Seismic assessment and strengthening of Dutch heritage churches with masonry vaults

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Abstract

Since 2014, Groningen has been identified as a seismic risk area due to gas extraction-induced seismicity. Fifteen out of 54 vulnerable historical churches have been deemed particularly at risk due to their varied masonry vault designs. Since 2017, Dutch engineering firm ABT and Italian Studio Calvi have been examining how to reinforce these churches while preserving their monumental value. Non-linear time history models are used for analysis, with a simplified mesoscale modelling strategy implemented in Extreme Loading for Structures (ELS) software using the Applied Element Method. Reinforcement measures aim to balance safety, liveability, and cultural heritage, including ties at vault intrados, steel frames, or reinforcement coatings. Combinations of these measures may also be employed. Addressing the vulnerabilities will help preserve the churches for future generations. Implementation of these measures is anticipated in 2025 and 2026.

Keywords: Seismic assessment; seismic strengthening; heritage buildings; masonry vaults.

1 Introduction

Like many other European countries, the Netherlands has a large heritage of historical buildings. Stemming from the Middle Ages, Dutch religious architecture in particular is very diverse and rich, with multiple building types characterized by strikingly different features, depending on construction period and location.

Since 2014, the province of Groningen, located in the northern Netherlands, has been recognized a seismic risk area. This due to the induced seismicity resulting from gas extraction from the Groningen gas field, one of the largest natural gas fields in the world, which extends below the province. The potential for building damage and loss of life has prompted the Dutch government to initiate an extensive building assessment and strengthening program. Launched in 2016, this initiative aims to evaluate and, when necessary, reinforce approximately 27,000 structures including 224 churches within the affected region over a five-year period. See Figure 1.

To date, 15 churches among a portfolio of 54 vulnerable historical churches under the Dutch Cultural Heritage Agency protection have proven to be particularly vulnerable, due to the presence of masonry vaults with different shapes, heights, spans and types. Since 2017, Dutch engineering firm ABT and Italian based Studio Calvi investigate how churches can be reinforced while respecting their monumental value if their seismic vulnerability (with a focus on vaults) is not acceptable according to the current regulation.

This paper describes the process of assessing the seismic behaviour and the proposed solutions for strengthening.

2 Assessment

2.1 Building typology

Dutch religious architecture exhibits a notable diversity and richness, resulting in various structural typologies. These buildings date from the 11th to the 14th centuries and extend into the 19th century.

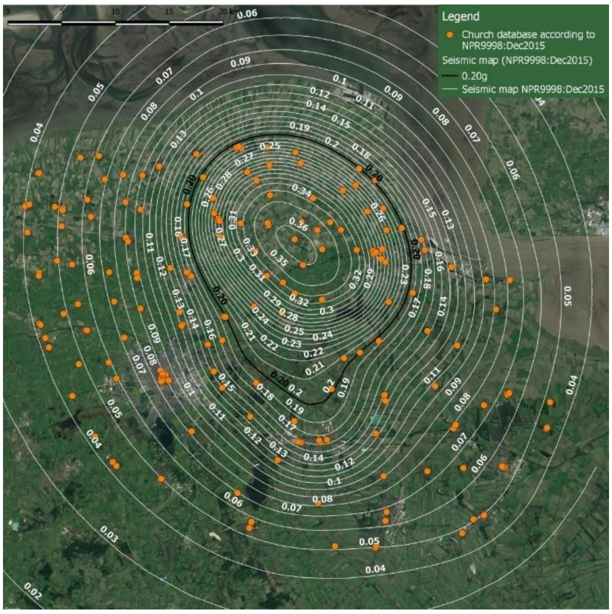

Figure 1. 224 churches in seismic hazard area, 54 churches within the 0.2g contour from 2015

Typically, a church structure measures approximately 40 to 50 meters in total length, with a nave width of 7 to 9 meters, and is often topped by a bell tower measuring 10 meters by 10 meters in plan and rising to a height of 20 meters. See Figure 2.

The construction of these churches primarily employs unreinforced masonry (URM), characterized by multi-leaf walls, with wall thicknesses ranging from 45 cm to 120 cm. The interiors feature vaulted ceilings and pitched timber roofs. Although clay brick is predominant in these structures, tuff is also commonly observed, especially in façades and foundations. Most buildings have undergone numerous modifications over time. Contemporary reinforcements might have been added, including a ring and transverse reinforced concrete beams at the attic level, to counteract the lateral thrust exerted by the timber roof structure and the vaults.

Various types of unreinforced masonry (URM) vaulted ceilings can be identified, including rib vaults, cross vaults, melon-shaped vaults, star vaults, and net vaults, frequently appearing in diverse combinations within a single structure. The ribs, which play a crucial role to connect the vault fields, are constructed from locally sourced squared stones or clay bricks.

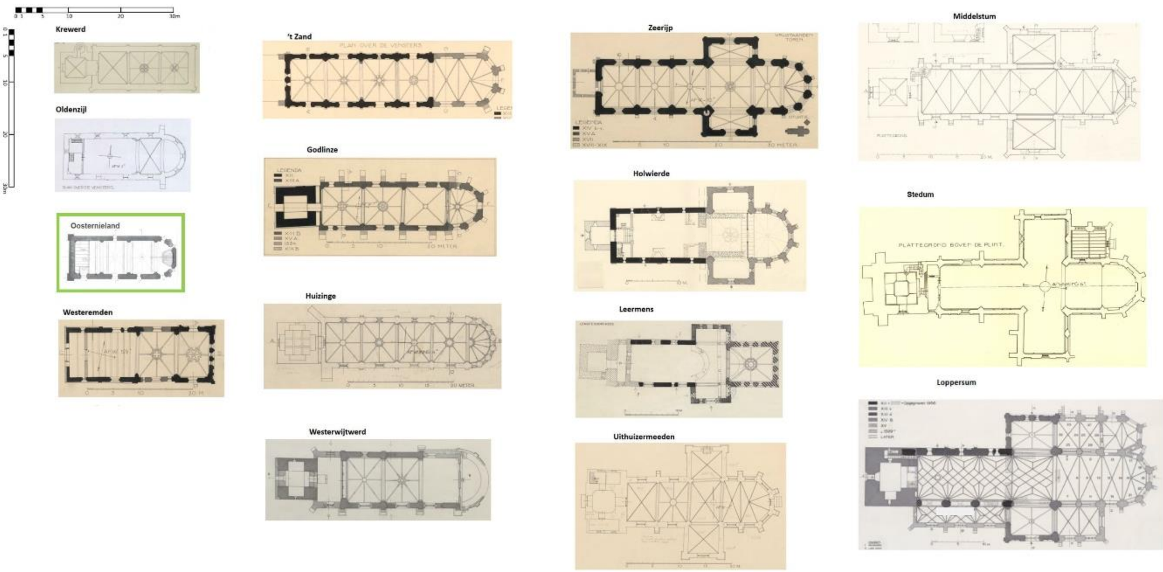

Figure 2. Building typology church buildings Groningen with masonry vaults

2.2 Assessment methodology

2.2.1 Previous assessments

The Netherlands has not historically been a seismically active region. The only exception to this is the southern tip of the country where the Roer Valley Rift System is active [1], most recently causing the 5.4Mw Roermond Earthquake in 1992. Standard design and construction practices in The Netherlands therefore do not consider seismicity, let alone medieval church buildings that never experienced any earthquake event until just recently. When in 2014 it was acknowledged that the province of Groningen had become a seismic prone area [2], a multilevel approach was developed by Studio Calvi to perform relative quick seismic scans of the initial stock of 226 historic Churches in the Groningen region in a tiered approach, allowing significant resource savings and therefore fast conclusions, by focusing on levels of analysis consistent with the available level of knowledge.

This Seismic Multilevel Assessment of Churches (SMAC) was developed based on the requirements for failure mechanisms, drift limits and capacity/demand comparison given by Eurocodes and literature on historic buildings. In-plane and out-of-plane analyses has been performed on simplified models for each wall of the church.

To facilitate the work, a series of automatic and semi-automatic tools have been developed to gather the information, analyse the available data, evaluate the behaviour of the buildings and define some performance indices to be associated to the churches at different levels. See Figure 3.

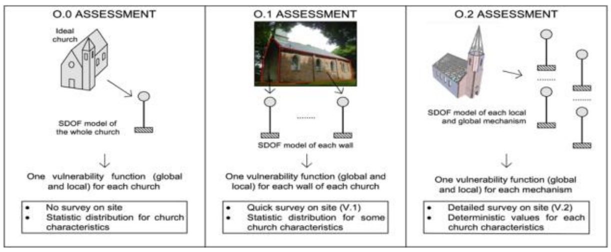

Figure 3. SMAC level 0-1-2

In phase 0, the seismic risk of the churches was assessed based on limited information obtained from a desk study based on the location of the church.

In phase 1, the churches were structurally assessed based on data obtained from a relatively quick inspection and a statistical analysis of thousands of automated structural calculations, for the in-plane and out-of-plane assessment of the masonry walls. In this, the churches for which the lowest 5% of all capacity/demand calculations were less than 1.0 were sent to the next phase.

In phase 2, the churches that did not meet the requirements statistically in the previous phase were inspected more extensively and their behaviour estimated using NLPO and NLKA, which made a deterministic assessment in accordance with the code, instead of a statistical assessment.

As a result of this procedure, a limited group of church building do not meet the requirements in terms of seismic resistance and must proceed to a more detailed 1:1 assessment, where there are also churches that do meet the requirements in terms of seismic resistance, but where a number of 'disclaimers' and warnings by inspectors still apply. Since the followed evaluation method focuses on the global behaviour, some final comments and remarks remained, the aforementioned 'disclaimers', on possible local failures, such as masonry vaults, omitting ties, rubble filled walls, the support and connections of the steeple, interior elements like large organs, and other observed damages.

All disclaimers have been mitigated in a process with involvement of a contractor specialized in restoring of heritage buildings. Some examples of these mitigations are visualized in Figure 4.

Figure 4. concealed new anchoring and anchor plate at the extrados – all historically restored techniques

2.2.2 NLTH

For a selection of churches that could not be verified with the SMAC-procedure, full-scale NLTH models have been setup for determining the seismic capacity and verifying possible strengthening. For the NLTH modelling, a 3D model of the complete building must be used. All buildings are laser-scanned and these scans are used to setup BIM-models, that serve as the geometrical information to build the NLTH model.

The software "Extreme Loading for Structures" (ELS) which is based on the discrete element method "Applied Element Method " (AEM) has been utilized to construct the structural model of the churches and assess the seismic performance of them by using a 3D Non-Linear Time History Analysis (NLTHA). Extreme Loading® for Structures Software (ELS), is an advanced non-linear structural analysis software tool, which allows to study the 3D behaviour of structures until collapse, including the structural behaviour during elastic and inelastic modes, automatic yielding of reinforcement, generation of plastic hinges, buckling and post-buckling, crack propagation, membrane action and P-Delta effect, and separation of elements. The resulting debris and impacts with structural elements are also automatically analysed and stress redistribution is inherently calculated.

Unlike many structural analysis software tools which are based on the Finite Element Method (FEM), ELS utilizes a non-linear solver based on the Applied Element Method (AEM). AEM identifies the structural systems composed of discrete elements, modelled as single unit rigid bodies which only has the mass and the damping of the system. The mechanical properties of the connection between each adjacent unit such as unit-mortar properties in case of masonry structures are defined by uniformly distributed zero-thickness interface springs considering simplified micro-modelling approach [3]. These springs simulate the non-linear dynamic behaviour of the materials they represent, up to the breaking of the bonds. Subsequently, the separation between the rigid bodies occurs and the bodies move and can collide according to the laws of bodies in space.

The large number of degrees of freedom makes the use of FEM micro-modelling approaches unsuitable for the seismic collapse assessment of complex systems, while the AEM simplified micro-modelling approach adopted in ELS decreases significantly the computational burden.

2.3 Seismic hazard

Since in The Netherlands it is not standard practice to design buildings against seismic actions, there is no code available. For example, Eurocode EN-1998 (also known as 'EC8') has not been adopted within the Dutch Building Act, nor is a National Annex or a Dutch translation of EC8 available. To overcome this lack of regulations, for the province of Groningen a Dutch Code of Practice (Nederlandse Praktijk Richtlijn or NPR 9998) has been established by the code authority [4] . This NPR has had quite a few versions in a relative short timeframe, since the insights on the actual hazard and how to approach best the assessment of the Dutch building stock have been chancing rapidly and constantly. For example the maximum expected peak ground acceleration, with a return period of 475 years, has changed from originally 0.42g (NEN, 2014) to 0.23g (NEN, 2018) for the centre of the region.

Because of the changing hazard and with application of article EN-1998-1 3.2.1 (5) about low seismicity that has been adopted in the NPR 9998, a group of church buildings were taken out of the scope, where others with applying the new hazard have been verified with a re-assessment with the SMAC-method. The group of church buildings still under investigation therefore reduced significantly.

The hazard definition for Groningen has been established based on a Ground Motion Prediction Model (GMM) [5]. The code authority in the Netherlands, NEN, has published the information on a website (Seismische Krachten - NEN), with a pga-map, location based spectra and ground motion as downloadable surface time history signals. These ground motions at surface given by the NEN-webtool are directly applied to the models, where for all models a rigid foundation is considered. In total a set of 11 signals are being used to determine the results of the assessment.

2.4 Materials

A rather difficult yet important aspect of the assessment is the choice of material properties. The NPR 9998 provide these properties based on a classification of pre- or post-1945 clay brickwork. These properties have been established through an extensive testing campaign [6]. Whether these properties apply to the medieval church buildings is difficult to verify, since testing of the material is virtually impossible because of the heritage status. A reduction factor of 40% on the strength and stiffness properties has been established, to account for aging and degradation of the masonry material. This reduction factor has been found in line with a similar approach, the Italian Masonry Quality Index method (IQM), to draw conclusions about the material parameters from visual inspection of the observed quality. A similar method is being used in the whole operation of assessments in Groningen [7].

2.5 Failure modes

The outcome of firstly assessed church buildings with NLTH confirmed that the vaults appeared to be the most vulnerable elements. The vulnerability is very much dependent on the span, the rise and the hazard (See Figure 5). An explanation of this vulnerability lies in the very different loadcase, where the vault is loaded horizontally in stead of vertically from gravity load. As long as the compression line is within the geometry of the arch, equilibrium is maintained, while horizontal acceleration distorts this equilibrium.

As a calibration/validation of the models the signal of the actual 2018 Zeerijp event (3.4Mw, 8 January 2018) has been applied to the church of Zeerijp, resulting in the expected no-collapse. Although the intensity and the frequency content of the Zeerijp signal is of course much lower than the hazard as defined by the code, careful study of the outcome was that the structure is very "close to" the collapse and minor modifications to the material parameters or meshes can lead to either verified or not-verified cases. This confirms that the material properties significantly influence the structural behaviour of the vaults, yet seem rather insignificant when assessing the vaults with the much more intense signals of the NPR 9998.

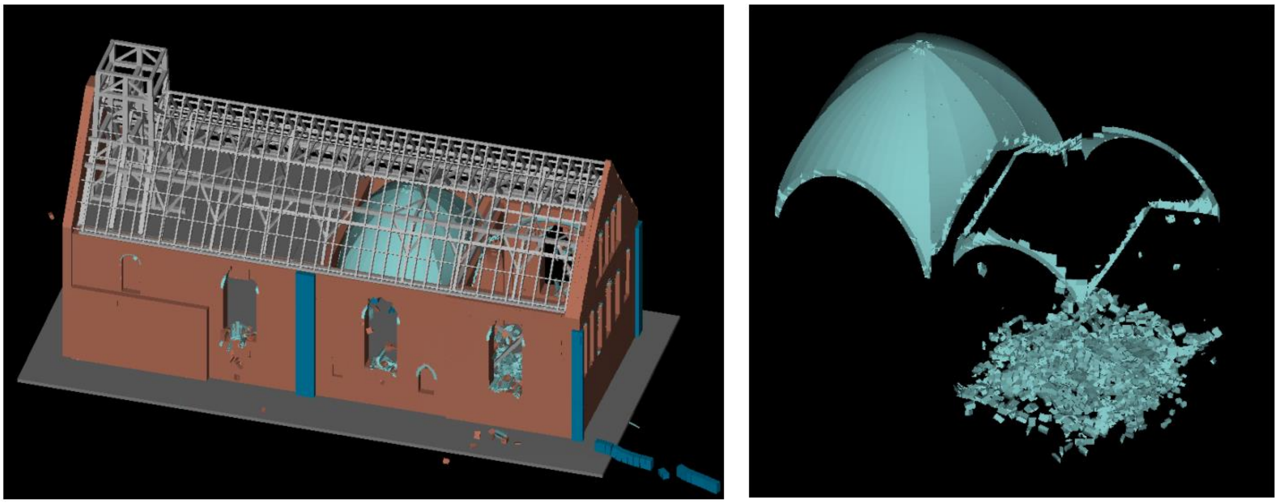

Figure 5. ELS model with end result of assessment, showing collapse of the vault

2.6 Assessment on vault typology

3D detailed nonlinear models of such structures are time consuming, therefore a typology-based assessment of the entire portfolio has been tried, based on the results of a smaller number of performed NLTH analyses. The criteria used to classify the portfolio are the pga, build-up type (e.g. ribbed, cross, etc.), span and rise-to-span ratio. Later, the presence of ties has been added as an determining aspect. A 'vulnerability' classification has been made to group churches together based on these properties, in Upper bound (UB), Medium (M) and Lower Bound (LB). See Figure 7.

PGA [g]_T5	Vaults	L_X [m]	L_Y [m]	t [m]	H_vault [m]	H/Lx	H/Ly	
0.1698	Ribed	8.8	8.5		7.000	0.795	0.824	UB
0.1738	Ribed	7.7	6.7		6.300	0.818	0.940	M/UB
0.2089	Ribed	7	8.2		9.400	1.343	1.146	M
0.1397	Ribed	8.6	7		7.200	0.837	1.029	UB
0.157	Ribed	7.2	5.6		6.300	0.875	1.125	M/UB
0.176	Ribed	6.5	4		3.500	0.538	0.875	M
0.1763	Ribed	7	7		6.200	0.886	0.886	M
0.1408	Ribed/Cross	6	5.2	0.15	5.200	0.867	1.000	LB
0.1426	Ribed	6	5		5.500	0.917	1.100	LB
0.2248	Ribed	8.5	7		7.200	0.847	1.029	UB

Figure 6. church classification based on vault properties

Based on previous analyses, churches with cross vaults are assigned to the Upper Bound rick class, because this typology is very vulnerable and has little chance to be verified.

The result of the risk class approach has proven to be unsuccessful and compliance with NPR questionable. No strong correlation could be found in this exercise (see Figure 7). Therefore it has been concluded that all churches should be individually evaluated based on NLTH analyses and, because many buildings could not be verified, the discussion on how to strengthen the masonry vaults with respect to the heritage value becomes very important.

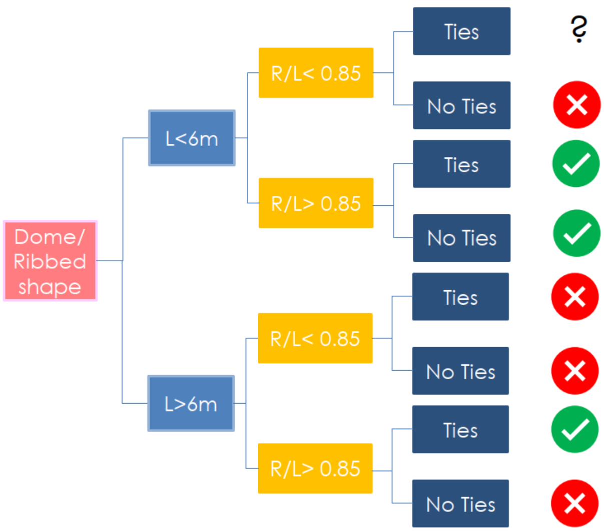

Figure 7. results from verification of various vulnerability classifications

2.7 Strengthening solutions

Strengthening of heritage buildings is a balancing act between monumental conservation and seismic safety (see Figure 8). In the retrofitting strategy it should also be considered that the hazard is likely to end in the future. This because the seismic activity is a result of the gas extraction that has been stopped in 2023. For this reason reversible solutions are preferred, mitigating the risk for a certain period of time but could be removed when the hazard is not present anymore.

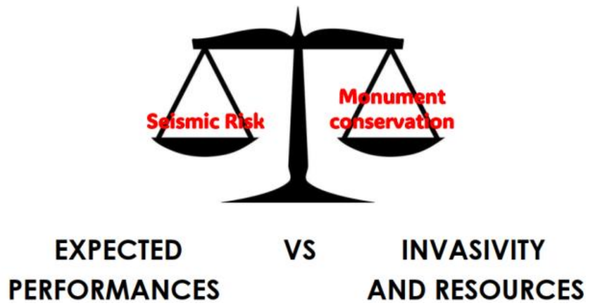

Figure 8. balancing act of strengthening

Apart from (unwanted) limited use of the church or crash decks to prevent bricks falling on the public, possible and well in seismic countries established mitigation measures are ties at the intrados of the vaults, a steel frame around the vaults at the attic level, or a reinforcement on the extrados of the vaults. Combinations of measures are of course also possible.

Ties at the intrados of the vaults have shown to improve the general stability and could avoid the collapse of the vaults. Ties should be anchored to the wall with external anchor plates (hidden or visible). See Figure 9.

Figure 9. Ties at intrados of the vaults, Santa Monica – Cremona (project by Studio Calvi)

Planar deformability can be reduced creating a rigid diaphragm at the attic level. The rigid diaphragm consists of perimetral steel profile elements and bracings. See Figure 10.

Strengthening at the extrados can be performed with either Fibre Reinforced Cementitious Matrix (FRCM) or Fibre Reinforced Polymer (FRP).

Figure 10. Steel diaphragm above the vaults (Palazzo Botta Pavia – project by Studio Calvi)

The FRCM-system represents a thin structural layer that integrates a specially formulated mortar—an inorganic matrix—with an inorganic fiber mesh reinforcement, which may include materials such as carbon, glass, basalt, aramid, or steel. See Figure 11. This approach appears to be particularly well-suited for historical masonry applications when compared to organic resins. Key advantages include superior adhesive properties in relation to rough surfaces, enhanced chemical and mechanical compatibility among materials, improved durability against environmental factors (such as fire and ultraviolet radiation), and straightforward installation processes.

Figure 11. Application of basalt fibre mesh and covering with NHL mortar, Santa Monica – Cremona (project by Studio Calvi)

Fiber Reinforced Polymer (FRP) strengthening systems leverage the combination of high-strength, long fibers and a matrix that serves as an adhesive, facilitating the transfer of stress from the substrate to the fibers. See Figure 12. The fibers, typically made from carbon or glass, are characterized by their high Young's modulus of elasticity and exceptional tensile strength. The matrix is predominantly composed of epoxy resins.

Figure 12. reinforcing system with FRP, ex-monastery in Bergamo (Italy), (project by Building Improving S.r.L)

3 Discussion and conclusions

3.1 Discussion

Seismic strengthening in the form of reinforcement on the extrados could contribute to technical damage to both the vault and the accompanying paintings at the intrados, but is also not easily reversible. It could in addition also solve the problem of recurrent cracks in some churches, due to foundation settlements or thrust forces from the roof and the vaults. The significant visual and experiential value, available for interested public, of the upper surfaces of the vaults necessitates the maintenance of clear visibility and recognition of the underlying materials (such as tuff and brick) and the patterns of masonry bonds. Yet assessments show that this type of reinforcement is very effective, since it improves the masonry tensile strength and bonding in a very direct way. Partial cover of the vault surface by means of stripes of reinforcement could be a compromise between seismic safety and visual impact of the measure.

Ties and rods and steel diaphragms may improve the surrounding support of the vaults but do not enhance the behaviour of the vault itself.

Where engineers can creatively contribute with technical solutions, deciding on what should be preserved and what is unacceptable damage of the heritage building is of course a different decision. The risk of the collapse of the structure with consequent risk of casualties, even if of probabilistic nature, should be carefully studied and examined for future decisions. Such balancing can only be done with a broad contribution of stakeholders, like the heritage committee, building authorities, owners and users and us engineers.

3.2 Conclusions

Addressing the vulnerability of the medieval masonry vaults and design strengthening measures with respect to the monumental values might preserve this heritage for future generations to admire ancient and present building techniques.

Per situation creative solutions weighed against all other aspects must lead to a successful solution.

The reinforcement measures are expected to be implemented in 2025 and 2026.

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