THE GOTHIC CHOIR OF THE N-D CATHEDRAL OF TOURNAI (B) : STRUCTURAL BEHAVIOUR OF THE FLYING-BUTTRESSES.

D. Lamblin[1], L. Deléhouzée[2], L. Van Parys[3], T. Descamps[4]

[1]Professor, Dept of Civil Engineering, Polytechnic Faculty of Mons,
Rue de Houdain 9 - B-7000 MONS, daniel.lamblin@fpms.ac.be

[2]Archeologist, Cellule de Recherches en Histoire et Archéologie du Bâtiment, CRHAB,
Rue Vigneroulle 49 - B-5100 JAMBES, lfgenicot@skynet.be

[3]Assistant Professor, Dept of Civil Engineering, Polytechnic Faculty of Mons, laurent.vanparys@fpms.ac.be

[4]Assistant Professor, Dept of Civil Engineering, Polytechnic Faculty of Mons, thierry.descamps@fpms.ac.be

ABSTRACT

The gothic choir of the Notre-Dame cathedral of Tournai (World Heritage - UNESCO) has suffered several structural pathologies for a very long time. In order to prepare for a future restoration project, the civil authorities decided to launch an interdisciplinary research campaign aimed at understanding the behaviour of the building and the origin of the problems encountered.

After studying documents of the episcopal archives, historians have presented evidence that the problems affecting the choir are not recent: the signs of weakness were visible very soon after construction. From on-site (underground and above ground) investigations, archaeologists have confirmed the conclusions of the historians. Moreover, they succeeded in providing precise morpho-chronological information about the history of the gothic choir.

This paper presents the related FEM study, performed by the department of Civil Engineering & Structural Mechanics of the Polytechnic Faculty of Mons, on the basis of the historical and archaeological conclusions of the CRHAB. Thanks to the interdisciplinary approach of the cathedral, it is possible to study the building at each major step of its life. Observation of situations the engineers of the past were facing, helps us to understand or justify the (sometimes bad) solutions they proposed.

KEYWORDS: historical buildings, interdisciplinary research, FEM, flying-buttress

INTRODUCTION

Since the civil authorities have understood the necessity of preserving heritage buildings for the benefit of future generations, important budgets have been allocated to finance heavy restoration campaigns. Many historical buildings have been forgotten for decades and often, an interdisciplinary approach is necessary: archaeologists, historians and structural experts work together to understand the "building" and to propose some efficient solutions for the future.

The engineers, by coupling powerful calculation methods with efficient on-site investigations, can predict the structural behaviour of the building. This paper presents an application of such an approach, based on the Finite Element Method, to study the complex history over the centuries, of the gothic choir of the Notre-Dame cathedral of Tournai.

THE GOTHIC CHOIR OF THE N-D CATHEDRAL

The cathedral of Tournai (see Figure 1) is composed of three main parts, presenting a high architectural richness: a robust roman nave, a slender gothic choir and, between them, a "transition style" transept with five bell towers.

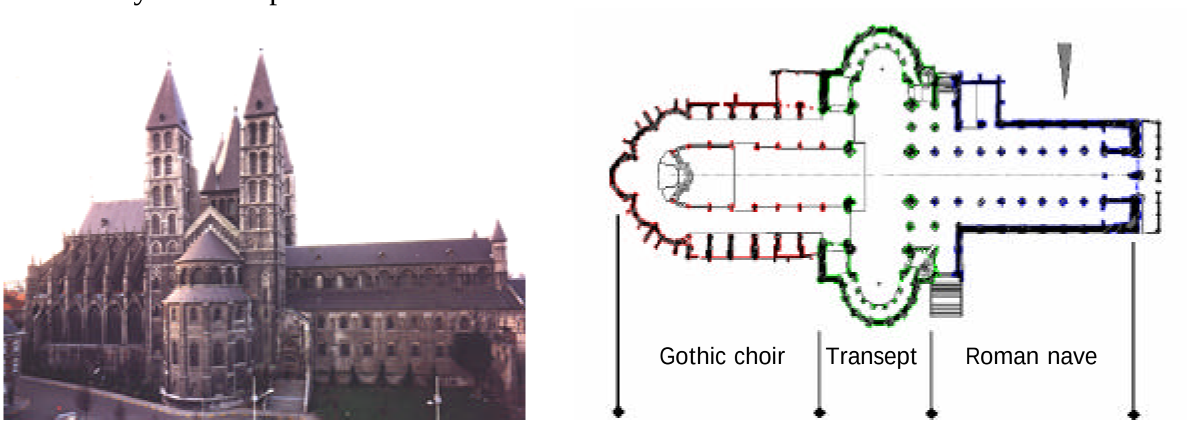

Figure 1 - The Notre-Dame cathedral: main parts

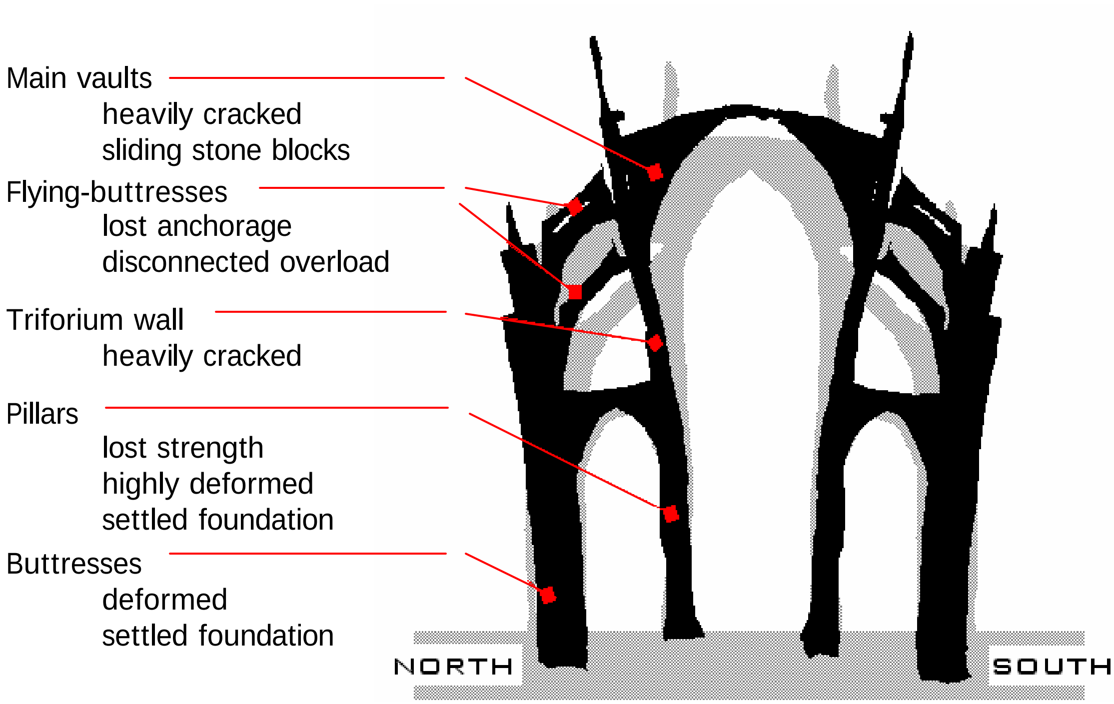

Figure 2 - The gothic choir of the cathedral: main structural pathologies

The structural pathologies affecting the nave and the transept are rather easy to understand. The ones affecting the choir are more complicated: most of the structural parts are affected as summarized on Figure 2. From a global point of view, the western part of the choir seems to be weakly damaged but pathologies become stronger when going from the transept to the absydium.

The settlement of the pillars and buttresses is as large as 180 mm while the clearance increase between opposite pillars of a same span reaches up to 800 mm.

PRELIMINARY STUDIES

A preliminary and very simplified FEM study of the choir has shown that most of the structural pathologies are explainable when imposing the observed settlement of the pillars and buttresses under self-weight. The analyses confirmed the major role played by the gothic foundation. Therefore, extensive geotechnical and archaeological investigations were launched and a better knowledge of the ground properties allowed the behaviour of the gothic foundation to be studied (FEM) [1]. Results explained the underground behaviour, but were not sufficient for a precise explanation of the particular problems concerning the flying-buttresses. Being aware of the usefulness of a specific FEM considering the history of the building, the civil authorities requested an interdisciplinary assessment of the buttressing of the gothic choir.

The episcopal archive fund of Tournai is very rich (few destructions along the centuries) and has been carefully explored by a team of historians. The erection of the gothic choir began in the beginning of the 13th century, partially on the foundations of a previous roman choir. On the basis of several documents, the historians assessed that, shortly after its completion, the gothic choir began to show signs of weakness. Strong structural interventions were necessary over the centuries: the addition of new structural elements (complementary pillars in the principal part of the choir, steel tie bars at the feet of the vaults, a second set of flying-buttresses under the existing ones, stone masonry overload on the flying-buttresses, ...) and total reconstruction (several buttresses, all the flying-buttresses, some walls,...) The recursive character of the numerous interventions made in time shows that the repairs have often been inefficient.

Archaeological investigations (below and above ground) launched at the same time confirmed the conclusions of the historians and allowed the rebuilt and repaired parts to be identified precisely. Moreover, they were able to propose some precise reconstitution (see Figure 3) for the three major steps in the history of the gothic choir. The initial configuration (13th century), comprised of one single openwork flying-buttress, was completed (14th century) by a plain flying-buttress erected under the existing one. This configuration was then modified (15th century) to obtain the actual one, presenting two plain flying-buttresses.

FIRST APPROACH : FLYING-BUTTRESS ALONE

According to the plastic theory of Heyman [2], the active thrust provided by a flying-buttress is located between two limiting values: the lower one corresponding to the passive thrust line and the upper one corresponding to the ultimate compressive strength. This section is concerned with the study of each flying-buttress individually, with the aim of understand the behaviour in the "passive configuration".

The geometry of the FEM model is based on very precise archaeological surveys and the study is performed with 2D plane stress elements (out-of-plane thickness being rather small). The material is considered homogenous and linear elastic. This kind of assumption has already been used by recognized specialists like Professor G. Macchi (University of Pavia, Italy) involved in the study of the Pisa Tower and Professor P. Halleux (University of Bruxelles, Belgium) engaged in the engineering calculation of the Townhall Tower in Bruxelles. The properties are computed on the basis of on-site investigations.

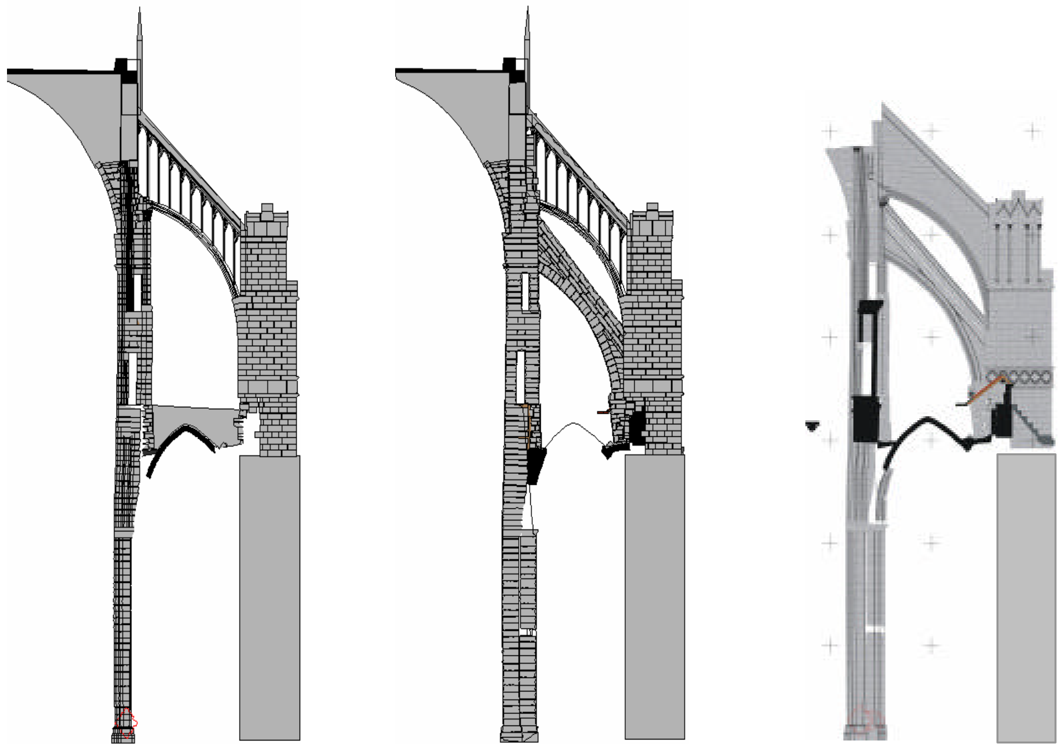

Figure 3 - Buttressing of the gothic choir along the centuries [after *L.Delehouzée*]

The **openwork flying-buttress** is a light construction composed of an arch, 11 slender small columns and a string course. The horizontal passive thrust is low (~27 kN) and the static study under dead loads shows the presence of zones of tensile stress. The structure is very sensitive to imposed displacements of the supports. Zones of high tension appear in the arch and string course and shearing in the small columns in the case of buttress vertical displacement (differential settlement), whereas high compression appears in the small columns in the case of horizontal displacement (bending deformation of the pillars). Moreover, the morphology of this flying-buttress seems to induce a global "brittle" behaviour.

The **lower plain flying-buttress** is composed of an arch completed by a masonry overload settled with no strong connection (no shear strength and overload able to slide). In the FEM study, short virtual truss bars connecting nodes of the upper face of the arch with nodes of the lower face of the overload were used to model the interface. The study was performed with an iterative approach: from one step to the next, virtual bars in tension were removed. This allowed the sliding of the overloads and the monitoring of shear and compressive forces.

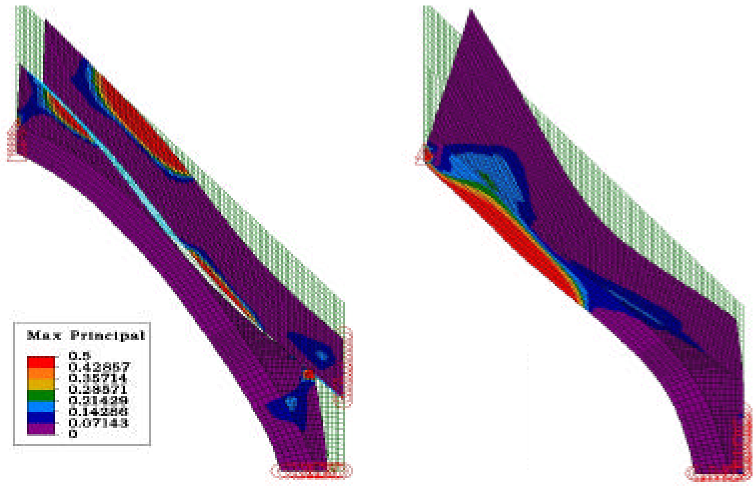

Figure 4 - Max principal stresses for disconnected and connected overload [daN/cm²]

The equilibrium configuration presents a disconnection between the arch and the overload leading to a horizontal passive thrust of 60 kN. The overload slides and 90% of the dead load is transmitted through the buttress. The disconnection and sliding of the overload are favourable, as the flying-buttress is then mostly submitted to compression (see Figure 4 - left). If the disconnection and sliding of the overload are not allowed, the monolithic construction is subject to bending moment (see Figure 4 - right) and behaves like a beam on two supports. This configuration is less favourable: the flying-buttress presents a lower horizontal thrust (~ 20 kN) and a high level of interaction at the interface between the arch and the overload. Imposed settlement increases the overload disconnection, decreases the passive thrust and leads to the appearance of zones of tensile stress at the inner surface of the arch.

The **upper plain flying-buttress** has been studied in the same way. The results obtained were similar: disconnection and sliding of the overload leading to a horizontal thrust going up to 60 kN and 75 % of the dead load being transmitted through the buttress.

SECOND APPROACH : FLYING BUTTRESS IN ITS CONTEXT

This section is concerned with the study of the various configurations of buttressing: the flying-buttresses are considered in their context.

The **initial configuration**, imagined by the gothic architects, is very important to consider: this seems to be the origin of most of the pathologies observed nowadays. It is composed of very slender pillars supporting the main vaults. These are buttressed by the openwork flying-buttress transmitting the load to a massive buttress. Between the pillar and the buttress is the vaulted ambulatory (see Figure 2). Above these vaults, a robust (and unusual) diaphragm arch connects the pillar and the buttress. The upper part of the choir (triforium wall) is build as a cantilever and perforated by two service ways.

The FEM study considers the model of half a span. The geometry is based on precise archaeological surveys, the material properties were obtained as previously described. The flying- buttress is connected to the rest of the structure with short virtual truss bars, allowing the forces transmitted through them to be monitored.

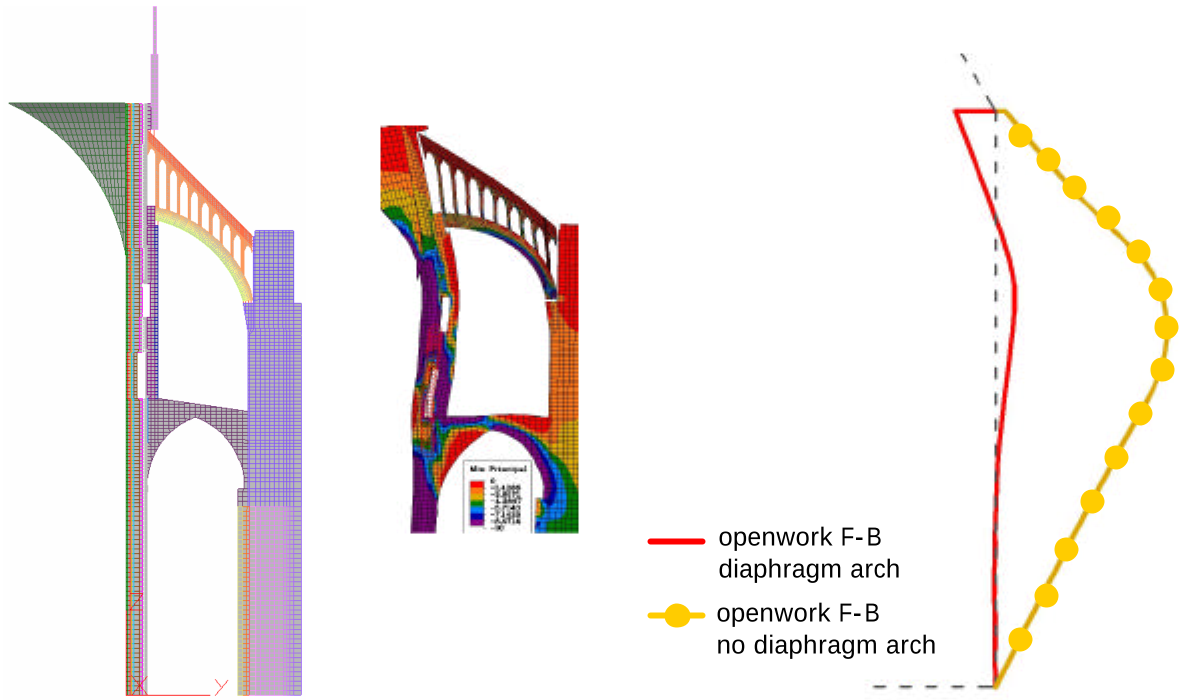

Figure 5 - Initial configuration: 2D model and synthetic results

It appears (see Figure 5 - left) that the openwork flying-buttress is placed too high to balance the vault thrust: the force is transmitted obliquely in the pillar (between the service ways) and joins the massive buttress through the diaphragm arch which acts as a flying-buttress. Removing the diaphragm from the model induces deformations 10 times larger (see Figure 5 - right).

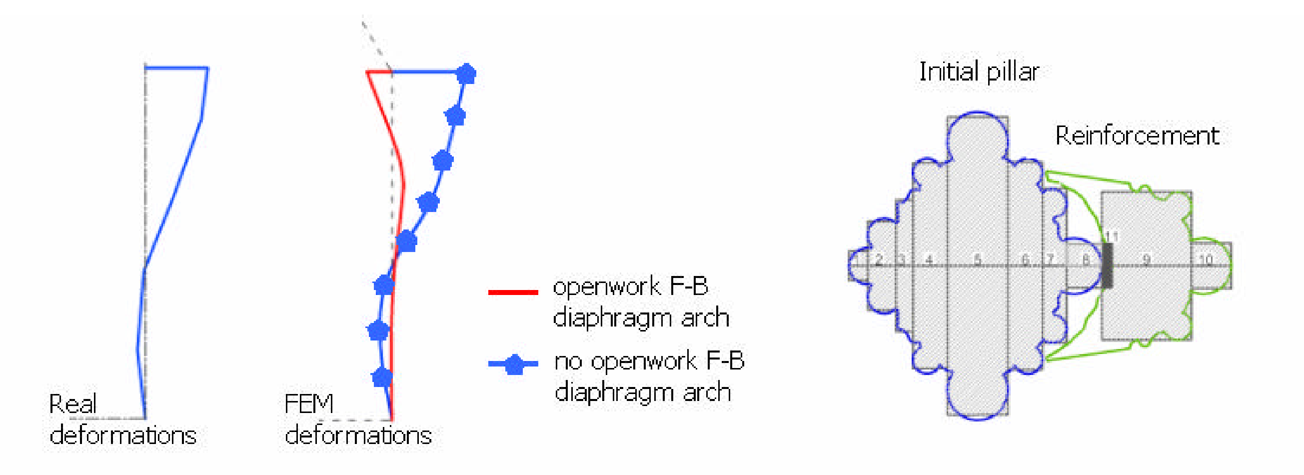

Figure 6 - Deformation of pillars (left) and pillar stone reinforcement (right)

The assumption of late vaulting of the choir, usually proposed to explain the observed bending deformations are not confirmed by the study. A better explanation seems to be the bad localization and design of the flying-buttress (active thrust of 60 kN to balance a vault thrust of 170 kN). A model without the flying-buttress presents deformation globally similar to the real ones (see Figure 6), the particular asymmetry being explainable by underground phenomena [1].

The **intermediate configuration** is derived from the situation that the structural experts of the 14th century were facing. They decided on several interventions: to balance the bending deformation of the pillar (see Figure 6 - left), they built a complementary plain flying buttress, localized just under the existing openwork one. They also decided to reinforce the very slender pillar by the addition of a complementary one (see Figure 6 - right). To achieve this aim, they had to demolish the half of the ambulatory vault (which thus became asymmetric) and the diaphragm arch whose major influence seemed to be misunderstood (the choir was, in fact, mainly buttressed by the diaphragm arches) .

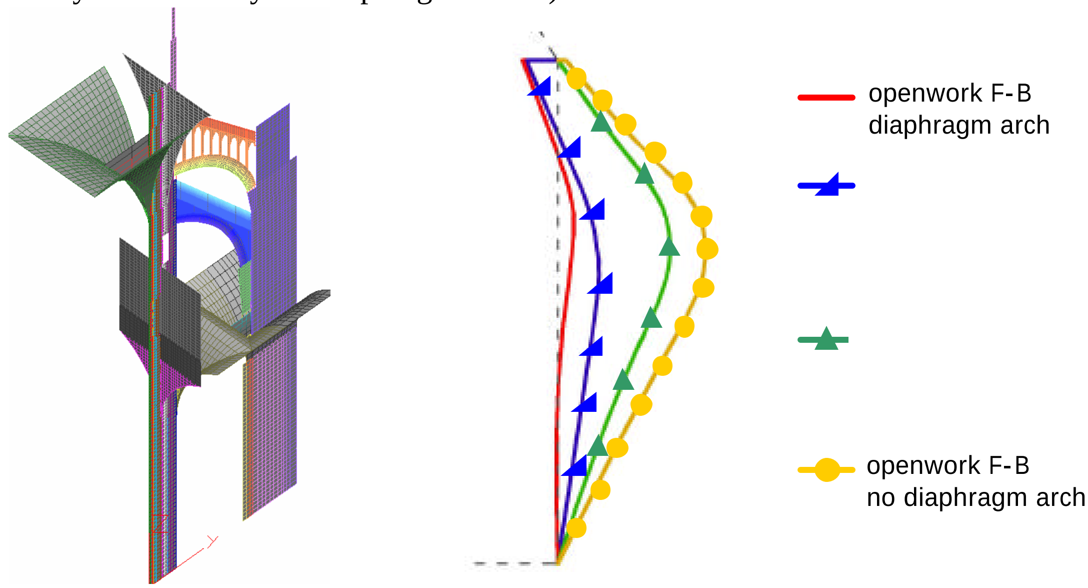

Figure 7 - Intermediate configuration: 2D model and synthetic results

The main conclusions are summarized in Figure 7: the disadvantages induced by the suppression of the diaphragm arch are compensated to a small degree by the doubled pillar influence (green curve), itself improved by the influence of the new flying-buttress (blue curve). The plain flying-buttress is correctly localized: the equilibrium state presents a disconnection between the arch and the overload, no tension in the arch and an active thrust of 150 kN. This high efficiency causes a particular deformation pattern leading to an extension of the openwork flying-buttress that can then only present its passive thrust (~27 kN). The presence of the overload on the arch of the plain flying-buttress is favourable: it reduces the curvature of the arch and makes it become more stable but does not really act on the active thrust. The high curvature observed on the unique flying-buttress presenting no overload confirms this consideration.

The **actual configuration** can probably be explained by the results observed, under wind loads, on the intermediate configuration: the plain flying-buttress is really efficient while the openwork one presents a poor behaviour and numerous zones of high tensile stress that have probably led to the destruction of this flying-buttress. Once it disappeared, the openwork flying-buttress has been replaced by a plain one, at the same place. The structural experts also decided to add pinnacles at the top of each buttress, to fill one of the service ways with stone masonry and to anchor steel tie bars at the base of the vaults.

The main conclusions are summarized in Figure 8: the lower flying-buttress presents a disconnection of the overload leading to a low active thrust (80 kN). No tension is observed in the arch. The upper flying-buttress shows disconnection and sliding of the overload and presents its passive thrust (60 kN) and important tensile stressed zone at the inner face of the arch. The connections between the flying-buttress and the buttress are particular: the lower one is supported on a corbel (favourable) while the upper one is only interfaced by a vertical mortar joint and the deformations lead to a punctual support of the arch.

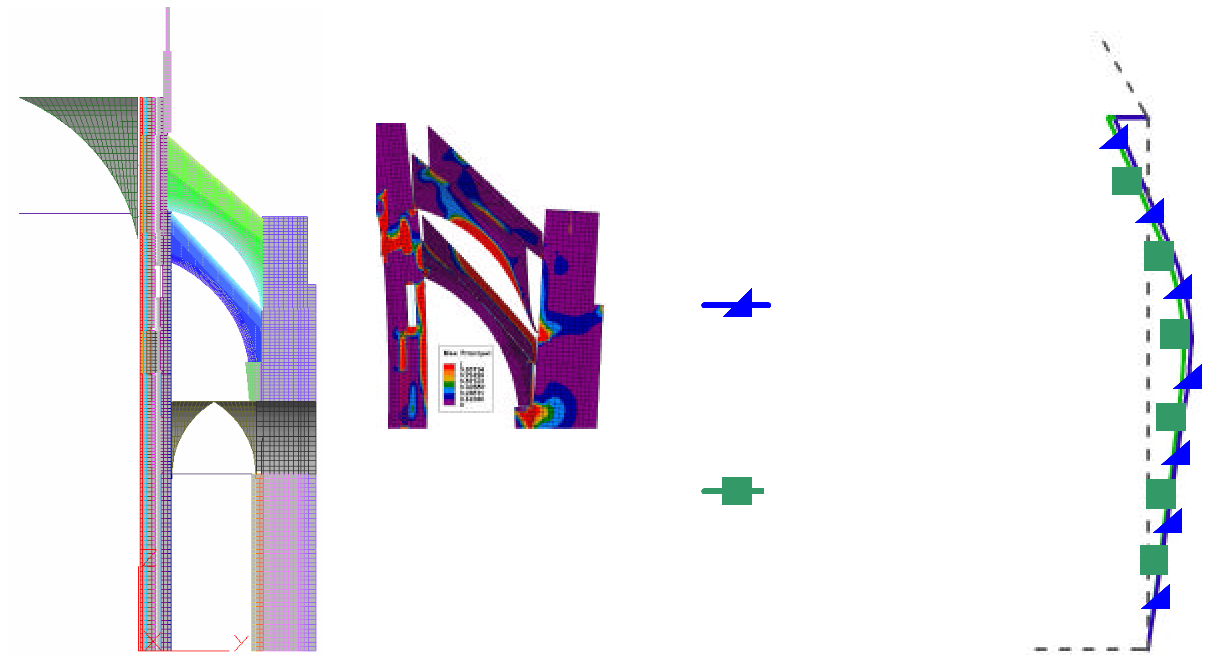

Figure 8 - Actual configuration: 2D model and compared results

The model can be compared with the actual observations summarized on Figure 9: open interface with the pillar (Upper Flying Buttress), disconnection and sliding plane of the overload (Lower Flying Buttress), curvature of the overload (LFB), open interface with the buttress (LFB), wide open joint at the inner face of the arch (LFB), wide open joint at the top face of the overload (LFB).

The influence of wind loads is similar to the previous configuration (the lower flying-buttress adapts itself and the upper one presents a critical behaviour) but the deformations induced are more important.

Figure 9 - Actual configuration: several views of flying-buttresses

A study performed on a hypothetical configuration (see Figure 10) without the upper flying-buttress confirms its relative inefficiency: under wind loads, the thrust in the lower flying-buttress is increased while the deformations are reduced!

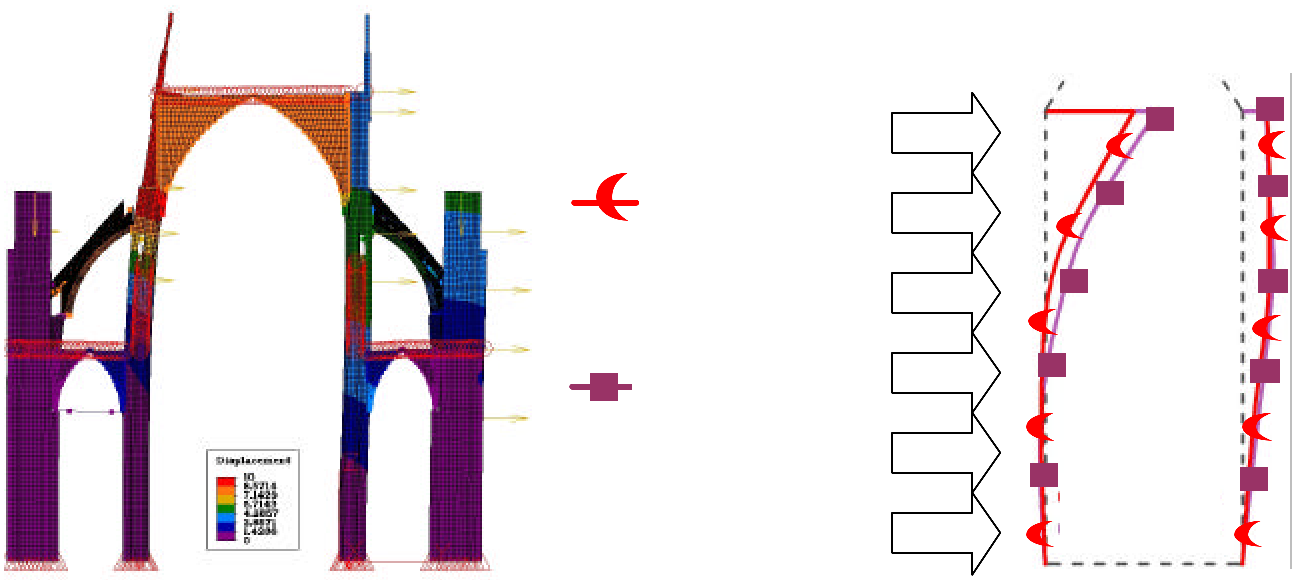

Figure 10 - Hypothetical configuration: 2D model and synthetic results

CONCLUSIONS

This paper presents FEM studies performed in an interdisciplinary framework with a view to understand the history of the buttressing of the gothic choir of a heritage building.

The models are relatively simple: 2D approach, homogenous linear elastic material. Moreover the second order effects are not taken into account: each model is studied from a hypothetical undeformed geometry.

The results present useful explanations for the interventions made by structural experts over the centuries.

The analysis of the actual configuration shows that the lower flying-buttress is well adapted (localization, design) and seems to be able to ensure alone the buttressing of the choir.
The study presents interesting ways to follow for a future restoration or stabilization campaign: favour the equilibrium configuration (disconnections of overload), allow the horizontal movements, constrain the vertical settlements,...

The results of this simplified preliminary study are encouraging and further numerical investigations are now in progress with the powerful ABAQUS software, including 3D elements, non-linear material behaviour and contact constraints.

ACKNOWLEDGMENTS

The authors want to thank the Professor L.F.Génicot (CRHAB - Belgium) for his precious help and the Province of Hainault (Service of Techniques and Buildings) for its support of this study.

REFERENCES

1. L. Van Parys, D. Lamblin, G. Guerlement, S. Datoussaïd and T. Descamps *The behaviour of the gothic foundation of the OL-Cathedral of Tournai (Belgium).* In Proc. Of 13th International Brick and Block Masonry Conference, July 4-7, Amsterdam, 2004
2. J. Heyman *The Masonry Arch*, Ellis Horwood Limited, Chichester, 1982