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# Disorders in north transept of the cathedral in Tournai (Be): Structural monitoring, simulations and temporary stabilization

# Uszkodzenia konstrukcji w północnym transepcie katedry w Tournai (Be): Monitorowanie konstrukcji, symulacje i tymczasowa stabilizacja

**Keywords:** Heritage, Cathedral, Tournai, Masonry, Monitoring, Simulation, Stabilization

**Słowa kluczowe:** dziedzictwo, katedra, Tournai, konstrukcja murarska, monitoring, symulacja, stabilizacja

## 1. INTRODUCTION

A great part of important heritage buildings have suffered to be forgotten for several centuries. As the public authorities have now clearly understood the necessity to transmit these master pieces to the next generations, the structural experts and their mastery of computational techniques become unavoidable in restoration works. This paper deals with the Our Lady cathedral in Tournai (BE), part of UNESCO World Heritage, unfortunately suffering of soil problems having induced structural disorders affecting its nave, its choir as well as its transept, the latter being the focus of the present paper.

## 2. HISTORICAL & ARCHITECTURAL PRESENTATION OF THE CATHEDRAL

Two thousand years ago, around 75 km from the North Sea shores, Roman people decide to settle down on the top of a hill, not far from the Escaut riverside. Some centuries later, the place is still busy. Religious habits have evolved; two churches have been erected on the former Roman site and later led to destruction (fire and/or invaders). During the 12th century, it is decided to build a cathedral on their ruins. The articulation between the 12th and the 13th century combines the end of erection of the Romanesque nave, transept and choir as well as the arrival of a new bishop deeply interested by northern practices associated with the Gothic architecture.

In this framework and intending to install an immense cathedral for marking his power, he initiates the construction of a new choir, erecting a huge apse several meters behind the Romanesque choir that is gradually dismounted as the Gothic one progresses closer and closer to the transept zone. Once the Gothic choir has been finished, a probable lack of money made the erection of a Gothic nave and Gothic transept in accordance with the first plans impossible, providing this way the impressive contrast between a slender and widely opened choir and a massive and robust nave and transept that remained nearly unchanged until today.

The unexpected source of architectural richness radiating from this combination of both the most important European medieval architectural styles from a single building has encouraged UNESCO to recognize the Our Lady cathedral as part of the World Heritage.

## 3. STRUCTURAL DISORDERS IN THE TRANSEPT OF THE CATHEDRAL

Further than these stylistic patterns those have clearly inspired the architecture of other great cathedrals in northern Europe, the visitor of Our Lady often surprised by the great number of signs denoting the existence of significant structural disorders. Such signs may be detected on pavements, walls, columns as well as vaults. The **crack patterns** constitute a first family of signs. They essentially affect the northern part of the transept where various structural masonry members are impacted: the three-ring diaphragm arch and the barrels vaults it supports, the floors and vaults

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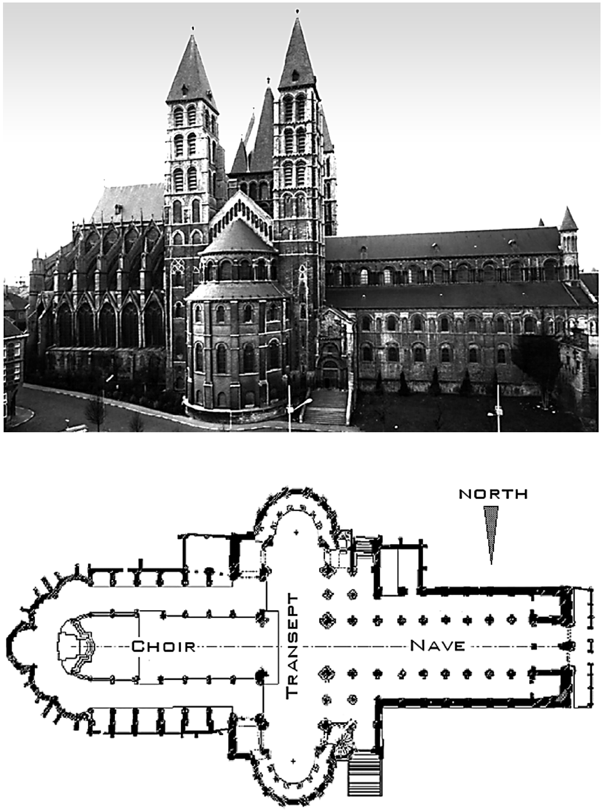


*Fig. 1. North elevation of Our Lady cathedral (left) – plan view (right)*

of the northern apse path as well as the walls of the major stairway located inside the Brunin bell tower are clearly concerned. Areas that are not accessible to the visitors definitely confirm the trend: wide opened cracks affect the impressive

*Fig. 2. Crack in wall upside vaults (left) – pillar settlement (centre) – global inclination (right)*

masonry walls supporting the roof system upside the vaults. The **differential settlements** represent a second family of signs. They affect portions of walls as well as particular pillars with sensible amplitude. They can easily be detected by respectively considering horizontally built stone bands (some of them are clearly inclined) or the vertical position of sculpted pillar basements relatively to the stone floor level that has been replaced some times during the 12th and 13th century and is then rather flat and horizontal (some of them are almost 10 cm embedded in the pavement). The **global system deformations** constitute a third family of signs. Hardly noticed through a local focus, they definitely appear as soon as a concerned system may be considered globally. Walking from the railway station, the severe inclination of the Brunin bell tower towards the west (80 cm at the top of the tower) visually appears in proximity with the four other bell towers. Through these signs, the cathedral clearly expresses the existence of pathologies implying its structure.

## 4. INTERDISCIPLINARY DOCUMENTATION OF PATHOLOGIES CONTEXT

Wide opened cracks, differential settlements and noticeable deformations led to outline as a priority to dispose of a sharp survey of the altered morphology. Therefore, a topographical survey has been initiated that allowed to objectively setup the knowledge of the current morphology: not the entire Romanesque structure appears to be submitted to settlements. In fact, a fictitious line inclined by almost 45 degrees on the conventional north-south direction should be considered for dividing the Romanesque part [1, 2]. Both the western thirds are affected by a settlement that keeps growing as we move away from the fictitious line while the eastern third of the Romanesque structure did never move. The architectural organization of the building (symmetry in shapes and roofs, unity of masonry material and similar window pattern) being not likely to provide any intrinsic heterogeneity in the structural response, the potential impact of an underground problem could clearly be supposed. In this framework, information concerning both the foundation system and the soil had to be collected.

As historians announced that no written data was available for documenting the Romanesque foundation system, several localized excavations have been realized in strategically chosen parts of the building (northern and western side of the nave, along the inclined Brunin bell tower).

These works were carefully carried out by a team of archaeologists under the direction of Professor BRULET (Université Catholique de Louvain – BE). They revealed precious information [3] bringing to light some historical elements of the birth and life of the building. The remains of the previous constructions were partly unearth and the works allowed recognizing the morphology, pattern and levels of the actual foundation system that is composed of impressive and continuous stone masonry walls (external leaves and mixed filling), homogeneously dispatched under external walls and internal pillar rows. In parallel to this information, the manual excavations also allowed confirming the clear continuity of each severe crack affecting the upper parts of the building throughout the foundation, leading to the total disconnection of elements in some places. In this framework, the continuous foundation system designed by the medieval builder for ensuring the stability of the Romanesque structure now appears to act as a set of independent blocks, namely in the problematic zone surrounding the Brunin bell tower. Continuing the manual digging action down to the basis of the foundations made it possible to observe the nature of the material on which the foundation is posed: soft soil in some places or carbonate bedrock in others.

The discovered heterogeneous nature of soil under the foundation justified the interest for a geotechnical investigation campaign. Carried out namely under the direction of Professor TSHIBANGU (Université de Mons – BE), it privileged the recourse to on-site drilling followed by lab analysis of collected cores. Achieving a structured testing grid was not easy partly due to the difficulty of entering testing devices through existing bays inside the cathedral (internal grid) and partly due to the deep embedding of the cathedral inside the urban tissue (external grid). Nevertheless, the obtained information advantageously completed with some geophysical measure-

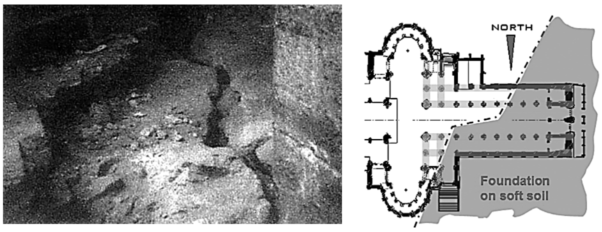


*Fig. 3. Crack in foundation walls under pavement (left) – synthesis of collected information (right)*

ments allowed establishing a 3D model of the underground stratification in the cathedral area: the layer of soil interposed between the top of the carbonate bedrock and the bottom of the foundation system reveals thicknesses varying from 0 up to 6 meters, sometimes abruptly (about 5 meters of vertical delta on less than 3 meters of horizontal delta) and the quality of this soil appears to be globally poor.

## 5. SIMPLIFIED FE MODELS FOR VALIDATING ASSUMPTIONS

Stone carrier used for ancient constructions (explaining the occurrence of steps in the level), karstic problems usual in the concerned region [4] (explaining the top bedrock alteration and poor quality of soils), modified water flows associated to seepage in local extractive activities (explaining the importance of settlements)… Although many interrogations remain concerning the soft soil layer, it clearly appears that its intrinsic nature should probably be considered as cause for explaining the observed disorders although establishing the validity of such an assumption is not easy. Implied in several European preservation committees, Professor BARTHELEMY (Université de Mons – BE), gathered Professor MACCHI (Pavia – IT) who carried out FE calculations on the Pisa tower and Professor HALLEUX (Université Libre de Bruxelles – BE) who managed the calculations in the restoration of Brussels Town hall tower. Together, they outlined modelling guidelines aiming at achieving a partial or total confirmation of an eventual relationship between the soft soil state and a consequent occurrence of various structural disorders affecting the Romanesque nave and transept. The elaboration of a FE model has been initiated, in this spirit, by a team directed by Professor LAMBLIN (Université de Mons – BE) [5]. The proposed study focuses on the problematic north transept and its neighbouring nave parts although southern parts are also involved in the model. The sharp morphology of the model has been established from the combination of a topographical survey and archaeological investigations. The physical and mechanical values that are required for the models are derived from published data in complement to laboratory tests performed on samples cored from masonry walls or stone pillars.

The masonry material is modelled using a macro-modelling philosophy: a fictitious homogeneous material is considered whose equivalent properties are computed on the basis of both material and morphological aspects. This fictive material is assumed to exhibit an isotropic, linear and elastic behaviour. Although no limitation is introduced concerning the compressive solicitations, a Rankine model is considered concerning the tensile solicitations: it is implemented under the shape of a discrete cracking process taking place in an iterative framework. On the basis of the general stress state associated to the iteration # i, the geometry of the mesh is adapted in order to introduce a discrete crack by node duplication at the point associated to the higher value of maximal principal stress and orthogonally to the related principal direction if this higher value is above the tensile strength for the considered masonry. Such an approach has already been applied with success [6] and is recognized to outline valid stress repartitions although the strain range is often underestimated.

The interaction between the studied masonry system and its direct neighbourhood is smartly managed. The effect of non-represented building parts (namely the junction with the choir) is taken into account through constraints applied along interfaces where no absolute motion has occurred since the erection. The effect of stone vault is replicated through equivalent point loading whose values are computed in an external FE calculation. The tie bars have been effectively modelled with truss bars as they are likely to play an active role in load redistribution. The effect of the roof system is taken into account through equivalent line loading whose values are estimated in a classical manner. The mesh is structured and relies on an 8-node-brick approach. Although the effect of wind loads has been proposed for some particular studies, the main calculations are carried out under the essential action of gravity. The developed models gave quite interesting qualitative results. So the influence of the disorders can be noticed and parametric studies can be carried out to highlight the relative variation of the stresses and strains but the absolute value given by the software cannot be considered in itself due the assumptions introduced in the model (see before).

The soft soil layers interposed between the top of bedrock and the bottom of the masonry foundations has been carefully modelled as it definitely drives load redistribution in our statically redundant structure. In practice, a preliminary approach

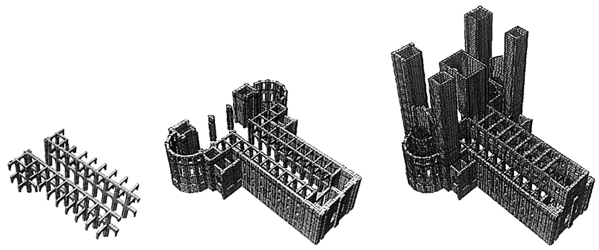

*Fig. 4. Erection of the simplified FE model for the transept and nave system*

with Winkler approximations[1] appeared to be insufficient as it was not likely to effectively capture the pressure bulb development and its potential effects. Then, the effective presence of soil material has been privileged, a simplified constitutive model being chosen as only the impact of deformations on the masonry system was interesting to be replicated. The bottom face of the soft soil is constrained for simulating the effect of the subsequent bedrock. Lateral earth pressure acting on each underground masonry foundation walls have been computed in the Lower Limit State according and applied as equivalent surface loads on the model.

A modelling of the first steps of the construction of the cathedral revealed that already shortly after their building, the foundations would have been submitted to excessive traction in the area of the good/poor quality soils transition line [7]. In this way, the superstructure of the cathedral seems to have been built on weakened foundations. Following these results, the assumption that the foundation system suffered from cracks in their early life could explain the fact that pathologies started to affect the newly built cathedral only decades after its erection as attested by historical documents.

At the scale of the entire model, the crack management allows to express interesting conclusions. Although a tensile stress limitation through a smeared cracking method could give suitable primary results, the recourse to a discrete approach where cracks are introduced as geometrical discontinuities enhances the quality of the models, outlining results that are closer to the real situation. In particular, the location and morphology of numerical crack patterns, the calculated settlement trends as well as the global deformations predicted by the proposed FE models appear quite in adequacy to the reality.

A routine developed by J. NOËL and improved by J. COUVREUR likely to automatically manage the evolution of cracking process in the models through nodes duplications [7] allowed to precisely follow the crack propagation inside the global system. It clearly appeared that the more the cracks progresses in the gable wall, the arch and the apse, the more the bell tower get inclines itself [8, 9]. The proposed simplified FE approach gives good clues concerning the causes for most of the pathologies concerning the north gable wall, the north apse of the transept and the inclination of the Brunin bell tower. Indeed, the presence of an important gradient in soil quality under the Brunin bell tower could explain some of the pathologies highlighted in the models and visible *in situ*. Three corners of the Brunin bell tower are posed on a thick layer of bad quality soft soil although the last one is directly posed on the bedrock. The massive stone structure of the bell tower makes an eventual settlement of soil layers to be significant.

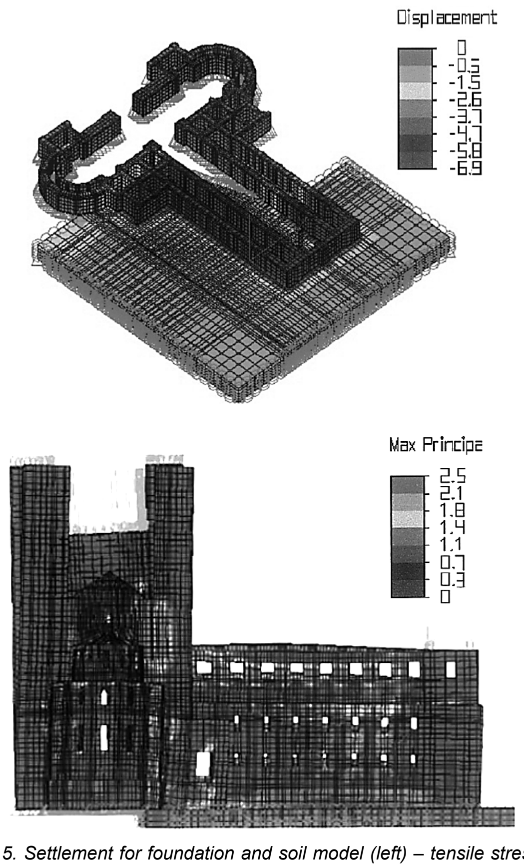


*Fig. 5. Settlement for foundation and soil model (left) – tensile stressed zones in the system (right)*

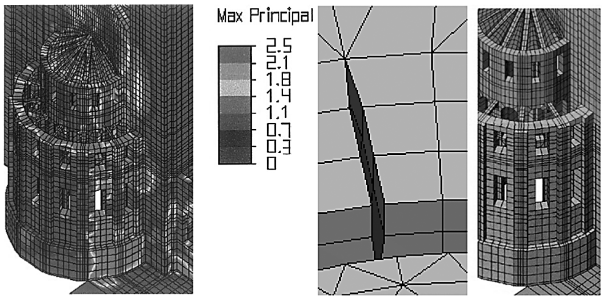


*Fig. 6. Tensile stresses around Brunin bell tower (left) – node duplication & concerned zones (right)*

The differential effect induced by the heterogeneous posing conditions brings the occurrence of parasite solicitation inside the system (bending, tension, shearing) that induce the development of disconnections, opening the way to still important inclination motions.

## 6. EVOLVING CHARACTER: SUPPOSITIONS AND RISK

Specific hydrological considerations concerning potential natural underground water flows between upper and lower area of the city (towards Escaut river) present the occurrence of soil particle transportation as a possibility, removing soil and potentially enforcing the evolving character of measured and modelled effects. Combined with the morphological configuration of disconnected blocks inside the Brunin bell tower and based on geometrical considerations, it was shown that the damaged system has got the possibility to avoid the convergence towards a stable equilibrium state. Some topographical measurements carried out on a limited period tended to confirm the effectiveness of evolution trends. Therefore, the recourse to a temporary stabilization structure preventing any increase in damages has been studied. Nevertheless, with such a structure likely to strongly constraint any further motion, it is not possible to easily detect evolutions any more as its installation "comes and breaks the thermometer". In this framework, a monitoring system coupled with the temporary stabilization structure and likely to manage a permanent structural survey has been proposed. It should detect local motions (with limited amplitude due to the constraints) and also provides information concerning the evolution of forces inside the structure (with great value due to constraints).

Designing an urgency stabilization structure for a cathedral submitted to significant soil motions is not usual and then not particularly easy. To become installed on a complex site, it has to be ingenious. The proposed solution relies on post-stressed steel bars for temporarily anchoring the Brunin bell tower inside undamaged bells tower along both the east-west and the north-south direction. For making the system to be efficient, the convenient localization of bars should be achieved as well as the choice of a suitable section and repartition system for avoiding potential failure occurring in the steel system or in the still undamaged masonry parts. The effective design and the related impact study has been carried out with FE models derived from the one presented previously. A 10mm settlement increase under the Brunin tower has been introduced in the cracked model and the efficiency of steel bars has been analysed. It gave birth to the solution that has been effectively: 2 bars × 50 mm bars placed at level 25,5 m from pavement with 6500 daN post-stressing each in the east-west direction, 4 bars × 50 mm bars placed at level 18,5 m combined with 4 bars × 50 mm bars placed at level 26,5 m with 5000 daN post-stressing each in the east-west direction. According to the FE studies, the chosen configuration of stabilization (position, number and post-stressing force) is likely to reduce the crack openings induced in gabble walls by any further settlement for more than 60%.

The prescription of the coupled permanent auscultation system was carried out under the direction of Professor BOLLE (Université de Liège – BE). It is composed of several complementary captors that are usually used for monitoring the global behaviour of civil engineering equipment like dams or tunnels. A review of some of them is proposed hereafter: it outlines the usual requests associated to each of them, the principle of the measurement and the classical usage in civil engineering.

An automatic pendulum has been installed on a pillar that leans against the Brunin bell tower. This device aims to measure the relative movement of two vertical points. The wire bearing the pendulum is anchored at the upper point and the reading device measure automatically the variation of the inclination of the wire. The pendulum is immerged in water in order to damp the movements and avoid vibrations and oscillations. The pendulum gives a measure of the global inclination of the pillar. Some clinometers are also recording the local variation of the tip angle of some critical structural elements of the cathedral. The variation in the inclination is measured through a small gravitational pendulum coupled

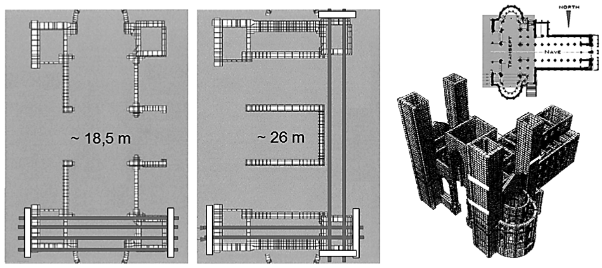


*Fig. 7. urgency stabilization system with post-stressed steel bars designed with FE models*

with electronic measuring equipment. Crack opening captors are monitoring the evolution of the cracks size in the transept, the apses, the arches and the tower. Vertical movements of the pillars of the transept and choir are monitored using soil settlement gages consisting of several tanks connected to each other by a liquid saturated tube. In each reservoir, a floating mass is sensitive to the variation of liquid level due to settlements. One reservoir is chosen as the reference level and the device gives then the relative vertical displacements of all the elements on which a tank is fixed.

## 7. EVOLVING CHARACTER: CONFIRMATIONS AND CONSEQUENCES

The day-to-day monitoring analysis was carried out by the team of Professor LAMBLIN, focussing on the data treatment and producing deliverables that could be interpreted by Professor BOLLE. The total interpretation of data collected along several years will not be discussed in the present paper. Nevertheless, it is important to notice that further than the

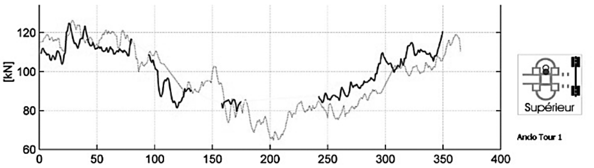


*Fig. 8. Evolution of forces in upper bars along the east-west direction (on 365 days)*

seasonal effects associated with meteorological conditions, the system clearly shows an evolving character for the phenomena: the complex masonry system is not yet arrived to a stable position, confirming the feared evolution trends.

In such an evolving case, the simplified FE models presented here have shown that the problem of Brunin bell tower stability was far to be the most critical aspect: the tower is still able to submit an important inclination before collapsing under its self-weight. Nevertheless, a three-ring arch supported by the Brunin bell tower is submitted to springing displacement and this is recognized to be problematic although the literature proposes only poor information concerning such problems. The complete study of this particular problem will not be detailed in the present paper but is proposed elsewhere [10].

## CONCLUSION

Since the experts have been asked to study the Our Lady Cathedral issue in 1965 [11], the building has been under permanent attention. The growing pathologies it suffers needed trans-disciplinary studies to be carried out. Engineers gathered architects, archaeologists and historians to find solutions to preserve this historical construction. These lasts focused on the birth, life and evolution of the building. Their excavations have put into light the hidden face of the building, its foundations and the previous constructions they are settled on. Using this information and after *in situ* and in lab investigations, engineers have analysed the stability of the edifice. They could highlight some of the causes of the observed pathologies and their work led to the installation of monitoring systems and temporary strengthening devices which are guaranteeing the survival of this exceptional part of the Belgian and World Heritage. The use of all the technological knowledge and the sensibility of all the present actors have managed to protect the Cathedral structure without taking away the aesthetic and cultural interest of the prestigious edifice. The evolving characters of the phenomena justify the setup of a permanent stabilization solution where important challenges will have to be taken up.

## ACKNOWLEDGEMENTS

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[1] Classical soil-structure approach where springs are connected at each node of the bottom face of the foundation with an individual rigidity computation based on soil properties as well as local layer thickness

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# Abstract

A great part of important buildings involved in the World Heritage have suffered to be forgotten during several centuries. As the public authorities have now clearly noticed the touristic potentialities and definitely understood the necessity to transmit these master pieces to the next generations, structural experts have often to play a great role in restoration works.

This paper concerns the Our Lady cathedral in Tournai (BE) whose architectural richness has encouraged UNESCO to recognize it as part of the World Heritage at the beginning of the 21st century. Unfortunately, serious geotechnical problems have, along the centuries, induced the occurrence of structural disorders that affect now the roman nave and the gothic choir as well as the "transition style" transept that constitutes the subject of the present paper.

After a quick introduction to the concerned historical and architectural contexts, the paper presents most of the pathologies that may be directly captured by direct observation in the transept of the cathedral. Then, the interdisciplinary campaigns carried out for achieving a better knowledge of the situation are described; the collected information is summarized as well as the Finite Element studies that have been carried out in order to get a sharp understanding of the problems. They are based on simplified macro-models taking a crack propagation process into account and they outline the interest to install a monitoring system proposing a permanent structural survey.

The effectively installed system coupling pendulum, settlement gages, crack opening captors and clinometers is described. The interpretation of the information collected during a first period is proposed and the interest to design a temporary stabilization structure is then discussed. The simplified Finite Element simulations leading to the effective design of these structures are described and the solution that has been effectively installed is illustrated, briefly summarizing the challenges associated with the implementation of a future permanent stabilization of affected masonry arch systems.



# Streszczenie

Duża grupa ważnych zabytkowych budynków z Listy Światowego Dziedzictwa trwała w zapomnieniu przez kilka wieków. Jednak obecnie władze wyraźnie dostrzegły ich turystyczny potencjał i zrozumiały konieczność zachowania tych arcydzieł dla następnych pokoleń, toteż eksperci specjalizujący się w tematyce konstrukcji zaczęli odgrywać istotną rolę podczas rewaloryzacji tych obiektów.

Niniejszy artykuł dotyczy Katedry Notre-Dame w Tournai (BE), której architektoniczne bogactwo skłoniło UNESCO do uznania jej za część Dziedzictwa Narodowego na początku XXI wieku. Niestety, w ciągu wieków poważne problemy geotechniczne wywołały uszkodzenia konstrukcji, występujące w romańskiej nawie i gotyckim chórze, jak również w transepcie w „stylu przejściowym", który stanowi przedmiot poniższej pracy.

Po krótkim wprowadzeniu w kontekst historyczny i architektoniczny obiektu, artykuł przedstawia najpoważniejsze nieprawidłowości jakie można dostrzec w trakcie bezpośredniej obserwacji transeptu katedry. Następnie opisano analizy interdyscyplinarne przeprowadzone dla uzyskania lepszego rozeznania w sytuacji; podsumowano zebrane informacje, podobnie jak badania metodą elementów skończonych wykonane w celu dogłębnego zrozumienia problemu. Bazują one na uproszczonych makro-modelach uwzględniających proces propagacji pęknięć oraz proponują zainstalowanie systemu monitorującego pozwalającego na stałą obserwację konstrukcji.

Opisany został skutecznie zainstalowany system, składający się z wahadła, mierników osiadania, czujników wychwytujących pęknięcia oraz inklinometrów. Zaproponowano interpretację informacji zebranych podczas pierwszego okresu obserwacji, a następnie przedyskutowano kwestię czasowej stabilizacji konstrukcji. Opisano uproszczone symulacje metodą elementów skończonych, prowadzące do optymalnego projektowania takich konstrukcji, oraz rozwiązanie, które zostało skutecznie wprowadzone, krótko podsumowując wyzwania związane z wdrożeniem planowanych rozwiązań trwale stabilizujących naruszone systemy kamiennych łuków.