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PREVISION OF THE BEHAVIOUR OF THE GOTHIC FOUNDATION IN OL-CATHEDRAL OF TOURNAI (BELGIUM)

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Abstract

The gothic choir of the OL-Cathedral in Tournai suffers for a very long time various pathologies. This article describes a related numerical study prepared in the department of Civil Engineering and Structural Mechanics of the Polytechnic Faculty of Mons. The analysis is based on full 3D models taking into account the bedrock, the soft soils, the foundation and the superstructure itself. All the materials involved in the study were assumed to be linear elastic. Some non linearities were introduced with a discrete iterative approach to simulate crack propagation. The obtained results confirm the assumptions of the experts about the influence of underground phenomena and the observed pathologies are much more understood than with previous simplified models. A previsionnal state of damages in the gothic foundation, useful for the future structural repairing work, is proposed.

Key words

FEM, foundations, historical buildings, cracks

1 Introduction

Since the civil authorities have understood the necessity to preserve the old building heritage to be transmitted to the next generations, important budgets are allocated to finance heavy restauration campaigns. Many historical buildings have been forgotten for decades and, often, the campaigns begin with an interdisciplinary approach :

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archeologists, historians and structural experts, all working together, are necessary to understand the "building" and to help to propose some efficient solutions for the future.

The engineers, by coupling powerfull calculation methods with efficient on-site investigations, can precise the structural behaviour of the building. This paper presents an application of such a method, the Finite Element Method, to study the complex configuration of the Cathedral made of interactions between the superstructure and the global foundation system (masonry + soft soil + bedrock).

2 The choir and its pathologies

2.1 Historical approach

The erection of OL-Cathedral in Tournai began during the 12th century, on the ruins of a previous merovingian church (Tournai has been the capital city of the Frankish Kingdom under Clovis' reign). In the beginning of the 13th century, the initial roman Cathedral was just finished when the bishop decided to build a new gothic one. The erection of an absydium at the eastern side of the existing building was the first new work, followed by the demolition of the small roman choir and the erection of the gothic one, joining the existing transept. Due to a lack of money, the works were stopped at this moment. History explains why the Cathedral has now a roman nave, a "transition style" transept and a gothic choir. This particularity added to the global architectural quality led the Cathedral to be recognized in 2000 by UNESCO as part of the World Heritage.

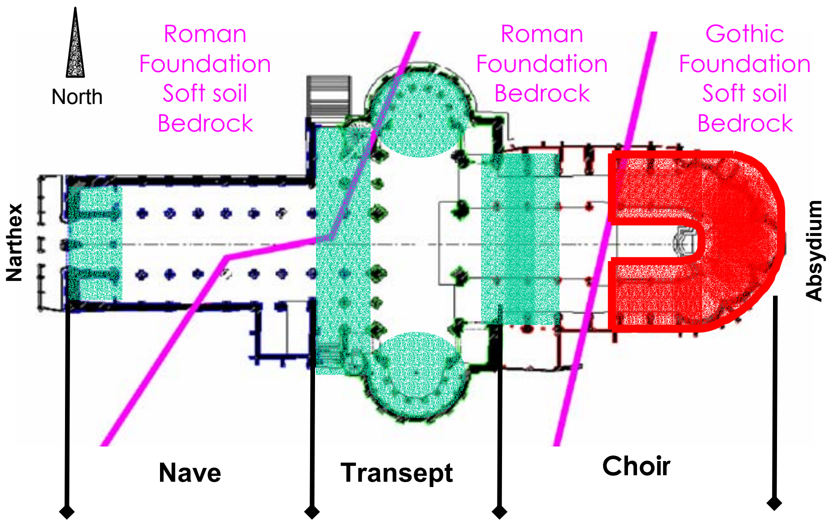


Figure 1 The Cathedral : parts, foundations and underground configuration

In 1999, a whirlwind strongly damaged the Cathedral and a college of experts was formed to study the structural pathologies mostly affecting the gothic choir. At this moment, it was discovered that most of the damages were not recent : according to the Cathedral's archives, the team of historians and archeologists attested that, early after its construction, the gothic superstructure showed signs of weakness. Strong structural interventions were necessary like :

- Addition of new structural elements : complementary pillars in the principal part of the choir, steel tie bars at the feet of the vaults, second set of flying-buttresses under the existing ones, stone masonry overload on the flying-buttresses, ...

* Total reconstruction for several buttresses, all the flying-buttresses and some walls.

Due to the recursive character of the various interventions made with the time (the same structural parts have been repaired or rebuilt several times), it seems that repairing was unefficient. Maybe it is due to the misunderstanding of the causes of the problem.

2.2 Actual approach

From a local point of view, the observation of disorders shows that pathologies affect the majority of structural parts (see figure 2a) but the level of damage is not homogenous : the western part of the choir seems to be weakly damaged and pathologies become stronger from the transept to the absydium.

From a global point of view, the eastern part of the choir seems to be submitted to a global overturning movement in the south-east direction (see figure 2b). This movement is a combination of the settlement affecting the basis of pillars and buttresses (up to 180 mm) and of a bending deformation affecting the top of the very slender pillars (variation of span up to 800 mm are observed between opposite pillars in a same span – see figure 10b).

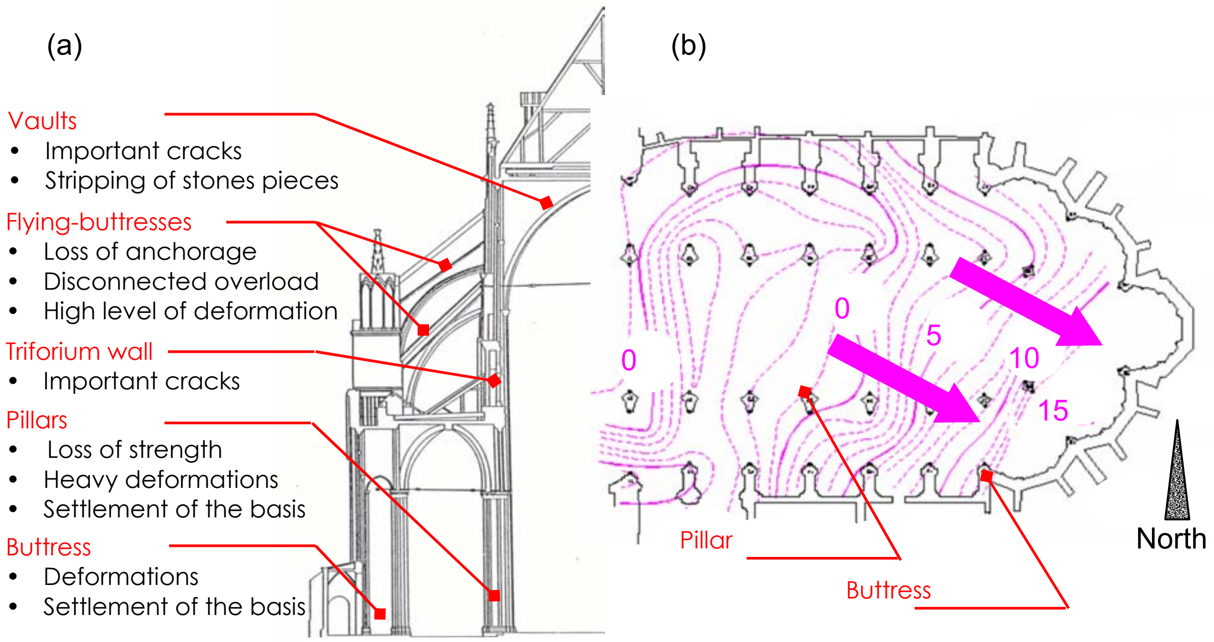


Figure 2 The gothic choir : geometry and main pathologies (a), lines of equal settlement [cm] (b)

3 From preliminary studies to a geotechnical campaign

On the basis of a very precise topographic survey, several hand calculations (graphostatical approach, limit analysis according to Heyman's theory,...) were performed. Unfortunately, they were limited to the study of half a span and took only the superstructure into account.

A few years ago, the Polytechnic Faculty of Mons began to study the problem using finite element analysis. The preliminary 2D studies were quite simple and made step by step considering first the behaviour of the flying buttresses, second the behaviour of half a span and finally the modelling of the entire superstructure of the gothic choir. The results were very interesting : the complete model of the superstructure (under dead loads) was able to explain most of the structural pathologies when imposing the settlement of pillars and buttresses. This preliminary results confirmed, for the first time, the major role played by the gothic foundation in the pathologies affecting the choir. At this time, it has been decided to focus on the underground part of the building.

An important geotechnical and archeological campaign has been launched. Due to different periods of construction, the gothic choir is founded on two types of foundations (see figure 1) : the western part is settled on the ancient roman foundation while the eastern part is built on a new gothic one. Although the roman foundation is composed of thick stone masonry walls directly based on the bedrock, the gothic one is an "horseshoe" shaped complex made of big flat stone pieces. This complex is about 4,60 meters thick and presents an unexplained groove (about 3 meters deep) between the basis of pillars and buttresses. Between this foundation and the calcar bedrock, there is a layer of bad quality soft soil for which thickness varies from less than 0.5 to more than 5 meters. The special relief of the bedrock justifies the variation of thickness affecting the soft soil and can be explained by the nature of the calcar stone which is very sensitive to karstic phenomena.

4 Finite element modelling of the gothic foundation

4.1 Setting of the model

On the basis of the collected geotechnical informations, a finite element model was elaborated for which setting was considered. To determine the parameters to be taken into account and the best way to introduce their effect, an iterative approach has been used : from the comparison between the results of calculations and the trends observed in the reality, the inadequations are outlined and a modification of parameters is proposed for the next calculation step. The iterative process is performed until a correct trend adequation between the model and the reality is achieved.

4.2 Geometry

The final model used for the computation is composed of different parts :

- Foundation : 3D model made with 8 nodes bricks, respecting the real geometry of the foundation (source : precise archeological survey)
- Soft soil :
    - the part under the bottom face of the foundation is modelized as 3D model made with 8 nodes bricks (compressive strength of the soil and pressure bulb). The geometrical extension of this model is about 15 meters wider than the model of the foundation and particular boundary conditions are used to simulate a continuous medium.
    - the soft soil beside the foundation is taken into account through applied pressure (compression acting on the top face of the model and lateral pressure acting on the masonry complex). The values are calculated from the characteristics of the soil.
- Bedrock : the bedrock itself is not included but its particular relief has been taken into account through variable thicknesses of the soft soil. The vertical translation of each node at the bottom face of the soft soil has been

constrained. The idealized relief is obtained by interpolation between the different levels recognized by boring during the geotechnical campaign.

- Superstructure : due to unsatisfying results obtained by previous and more simple methods, it became necessary to build a complete 3D model of the superstructure made with 8 nodes bricks. The vaults are modelized with 2D shell elements, the arches with 1D beam elements and the tie bars with 1D truss elements.

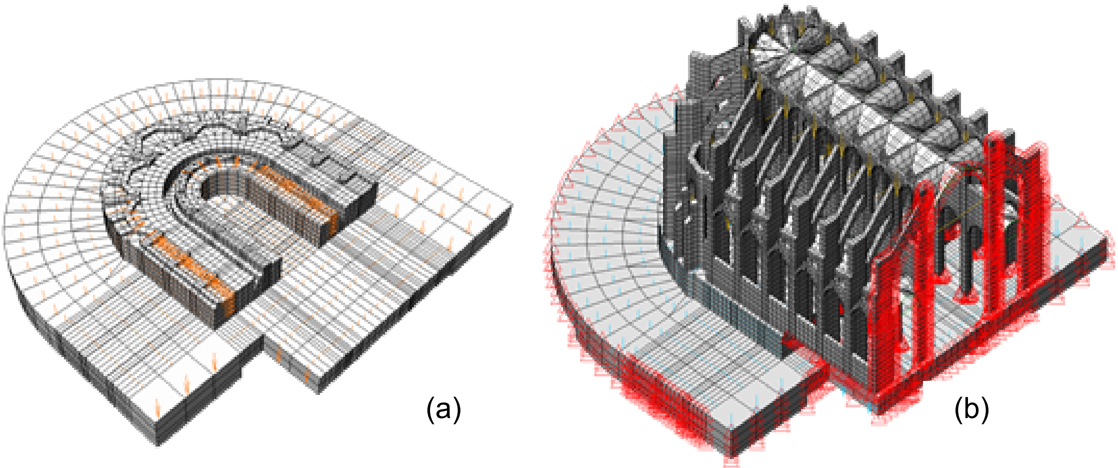


Figure 3 Model of soft soil and foundation (a) and global model (b)

According to the relative stability of the western part of the choir, the interface transept/choir has been constrained in displacement. The basis of pillars and buttresses were constrained too because they are settled on the stable roman foundations. It's important to notice that, although geometrical simplifications were necessary, inertia and cross-section area properties were carefully respected.

4.3 Materials

Due to a lack of knowledge about the characteristics of the walls of the Cathedral (no test results were available), we decided to consider each material as homogenous and linear elastic. Of course this kind of behaviour, only appropriate for the steel tie bars, is less appropriate when applied to masonry structures and soils.

Nevertheless, this kind of assumptions has already been used by recognized specialists like Professor G. Macchi (University of Pavia, Italy) involved in the study of the Pisa Tower (for which soils and masonries were interacting) and Professor P. Halleux (University of Bruxelles, Belgium) engaged in the engineering calculation of the Townhall Tower in Bruxelles.

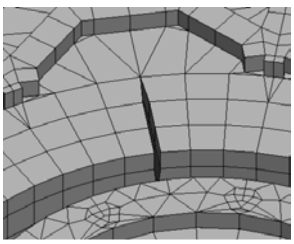


Figure 4 Initiation of a crack through node duplication

Moreover, a crack propagation process has been added to the model of the foundation. This is a discrete and iterative process based on the value of the maximum principal

stress : it is assumed that a crack appears in the most stressed zone if the tensile stress is greater than a given limit value. Initiation of a crack is simulated locally by duplication of one node into two nodes in the model (see figure 4). On the basis of this new geometry, a new calculation is performed and propagation of crack is simulated. This process continues until stabilization of the stress state is reached everywhere in the model.

The total model presents about 60000 nodes and 180000 equations : a reasonnable calculation time is a limitation criterium for the geometrical precision and the constitutive law. Although the model can be improved (geometrically and materially), it can give to the problem a good solution with correct understanding of the behaviour of the gothic foundation. Surprisingly, properties of materials have only limited influence on the trends given by the solution.

4.4 Preliminary results : new assumptions for the bedrock relief

A first study was performed with the assumptions reported by the experts concerning the bedrock relief. The results are not presented here but are just summarized as following : the model confirmed existing pathologies of the superstructure and a "special behaviour" not observed in the reality. After a lot of verifications, it was decided to reconsider the results of the geotechnical campaign and a new interpretation for the bedrock relief was proposed, taking into account some measurements previously put away of the study because considered as "out of range". It emphasized how important is the permanent interaction between assumptions and results in the special topic of ancient buildings.

4.5 Major results : possible scenario for the behaviour of the gothic foundation

4.5.1 Multi-step analysis

With the corrected bedrock relief, a full study was performed. The first finite element analysis gives the stress and deformation fields in the uncracked model (see figure 5). The stress distribution is used for the crack propagation process previously described. The observation of the deformations is quite interesting too. The trends (but not the absolute values) given by the simulation are the same as in the actual structure (see figure 5a in comparison with the experimental settlements illustrated on figure 2b).

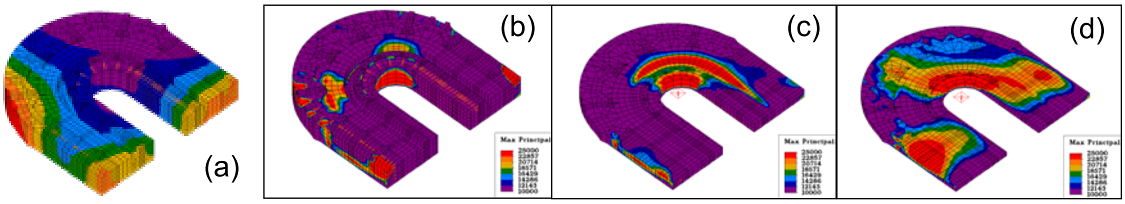


Figure 5 Uncracked model :deformations (a), max principal stress in the different layers of the foundation (b,c,d)

At each step, it is possible to verify the occurence (or not) of sliding at the interface between the model of the foundation and the model of the soft soil. This is done using a Coulomb's friction model. At the initial step (uncracked model), the main following phenoma are outlined :

- a comfortable safety against sliding
- some differential compression. The compression of the soft soil under the south part of the absydium is about twice the compression under the north part of the absydium. This particular behaviour was not noticed with the previous

assumptions for the bedrock relief and could explain the global overturning movement of the superstructure in the south-east direction.

From the initial step, the sequences of the crack process (for which major steps are illustrated in figure 6) appear as following :

A first crack front appears at the top face of the U shaped groove. This weak point is strongly loaded and, once the cracking is initiated, it quickly leads to a total disconnection along a J shaped line before stabilization.

A second front appears quite early on the bottom face (interior side) of the foundation, in the axis of the buttress B south. It seems to be caused by a bi-axial bending phenomenon affecting the gothic foundation. At the intersection place, high tensile stresses appear and lead to a crack. That crack initiation will become more and more important and further steps will show the apparition of some cracks initiations on the top face (interior side too) of the foundation. The phenomena lead to a total disconnection.

A third crack pattern is located between the spans A and B north. This front will create a total disconnection too.

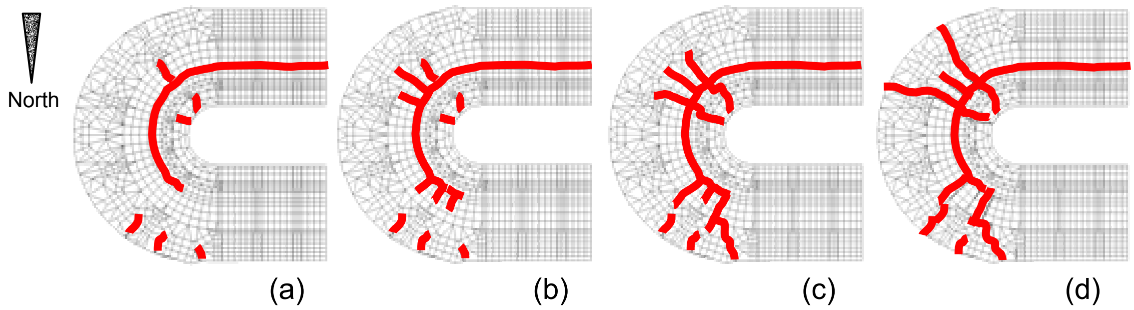


Figure 6 Major steps in the crack propagation process (a,b,c) , final step (d)

At the last step, the crack pattern illustrated on figure 6d is obtained. All the process has to be nuanced by the following remarks :

- Eventual sliding movement of some parts of the model is not taken into account. If the non-sliding condition previously discussed was easily verified in the beginning of the crack process, it is not totally verified in the last steps but the model is not able to manage this fact. So, at the final step, the soft soil is restraining some eventual movement of disconnected parts of the foundation and the opening of some cracks is probably unrealistically limited.
- High local vertical shearing in the soil is unallowed by the elastic nature of the material of the model. In reality, effective shearing will produce relative displacements.

Nevertheless, according to the model, it is suggested to retain the final damage of the foundation as characterized by three fronts of cracks leading to the formation of 5 disconnected foundation blocks (see figure 7).

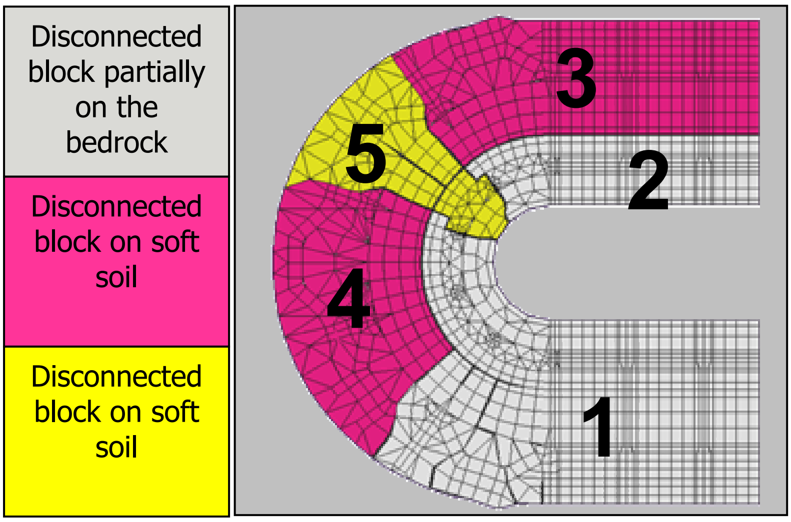


Figure 7 Final step in the crack propagation process of the gothic foundation

4.5.2 Possible global scenario

A possible explanation of all the disorders of the Cathedral can be summarized with the following cause–consequence organigram (see figure 9).

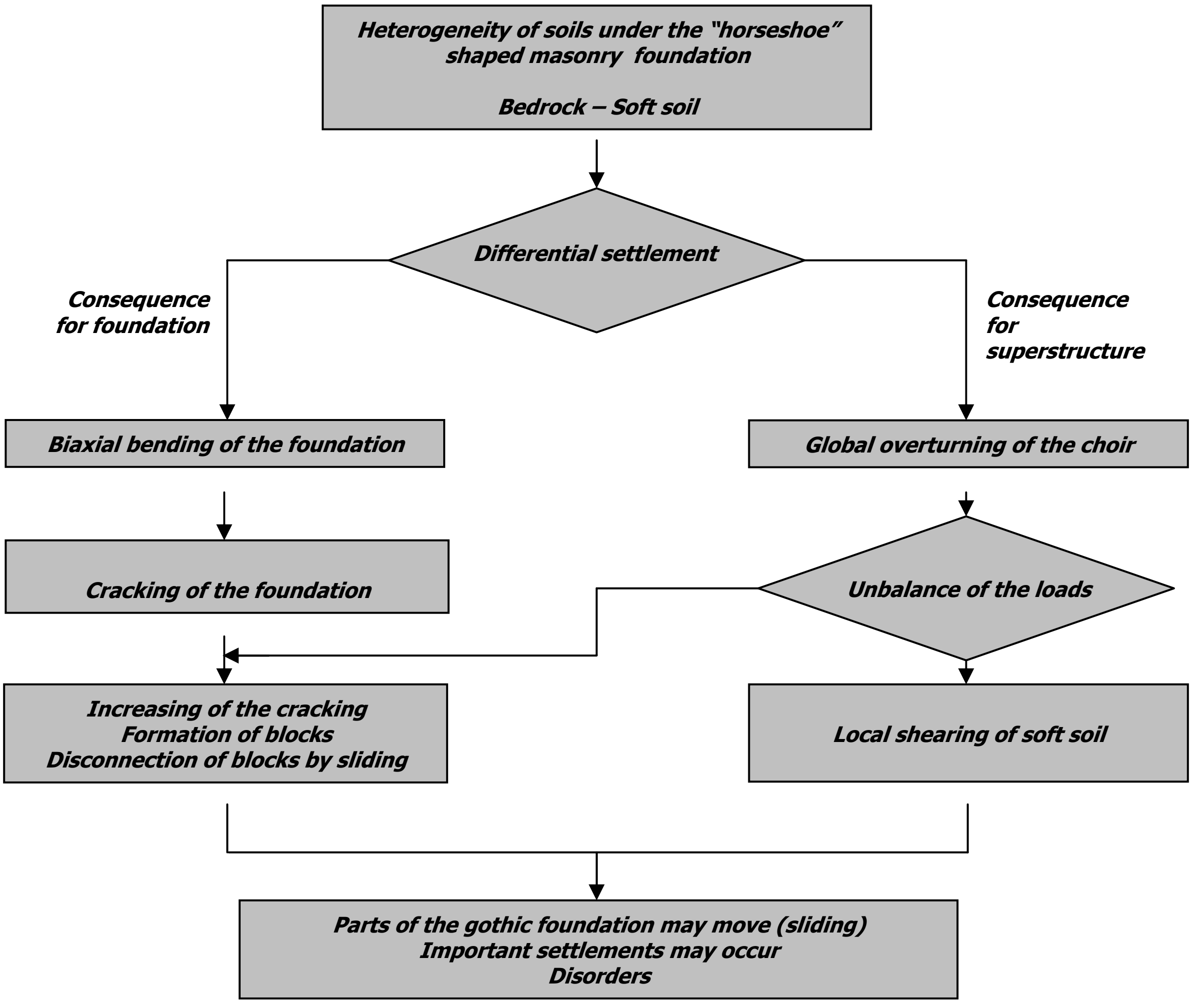


Figure 9 Possible global scenario to explain the disorders of the Cathedral

4.6 Complementary results : considerations about the superstructure

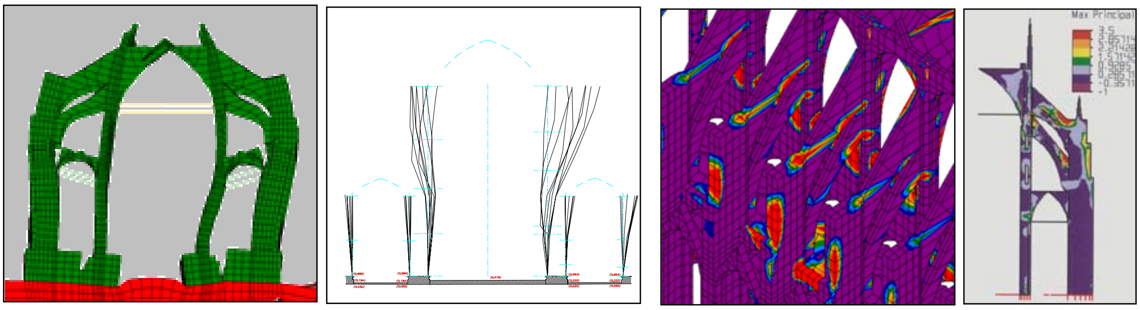
While this is not the major topic of this paper, some results concerning the superstructure are summarized. They are just presented to illustrate the convenient adequation of behaviour achieved with a simple model. We illustrate some particular points :

- Deformation of pillars : the model explains the dissymetry (more important deformation of the pillars located in the south-east part of the choir) noticed in the reality (see figure 10a and 10b).

- Crack zones in the walls : real cracks observed on the structure (triforium wall, flying-buttresses, vaults and arches) appear in the model.

- Rebuilt zone : any damage was found in reality in some zone strongly cracked in the model. Archeologists gave confirmation of complete rebuilding of this zone during the 19^{th} century.

- Behaviour of the flying-buttresses : convenient explanation of the pathologies affecting the flying-buttresses (see figure 10c and 10d).



(a) (b) (c) (d)

Figure 10 Transversal deformations (a,b), stress state in flying-buttresses (c,d)

5 Conclusions

This study concerns a finite element analysis performed on an heritage building. Using elastic constitutive laws for materials and a discrete iterative cracking process, previsions were made for the damaged state of the “horseshoe” shaped masonry foundation. Such previsions are important for their consequences on the superstructure. They constitue an efficient and helpful tool for engineers engaged in the preservation of the building.