and D (east)

a) b)

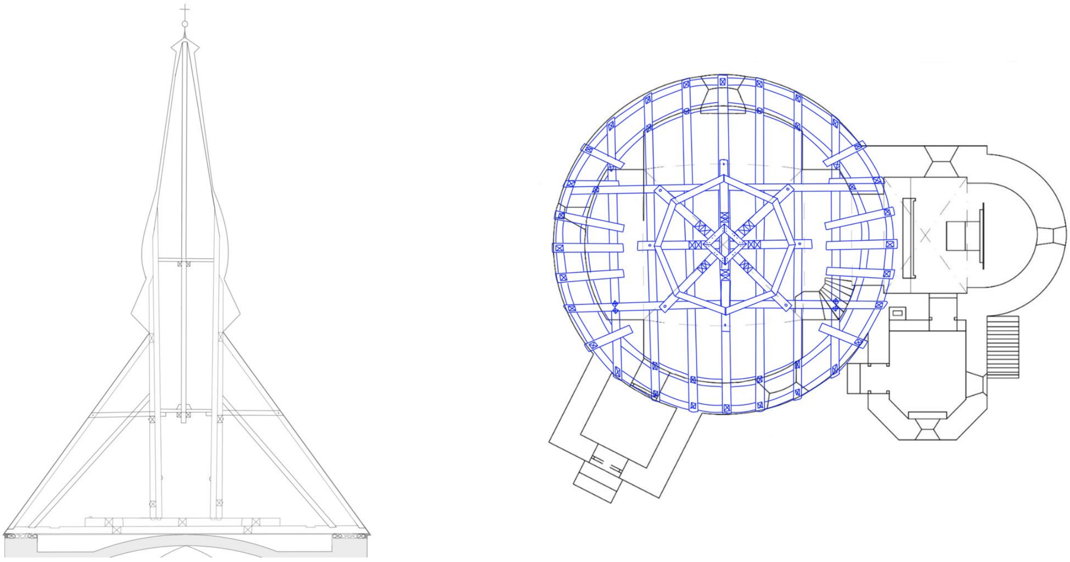
Figure 4.3: Sectional view of Skörstorp's Church a) section A north and b) section B south.

a) b)

Figure 4.4: Sectional view of Skörstorp's Church a) section C west and b) section D east.

The vault over the round main nave is built from natural, uncut limestone and the vault over the choir is made from brick. The walls are composed of outer and inner limestone shells filled with shingle. The church lacks a clearly defined stone base or plinth but features a projecting foundation. There are some significant differences between the masonry in the lower and upper sections of the surrounding walls of the main nave. The lower part consists of finely jointed limestone blocks laid in horizontal courses, while the upper part is made up of larger, more roughly shaped stones embedded in thicker mortar beds.

The roof of Skörstorp's Church rests on the walls of the round main nave. See Figure 4.5 for a) principal drawing of the roof structure from side view and b) principal drawing of the roof beam layout in the roof structure seen from above. Atop this are two concentric rings of timber wall plates made of oak. These support nine primary tie beams, seven running north-south and two intersecting them east-west. The central feature is the star-shaped frame (stjärnbjälklag), composed of a central square with eight outward-radiating arms connected to an outer octagon. This framework anchors the eight vertical posts that support the church spire and originally distributed the load during construction. Due to the large span of the tie beams (10 meters) and their deep notches, the structure is not intended to carry significant loads. The roof load is instead transferred through 28 rafters and 16 braces that rest on a total of 44 support points across the tie and stub beams.



a) b)

Figure 4.5: Schematic of roof structure a) vertical section view b) horisontal section of the spire roof structure on top of the planview of the church

4.1.2 Historical Developments and Modifications

Skörstorp's Church has undergone interventions over the centuries due to structural and aesthetic challenges. According to an inventory from 1583, the church had been burned by enemy forces, likely during Danish raids in 1566, which resulted in the collapse of the roof and vault. Although records are unclear on the exact timing of its reconstruction, the spire was erected in 1666, indicating substantial rebuilding had occurred by then. The spire was later extended in 1899 and shortened again in 1935.

In 2021 an archival study was made by Carl Thelin for Tyréns. Available documents primarily from the 1920s and 1930s, as well as from the 1980s to the present day, were studied, although some photos and documentation exist from before the 1900s. The earliest documented major renovation in this archival study occurred in 1899. It involved comprehensive re-plastering and new foundations for the choir and sacristy (Thelin, 2021). It is also likely that significant repairs to the roof structure were carried out at this time, maybe in conjunction with the spire being lengthened. However, instead of replacing some decayed components, damaged areas in the southeastern section and beneath the spire were instead reinforced with timber and iron fittings. Although not a full restoration, these measures appear to have prevented structural failure and ensured the roof's survival into the present. Minor repairs seem to have continued during the 20th century, with varying quality in elements such as rafters and wall plates (Skörstorp's Church sign, 2016). Although archival material from this period is scarce, an 1892 photograph shows visible cracks in some areas of the masonry, cracks that still persist today. This suggests that the structural problems addressed in later interventions were already emerging by the late 19th century (Thelin, 2021).

In 1927, engineer Nils Royen conducted a detailed survey of the church in response to worsening structural cracks. He attributed the damage to uneven settlement caused by insufficient foundation depth and soft subsoil. Royen proposed several measures, including cementitious grouting, concrete undercasting, and the installation of a steel tension ring around the church to stabilize the walls. However, archival records indicate that only parts of his recommendations were implemented during restoration work led by architect Axel Forssén in 1933–34. The church's foundation was reinforced with concrete and drainage systems were added, but the proposed steel ring and internal masonry ties were never installed.

From the 1940s through the 1980s, documentation of structural measures is largely absent. However, by the late 20th century, increasing reports of moisture damage and plaster detachment prompted renewed attention. In the early 1990s, a renovation was carried out removing cement-based plasters, reapplied with hydraulic lime mortar. A comprehensive masonry survey conducted during this time supported earlier theories about the church's layered construction. Notably, differences in masonry between the lower and upper sections of the nave suggest that the upper walls may have collapsed and been rebuilt (Thelin, 2021).

By 2015, major degradation had occurred in the roof, including severe infestation of dry rot, particularly in the tie beams, braces and beams on top of the masonry wall. The central tie beam had buckled and pressed against the crown of the vault. The renovation, carried out between 2015–2016, replaced all beams on the walls, four tie beams, three braces, four stub beams, and a central hand beam. Eleven of the vertical rafters were repaired, and the star-shaped beam system in the middle was almost entirely replaced, except for five sections of its outer ring. Additionally, the 13 meters long and over 600 kg central tie beam was replaced. The entire church tower had to be lifted 15 cm using hydraulic jacks at 12 points to insert the new beam. All tie beams were connected with timber pieces bolted above them to stabilize the structure during the lift (Skörstorp's Church sign, 2016).

The intervention also included full replacement of decayed wooden roof plates. Approximately 17,000 tar-treated roof plates were hand-fitted and nailed in place, covering the entire dome up to the spire, and parts of the sacristy roof. The masonry crown was also chemically treated to prevent future fungal growth (Skörstorp's Church sign, 2016).

4.2 Crack Survey and Damage Investigation

In response to the reappearance and progression of cracks over the past few decades, several damage assessments have been carried out at Skörstorp's Church. The most recent investigation, initiated in 2020 by Carl Thelin (Thelin, 2020), served as a preliminary study before the archival survey, which was recommended and carried out in 2021. Crack-width monitoring was established at multiple locations around the building, and existing cracks were documented on both plan view drawings and in photos. In favor of this thesis, a site visit was made by the author on 02/05/2025 to evaluate the current situation regarding the cracks and damage on the church.

4.2.1 Previous crack survey

As previously mentioned, some surveys were done prior to the one in 2020, all of which reported vertical and radial cracking both externally and internally, particularly around windows, vaults and the area behind the pulpit. Several cracks extended from the vaults to the floor and showed widening at the attic level. A foundation analysis was also done, which identified shallow footings set only 30 cm below the surface. It was concluded that uneven settlement and lateral shifting had likely been occurring for centuries. This resulted in interventions taking place to rectify the settlement problem. Archival documents from the late 20th century confirm that cracks remained visible and suggest that interventions had only a temporary stabilizing effect. Observations from the 1980s and 1990s noted further damage, including cracked vaults, plaster detaching, and damp-related deterioration. Conditions that have persisted into the present day.

In 2020, a detailed crack survey was conducted at Skörstorp's Church to investigate the long-standing and evolving cracking in the round nave. The investigation revealed a widespread pattern of cracks, with cracks visible in the interior walls, the attic space, and the exterior façades of the church. The crack mapping, see Figure 4.6, shows different zones: red-marked cracks (numbers 1–5) inside the nave and vaults, blue-marked cracks (numbers 9–11) in the attic, and green-marked cracks (numbers 6–8) on the outer walls.

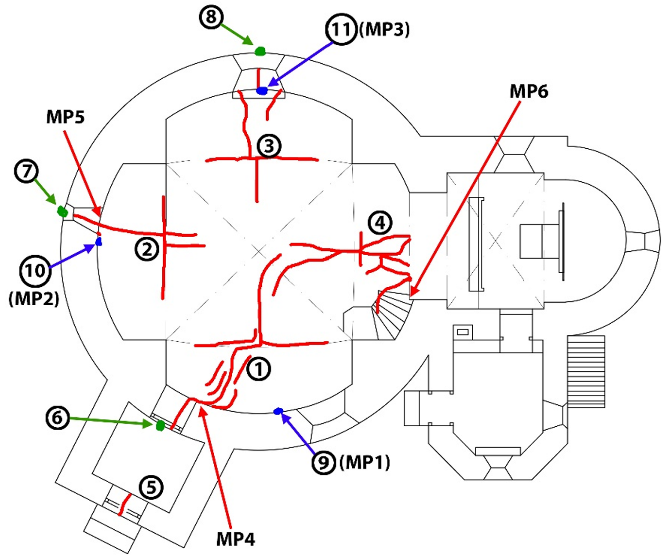


Figure 4.6: Plan view of Skörstorp's church from crack-investigation carried out by Carl Thelin in 2020 with cracks marked out in red, used with permission.

Earlier measurements between 2015 and 2016, during the roof structure restoration, showed minimal changes in crack width, at most 0.3 mm. However, considering a possible reporting error, these may have been as much as 3 mm, which would be notable over such a short period. Further checks in 2020 showed that some cracks, particularly in the attic (like measurement point MP2 on crack 10), had widened by 1 mm since 2015, indicating an ongoing deformation process.

Moisture problems were also noted, although the role of dampness and soil conditions in the cracking remains uncertain. Nevertheless, the primary conclusion of the 2020 survey was that the cracks reflect an active structural problem, not merely historical damage. To address the issue, the report emphasized the need for several follow-up actions: immediate resumption of crack width monitoring, archival studies to fully understand past reinforcements and structural changes, and detailed analysis of the vault-wall interaction and the wall inclinations. These steps would aim to clarify whether the movements are slowing down or ongoing and whether structural reinforcements will eventually be necessary.

4.2.2 Current crack survey

On 2 May 2025, a site investigation was carried out by the author at Skörstorp's Church to assess the current condition of the cracking in the round nave. This investigation focused on visual observations, photographic comparison, and field sketches. Due to limited access, it was not possible to enter the attic and upper surfaces of the vaults, nor was it possible to conducct crack-width measurements. Therefore, the analysis presented here is based solely on photographic evidence and visual comparison with earlier documentation.

The vault exhibited extensive cracking on all sides, with several cracks measuring a few millimeters wide. Notably, many of the interior cracks pass entirely through the wall thickness and are also visible from the exterior. Looking at the state of the exterior, it seems like it would have been re-plastered not too long ago, which would indicate that any cracks that were then covered has since reopened. Along the lower exterior walls, sections of plaster have been cut away, likely due to past moisture-related problems.

The plan view of the church from the 2025 investigation, see Figure 4.7 a), highlights the differences from the 2020 crack-mapping, with new or worsened cracks marked in red. Notably, cracks now appear to span fully across the vault, and previously separated cracks are now connecting at multiple points. A detailed crack pattern was also produced; see Figure 4.7 b), showing both the larger and the smaller cracks across the vault and walls.

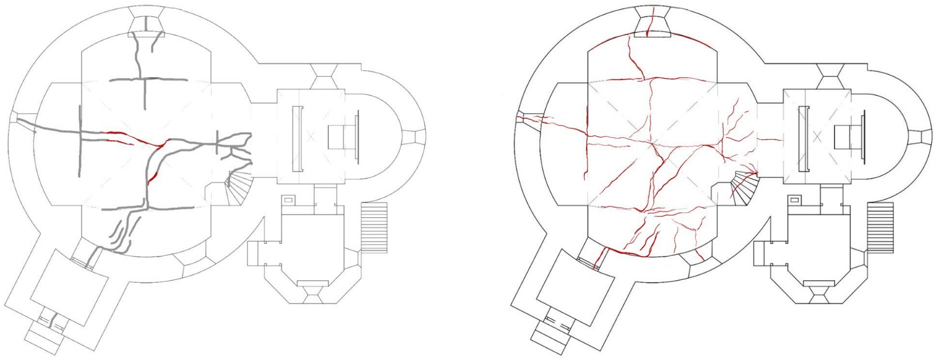
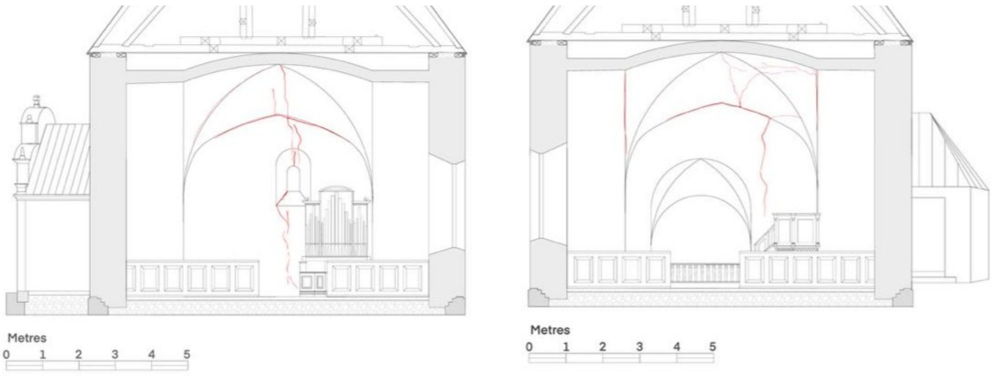


Figure 4.7: Plan view of Skörstorp's Church from crack-investigation made by the author in 2025 with a) difference from 2020 marked with red and b) a more detailed view of the cracks (marked in red).

To better understand the vertical extent of the damage, sectional views were prepared. Figure 4.8 and Figure 4.9 show sections across the north-south and east-west diagonals of the round nave. These sections reveal that some cracks extend continuously from the crown of the vault, down through the wall, passing window and door openings, and continuing down to the foundation level.

a) b)

Figure 4.8: Section view of Skörstorp's Church from crack-investigation 2025 with cracks marked in red a) North and b) South



a) b)

Figure 4.9: Section view of Skörstorp's church from crack-investigation 2025 with cracks marked in red a) West and b) East

The vault shows pronounced cracking along the perimeter where the square-shaped groin vault meets the circular outer walls. Cracks also radiate from the crown of the vault, extending downward to structurally weaker points, such as windows and door openings. This pattern indicates a combination of vault thrust and local wall weaknesses. Compared to the previous crack-mapping carried out in 2020/2021, there has been a slight increase in cracking with plaster falling of in some places, although the most significant deterioration occurred between 2014 and 2020.

Analyzing the crack patterns suggests several interacting factors behind the ongoing damage. The diagonal cracking across the vault, particularly toward the southeast, may point to settlement on that side of the building. See Figure 4.10a showing a map overview of soil types, taken from SGU (SGU, n.d.), of the area where Skörstorp's Church is situated. Close to the church, a small pond was observed in the south-east direction, aligning with the natural flow of water from north to south, indicated by the waterflow direction of the nearby stream. These aspects may suggest the presence of a slow process of soil movements, which may contribute to differential movements. Figure 4.10b shows a close up of this map with indications on the type of soil in the area, which is mostly moraine. In conjuntion with the roof renovation a soil sample was taken to investigate the church foundation walls. It was found to be topsoil to a depth of 0.4 m and below that clay-mixed morain, consistent with the map from SGU.

a) b)

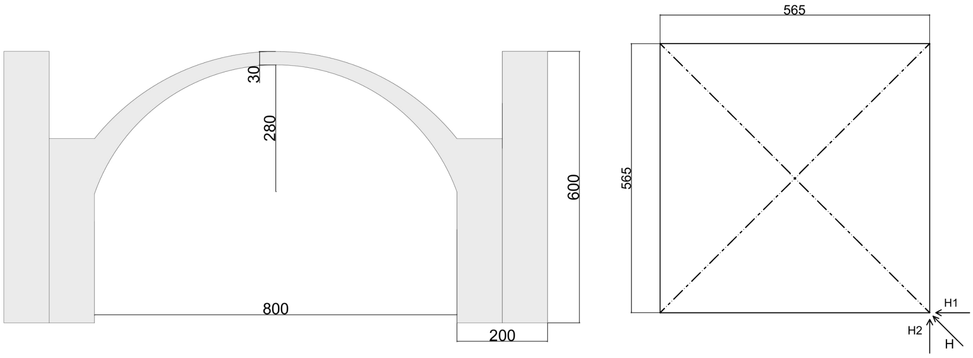
Figure 4.10: Images taken from SGU on geological aspects a) showing a map of the area where the church is situated and b) a close up indicating type of soils.

Large wall cracks indicate outward-loading forces, likely caused by the horizontal thrust of the square-shaped groin vaults combined with irregular loads from the roof structure. This is supported by the attic-level cracks, which show stress concentrations at the upper walls, while exterior cracks, though less pronounced, mirror internal deformations and confirm that the stresses reach through the full wall thickness. Notably, no significant cracking was observed in the chancel, sacristy, or adjoining areas, indicating that the structural issues are largely confined to the round nave. Overall, the combined crack patterns and their progression over time point to gradual outward pressure on the walls from both the vaults and roof; where the walls and foundations cannot resist these forces, the masonry deforms and cracks to accommodate the shifting geometry.

In summary this presents a concerning picture: while some cracking is typical for historic groin vaults, such as cracks running from the crown toward the springing points, the combination of diagonal cracking, square-like cracking around the vault edges, and the extensive wall cracks points to possible outward wall movement. This may be due to a combination of soil settlement, structural instability in the vault, and additional irregular loads transmitted through the roof structure.

4.3 Evaluation of TRM's applicability to Skörstorp's Church

The vault in Skörstorp's church can be analyzed with simple limit analysis. To present the model, dimensions and geometry will first be presented. In Figure 4.11a, a section of the diagonal of the vault is presented, and in Figure 4.11b, the dimensions of the vault in plan view are presented. The dimensions in the Figures are shown in cm. The vault is square with the dimensions 5.65 x 5.65 m with a total height at the crown of 5.7 m to the intrados and 6 m to the extrados, meaning the vault have a thickness t = 0.3 m. The length of the diagonal is 8 m, along this section the buttress and wall equal 2 m in total, 1 m in thickness each. The rise of the arch f, is f = 2.8 m. In Figure 4.11b, the horizontal thrust H1 and H2 are also shown with the resultant H representing the thrust along the diagonal groin. For clarification, the dimensions shown here are simply an estimated guess from observation measuring by hand. Since it is quite an old structure, the vault in reality is not entirely uniform, with a slight crookedness to the structure.



a) b)

Figure 4.11: Geometry of the studied vault in Skörstorp's Church with measurements shown in cm.

4.3.1 Limit Analysis

From *The Stone Skeleton* (1995) by Jaques Heyman (Heyman, 1995), a simplification can be made to approximate the horizontal and vertical forces generated by the vault using Ungewitter's table. The vault is assumed to be an idealized shell with uniform thickness, which then provides a variation in vertical and horizontal forces based on the length and width of the vaulting bay, the rise of the vault from springing to crown, and the thickness and material of the vault webs. The rise to span ration for Skörstorp's Church is roughly 1:2 and quite similar thickness and material parameters can be found in e) in Ungewitter's table presented in *The Stone Skeleton* (Heyman, 1995). The parameters are a thickness of 300 mm and a density of $24kN/m^3$. Considering the vaults in Skörstorp's Church are made of limestone and the same thickness, this provides a sufficient estimate. The vaules provided in Ungewitter's table based on these parameters are then $V0 = 12kN/m^2$, and $H0 = (4.8 - 5.5)kN/m^2$, with the vertical weight and horisontal thrust calculated for the unit plan area.

To get the forces supporting the vault at each buttress, one quarter of the vaulting bay must be considered since the vault is supported by four buttresses. The vertical weight V and the horizontal thrust H1 and H2 (seen in Figure 4.11b) in x and y direction (along the vaults arching bands) are then provided by following equations:

$$V = 1/4 * (5.65)(5.65) * V0 = 95.8kN$$
$$H1 = H2 = 1/4 * (5.65)(5.65) * H0 = (38.3 - 43.89)kN$$

Looking at crack formations in the church it is clear that the most damage is occuring in the vaults and in the walls of the round nave. For simplicity we can see the chancel, sacristy and the entrance as more stable parts. Due to symmetry and considering the adjacent stable parts, one quarter of the round nave of the church can be studied. In Figure 4.12, this part is shown with a dash-dotted line. As can be seen in the Figure, it is the north-west quarter of the church that will be studied.

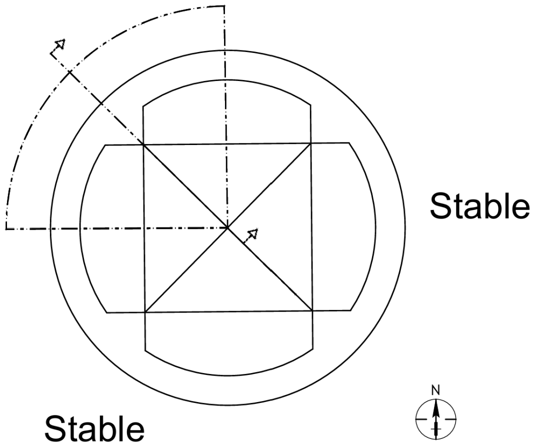


Figure 4.12: Simplified schematic drawing showing the analysed section of the vault in Skörstorp's Church.

Part of the vault, from the section indicated in Figure 4.12, is illustrated in Figure 4.13. As shown in the Figure, the force paths can be interpreted as acting along the diagonal groin. To simplify the analysis, we use the previously derived horizontal thrust from Ungewitter's table to estimate the corresponding thrust in the diagonal direction. While the actual behavior is more complex, this approach provides a sufficiently accurate approximation for a preliminary analysis.

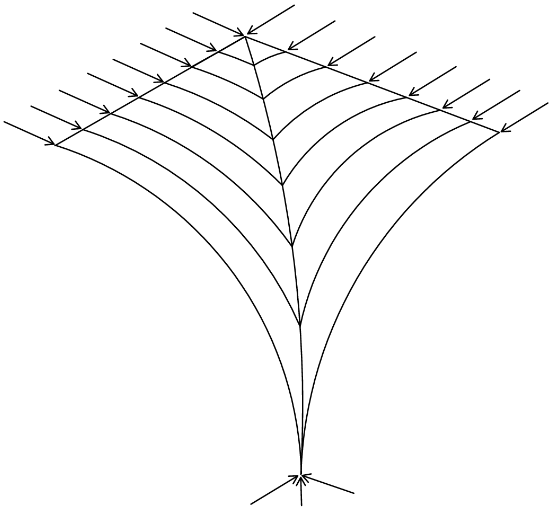


Figure 4.13: Portion of the vault studied in Figure 4.12 without buttress, also illustrated with force paths acting along the arching bands in the orthogonal direction along the sides of the vault.

The diagonal groin is illustrated in Figure 4.15. To translate the previously calculated forces to the diagonal, the horizontal thrust is equal to the resultant of H1 and H2, meaning $H = \sqrt{2} * H1 = (54.16 - 62)kN$. The vertical weight V stays the same. Figure 4.15 shows the position of the thrust line in the vault. When only analyzing the vault and assuming the larger of the horizontal thrust $H = 62kN$ we get a resultant that is $R = 105.3kN$. Without considering the added vertical weight of roof and buttresses and a lever arm $h = 2.9m$ (from the ground up to the thrust line) the eccentricity this provides is $e = (H * h)/V = (62 * 2.9)/95.8 = 1.88m$. This highlights the importance of added weight from buttresses in providing stability to the structure.

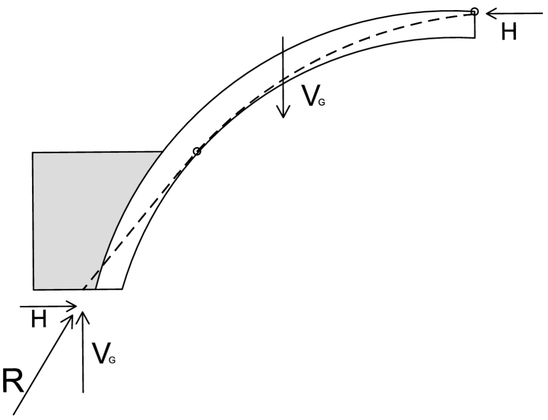


Figure 4.14: Vault diagonal showing position of the thrust line (dashed) in the diagonal of a groin vault.

Since the added weight of the roof, buttress, and wall changes the vertical resultant and therefore changes the position of the thrust line in the wall, these aspects must also be considered. Assuming the same density as the vault for the wall and buttress, $24kN/m^3$, a height of 6 m for the wall, a height of the buttress as roughly 4 m, and a base area of $W = 2m^2$ and $B = 1m^2$, a weight of $V(B + W) = 384kN$ is given.

The roof load was estimated by calculating the approximate weight of the tar-coated roof tiles and by estimating the volume of the roof structure, then determining the proportion of that volume occupied by timber elements. The weight of the roof is then estimated to be roughly $VR = 354kN$, more detailed calculation can be found in the Appendix. Considering our studied quarter we assume less than 1/4 of the roof load is applied to the buttress. The total vertical resultant force is then given by:

$$Vtot = VG + VR/4 + V(B + W) = 95.8kN + (354/4)kN + 384kN = 568.3kN$$

Figure 4.15 shows the section analyzed for equilibrium, with the thrust line position indicated by the dashed line. The position of the thrust line represents a settlement state between the static and kinematic state. It is in equilibrium while also showing the positions of the hinges for the considered settlement mechanism.

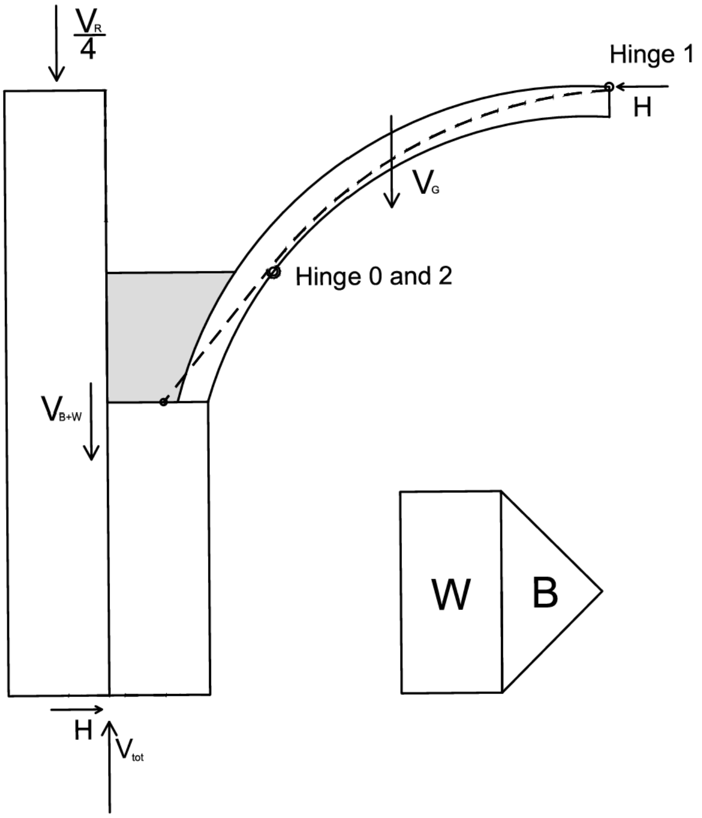


Figure 4.15: Vault diagonal showing position of the thrust line (dashed) in the diagonal of a groin vault.

To find if the buttress is thick enough to withstand the horizontal thrust, we can study the thrust line position in the buttress and whether the resultant vertical force acts within the thickness of the buttress and wall to prevent the overturning moment created by the horizontal thrust. To find this position, we calculate the eccentricity. In Figure 4.16 the wall and buttress is are isolated showing the position of the horizontal thrust acting on the buttress. The horizontal thrust has a lever arm of $h = 2.9m$. The overturning moment given is then $M = H * h = 179.8kNm$. The eccentricity e, is then given by $e = M/Vtot = (179.8)/568.3 = 0.316m$. This means that the vertical load shifts 0.316 m from the center of the buttress and wall structure to balance the overturning moment, which is well within the thickness of the vault, indicating that in its equilibrium state the walls are thick enough to resist the horizontal thrust generated by the vault geometry. For a more conservative approach, and to consider the buttress and wall in pure compression, a general rule of being within the middle third is recommended. This means that the eccentricity should be less than b/6=0.333, which is also fulfilled.

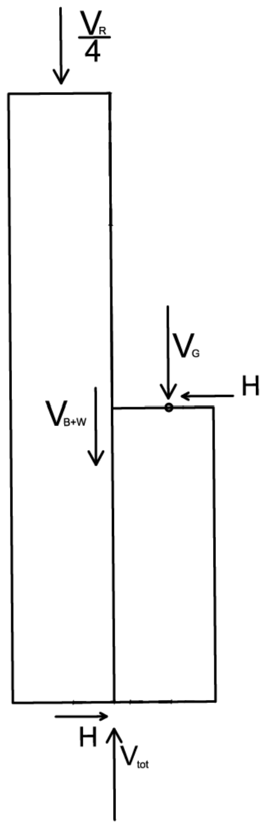


Figure 4.16: Wall and buttress isolated with horizontal thrust acting on the buttress.

4.3.2 Kinematic Response: Collapse Mechanism

Considering the kinematic response of the vault, a probable collapse mechanism has been studied. As illustrated in Figure 4.17, the diagonal section highlights the part of the structure considered in the analysis. A schematic drawing of the proposed collapse mechanism for the vault in Skörstorp's Church is presented in Figure 4.18.

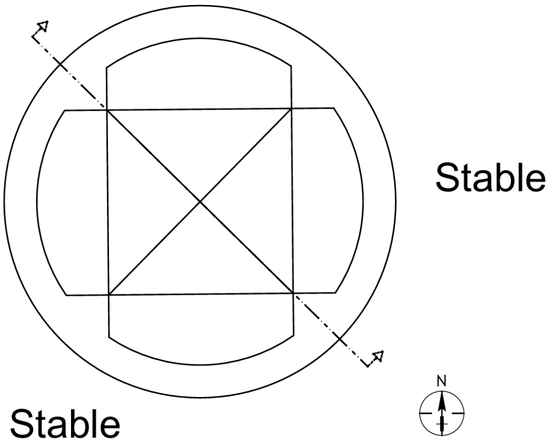
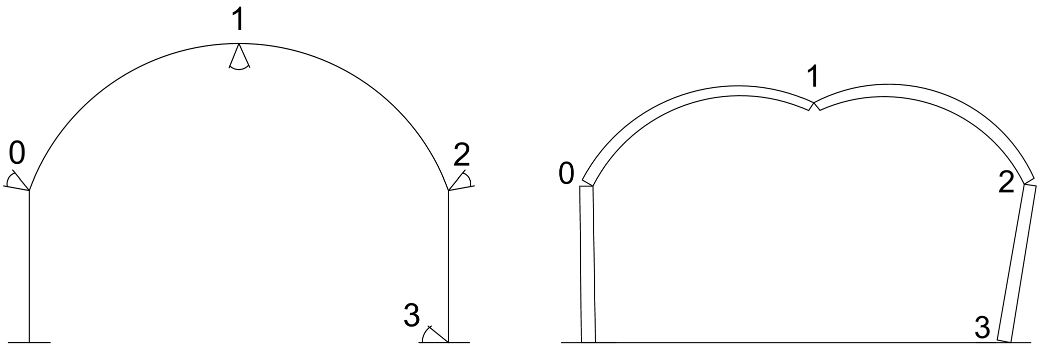


Figure 4.17: Schematic drawing of plan view indicating the position of the diagonal section of the vault in Skörstorp's Church.



a) b)

Figure 4.18: Schematic of chosen probable collapse mechanism of the vault.

While the actual collapse of a vault is a very complex three-dimensional phenomenon involving the entire structure, a simplified approach is appropriate at this preliminary stage. Based on observations of the damage to the structure and common structural behavior of groin vaults, a simplified four-hinge mechanism is adopted to represent the failure mode. This approach allows for an efficient yet sufficiently accurate evaluation of the vault's stability in a preliminary stage.

In this mechanism, it is assumed that the left side of the vault (in the schematic) remains more stable, effectively acting as a restraint. Hinge lines are expected to form along the groin (hinge 1) and at the springing line, where hinges are assumed at the corners (hinges 0 and 2). The collapse would then proceed through the rotation of the four vault quadrants around these hinges (hinge 3), ultimately resulting in the downward failure of the vault segments.

4.3.3 Possible Solution for Skörstorp's Church

One potential approach to strengthen Skörstorp's Church could involve the application of TRM on the extrados of the vaults. Depending on the detailing of the TRM, the formation of hinges, particularly hinges 0 and 2, see Figure 4.18, could potentially be prevented, thereby disrupting the development of a full collapse mechanism or at the very least mitigating its progression.

This suggestion aligns with the strategy employed by Schultze (1970) in addressing a similar case involving a historic structure with massive masonry walls and evidence of soil settlement. His approach was to begin with the reinforcement of the vaults, the "cap," to stabilize the overall structure. If the cracking continued to evolve or new cracks emerged, indicating that the mechanism of deformation had not been stopped, particularly the formation of hinge 3, it would be necessary to improve the foundation.

Translating this methodology to the context of Skörstorp's Church, one possible course of action would be to begin by strengthening the vaults. Such a measure could contribute to greater structural safety for the faithful and visitors. However, it is essential that this intervention be followed by a systematic program of monitoring. Should the structural symptoms persist or worsen despite the vault reinforcement, this would suggest that the underlying deformation mechanisms remain active, in which case more extensive interventions, likely targeting the foundations, would need to be considered.

This proposal should be viewed as a possible solution, subject to further investigation, modeling, and verification to assess its feasibility and effectiveness in the specific context of Skörstorp's Church.

5 Discussion

Historical masonry vaults are very complex structures and often part of an intricate, larger design. The application of Textile Reinforced Mortar (TRM) at St. Bassiano reveals both potential and limitations, raising important questions about how such methods might translate to other historic masonry structures such as Skörstorp's Church.

The main question to be answered in this thesis was "How effective is the use of TRM in strengthening and preserving masonry vaults in (historic) buildings, and what lessons can be drawn from the case of the church of St. Bassiano for possible application to Skörstorp's Church?". To answer the question, the primary aspect studied was to assess the effectiveness of TRM as an intervention technique for stabilizing historic masonry vaults, using the Church of St. Bassiano in Italy as a case study. Over a ten-year period, the TRM intervention of St. Bassiano have proven to be effective in stabilizing the vaults in the main nave of the church. Notably, there has been no development of new cracks in the treated areas, indicating that TRM can be effective in mitigating progressive deformation in historic masonry vaults.

However, the long-term assessment also revealed certain limitations. Increased cracking appears to have developed in the unreinforced side aisles, potentially due to ongoing soil settlement combined with the added stiffness in the reinforced vaults in the main nave. This combination may have led to a redistribution of internal stresses to more vulnerable unreinforced areas as a result of localized stiffening. These observations underscore the need to view the TRM intervention within a broader context. Rather than treating it as a standalone solution, it should be integrated into a comprehensive reinforcement strategy. Without a holistic approach that considers the entire structural system, localized interventions risk unintentionally shifting loads in ways that could aggravate weaknesses elsewhere. In the case of St. Bassiano, the intervention strategy was to first secure the vaults, for the safety of visitor frequenting the church. Future stabilization efforts would benefit from addressing the side aisles and underlying foundation conditions, particularly in light of ongoing soil settlement that continues to influence crack development.

The secondary objective of this thesis focused on evaluating the possibility of applying TRM as a strengthening intervention to Skörstorp's Church in Sweden, which presents similar structural and environmental challenges. Skörstorp's Church has been subject to ongoing deterioration, including widening cracks in the vault and surrounding wall, likely driven by factors such as vault thrust, soil instability, and roof load. Past repair efforts, for example on the foundation, seem to have been insufficient in stopping the ongoing cracking. Although a more comprehensive study including nonlinear analysis, has not yet been performed, preliminary observations suggest that TRM may offer a viable means to reduce deformation and improve stability. The comparative analysis between St. Bassiano and Skörstorp reveals both opportunities and reservations. While the TRM application at St. Bassiano appears to have been effective in stabilizing the vaults, it is still only the first part of the needed total intervention of the church. Considering the fact that differential settlements seem to be a problem for Skörstorp's Church as well, it is likely that if soil settlements in the area continue the need for an intervention of the foundation will be imperative.

Moreover, further studies need to be made for the case of Skörstorp's Church. Notably, the absence of precise data regarding the rate of crack propagation at Skörstorp's Church limits the reliability of current evaluations. It is essential to implement systematic monitoring protocols to better understand whether the deterioration is ongoing or stabilizing. Until such information is obtained, any recommendation for intervention should be considered preliminary.

Beyond the technical evaluation, this thesis also recognizes the cultural and ethical dimensions of heritage preservation. St. Bassiano is a prime example of Romanesque architecture within the historic fortified townscapes of the Lombard region. Similarly, Skörstorp's Church is one of the few remaining round churches in Sweden. Both churches serve not only as physical monuments but also as active centers of community and spiritual life. As such, the preservation of these sites transcends structural performance, contributing to cultural continuity and the integrity of the historic environment. This study aims to contribute to the growing body of research advocating for technically sound, culturally respectful, and environmentally sustainable methods in the conservation of historic structures.

From an environmental standpoint, the adaptive reuse and reinforcement of existing structures represent a sustainable alternative to demolition and reconstruction. TRM offers advantages in this regard, given its low material profile, minimal invasiveness, and long-term stability. While effective in seismic strengthening and therefore advantageous in regions like Italy, emerging research suggests that TRM also performs well under the climatic conditions typical of northern Europe. TRMs adaptability of the materials used makes it possible to perform well even in areas like Sweden where alkaline-rich materials such as limestone, are frequently used. Although further region-specific testing is still needed to validate its performance under Nordic environmental conditions.

As studies on the possibilities of TRM are still very much new and emerging, there are many gaps in research that needs to be filled. In the thesis one existing gap in literature is addressed by examining a case specific, real-world TRM intervention at the Church of Saint Bassiano in Italy, with as previously mentioned, over a decade of data available. Through the comparative assessment of both reinforced and unreinforced areas, the study offers a nuanced perspective that may enhance our understanding of how TRM influences structural behavior beyond the immediate intervention zones. Furthermore, by considering the possible application of these techniques to a Swedish heritage structure, the research introduces a cross-cultural dimension that could inform the adaptation of TRM methods in diverse contexts. In this way, the research offers insights that may inform the ongoing technical discourse surrounding TRM, while also highlighting its potential as a sustainable and conservation-conscious approach to heritage preservation.

6 Conclusion and Outlook

The preservation of historic structures involves more than maintaining their physical form, it requires a deep understanding of how past and present construction techniques interact across time. In this study, the use of Textile Reinforced Mortar has been examined as a technical solution for strengthening historical masonry vaults, framed within the context of heritage conservation.

Two case studies have been performed on the Church of St. Bassiano in Italy and Skörstorp's Church in Sweden. For the case of St. Bassiano, the long-term performance TRM in historic masonry vaults has been evaluated and the possibility for TRM to be applied to the Swedish case study, Skörstorp's Church, has been explored.

The findings indicate that TRM can prove to be very valuable in the context of strengthening heritage structures. The intervention was shown to be an effective and minimally invasive method of stabilizing masonry vaults, although if ongoing soil settlements are the main cause for the deterioration, further intervention of the foundation might prove necessary. This is also the case for Skörstorp's Church; a preliminary suggested solution would be to first stabilize the vault. If cracks continue to form, further intervention of the foundation in particular could be deemed necessary. As always with respect to heritage structures, it is important to know the whole history of the structure to understand the causes of the problems and to choose a fitting intervention strategy thereafter.

In conclusion, TRM presents a promising solution for conserving vulnerable masonry vaults in historic buildings. Through the research conducted as part of this thesis, the many exciting possibilities of TRM have become evident, not only in the preservation of architectural heritage. Studies on the material have been made outside of building conservation, with possibilities of using it to create slender concrete structure, aiding in both architectural and sustainability aspects. The adaptability of TRM opens avenues for tailored solutions depending on local conditions, such as using stiffer fiber materials in seismic zones to enhance performance during earthquakes. These findings point toward a possibility of further study into context-specific TRM applications, including detailed assessments of fiber-matrix combinations for various environmental and structural demands. Ultimately, TRM holds great potential to become a cornerstone technology in both heritage conservation and modern masonry and concrete reinforcement.

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Appendix

6.1 Roof Weight Calculation

The calculation of the weight of the roof structure on the roundhouse of Skörstorp's Church was made by approximating the weight of the tar coated roof tiles and the weight of the timber. The approximation of the weight of timber was based on the volume of the roof structure and then a percentage 15 of that volume was assumed to be filled by timber. As stated this is merely an approximation and more thorough calculations would be necessary for further study.

6.1.1 Geometry of the Roof

Information given about the roof structure from the roof renovation is the lower circumference of the "cone" which is 38 m (6 m radius), and the circumference at the breaking point between the cone and the rounded spire, or "onion shaped dome-spire" as it was described in the roof renovation, which is roughly 9.5 m (1.5 m radius).

The rest of the measurements of the structure were estimated from the drawings of the roof. See Figure 6.1 for geometry of the roof structure. The roof is divided in 5 parts and the estimated volume of each part can be seen in Table 6.1.

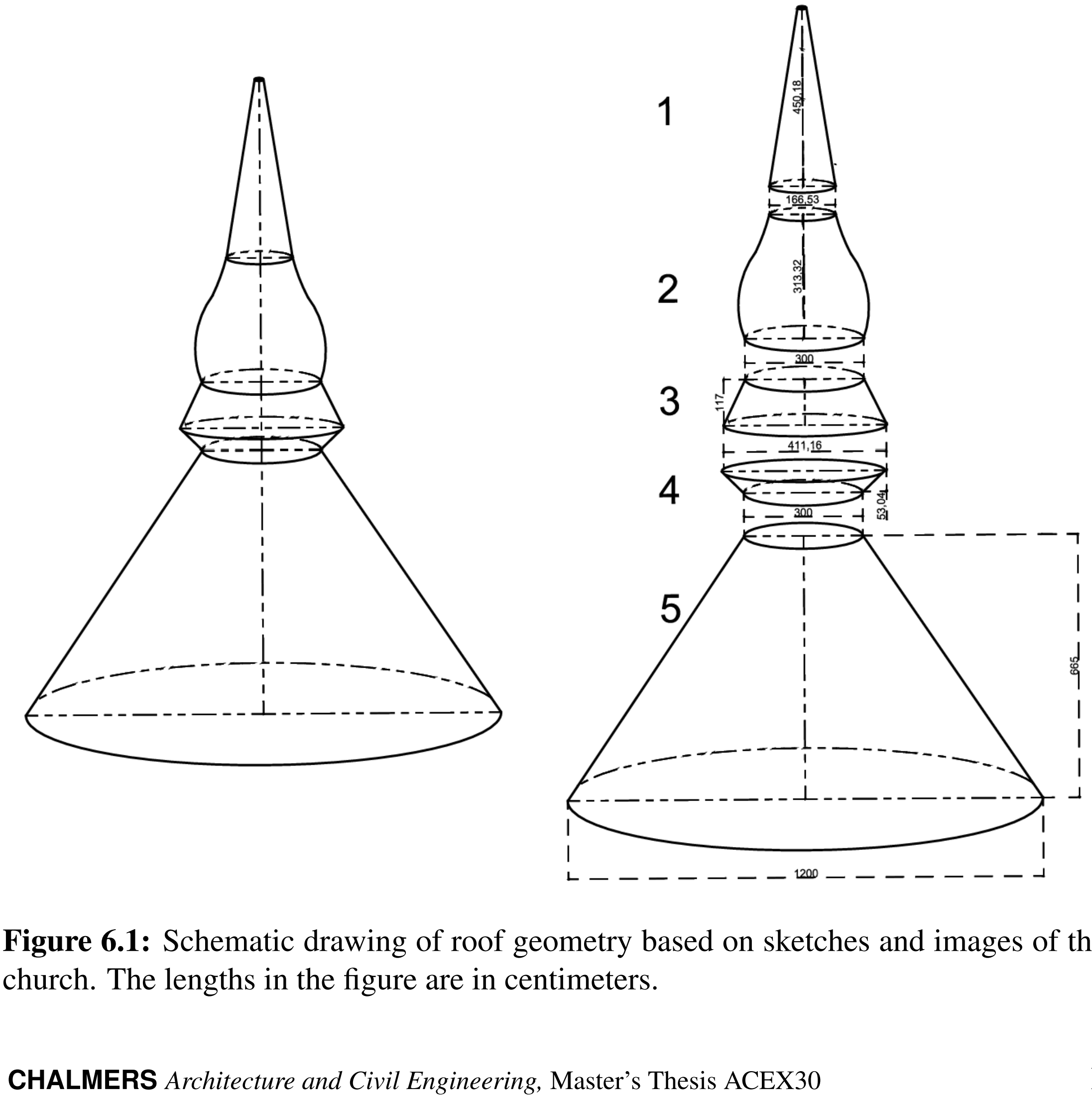

Figure 6.1: Schematic drawing of roof geometry based on sketches and images of the church. The lengths in the figure are in centimeters.

Roof part	Volume$[m^3]$
1	3,25
2	18,70
3	11,72
4	5,31
5	329,49
Total	368,48

Table 6.1: Estimated volumes for all the parts of the roof structure.

6.1.2 Roof weight

The timber used in the roof structure is reported to be mostly of pine, although, some parts like the main tie beam is made of oak. For simplicity, pine will be assumed throughout the entire structure. The density used for pine is $500kg/m^3$. Based on images from the enterior of the roof structure and the schematic drawings, the assumed timber volume is 15% out of the entire roof-volume. A weight of $270kN$ for the timber is then given.

The entire roof is also covered in tar-coated roof plates. From the roof renovation it was stated that the entire cone-structure up to the breaking point of the spire, the north side of the choir roof and half of the south side of the choir roof where renovated with new roof plates. An entirety of 17 000 plates with a weight of 7.2 ton were fitted to the roof.

The surface area for the cone is $150m^2$ and for one side of the choir roof $18.4m^2$. The approximated surface area for the renovated parts then equates to $178.6m^2$. The approximate weight per area is then given as $40.3kg/m^2$. The old roof tiles on the spire part of the roof structure are estimated to weigh the same per unit area. The entire surface area of the roof is $212m^2$ which results in a weight of 84 kN.

The entire weight of the roof is then equals to 354 kN.

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