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Wind strength of Gothic Cathedrals

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ABSTRACT

Aim of the paper is the evaluation of the wind strength of one of the most amazing structural typology of the Middle Age, the Gothic Cathedral. Among his most significant structural problems, wisely solved by the ancient builders, there was the need to realize structures with high lateral resistance, in order to counteract the action of the wind. Deformations of the cathedral under the wind action are negligible, both in longitudinal and in transverse direction, owing the high stiffness of the structure. Wind action is therefore essentially *static* and it can be represented by a suitable distribution of horizontal forces. In this framework the paper evaluates the collapse wind load according to the kinematic approach of the Limit Analysis considering various failure mechanisms as, among them, the semi-global mechanism, involving only the leeward side and the global, interesting both sides of the structure. The analysis is performed making reference to a cathedral modulus similar to that of the Cathedral of Notre-Dame of Amiens, one of the most important examples of Gothic Cathedrals. The paper shows that the stone skeleton of these cathedrals is able to sustain the action of fierce winds whose intensities are larger than those prescribed by actual codes.

1. Introduction

The skyline of plains of the North Europe is marked by the high profiles of ancient cathedrals rising above the housings of cities and towns. We can immediately image the intensities of winds blowing through these plains that strike the cathedrals facades and their upper structures. It is not so difficult to understand the challenges facing architects and engineers of the time to build these stone constructions able to withstand the actions of these fierce winds.

The paper aims to inquire into this subject, trying to confirm the skill of the old builders. Specifically, it examines the lateral strength of the cathedral (Fig. 1), the weakest side to the wind action compared to the longitudinal one. The cathedral structures, in fact, are much stronger in the longitudinal direction owing to the presence from one side, of the heavy façade, and of the curved apse from the other.

In the literature, the methods used to study masonry structures can be divided into two main categories: those based on the Limit Analysis, aimed to the collapse load assessment and those based on the application of the Finite Element Method, (see for example [5–7]). The first approach moves in the no tension framework and simplifies the real geometry of the structure, considering only its more relevant components. In this context, the studies can be conducted by means a static (as in [8–11]) or a kinematic approach (as in [12–14]). Furthermore, the real response of the masonry material is properly considered assuming the Heyman model.

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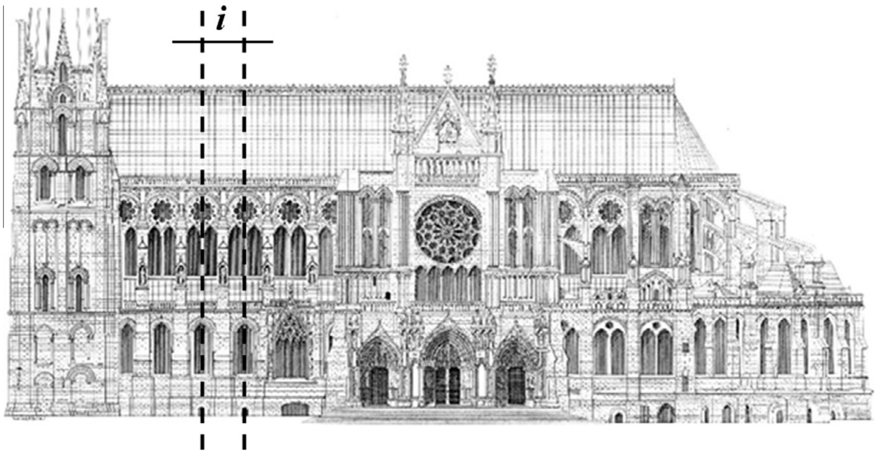

Fig. 1. The side view of a cathedral and the considered transverse modulus.

According to the second approach, the actual geometry of the structure is considered and, at the same time, the real non linear behaviour of the material can be taken into account. This method allows to evaluate the limit strength of the entire structure but, due to the great complexity of the model, there is the risk to evaluate the failure load of only a small component of the system, without grasping the real significance of the collapse of the structure. The used non linear software can present convergence problems and many trials are required to assess the result. These considerations show the difficulties that may be encountered using non linear software to analyse the behaviour of complex structures and the corresponding need for time-consuming analyses. Conversely, in case of a successful analysis, there is the result to have analysed a complex structure in all its aspects.

This is the reason that has induced the authors to evaluate the lateral wind strength of the cathedrals considering the direct application of the Limit Analysis and considering only a segment of the nave, having a length equal to the longitudinal piers span and representing the essential structural component of the cathedral. All the possible failure mechanisms are properly considered and the research of the minimum value of the various load multipliers assures to obtain a proper value of the critical wind velocity.

The analysed cathedral has a geometry similar to the Cathedral of Notre Dame in Amiens, one of the tallest in Europe. Fig. 2 shows a comparison of the sectional geometry of three of the more important Cathedrals of France.

The study adopts the rigid no-tension constitutive model of the masonry, with no sliding and no material penetration, firstly introduced by Heyman [3]. In this framework the collapse load of a masonry structure is related to a failure mechanism, kinematically compatible according to the Limit Analysis assumptions.

The cathedral of Amiens is composed by a central nave and two lateral aisles (Fig. 3). The church has a wide apse, divided into four sectors, and an ambulatory with seven side chapels. The structural frame of the Cathedral is a complex system in which all its elements (vaults, piers, buttresses, flying buttresses) are involved in the possible failure mechanisms triggered by wind action. In the paper, the study concerns only the transversal direction because it represents the weakest side of the Cathedral to the wind action. Moreover, the structural regularity along the longitudinal direction, allows to consider only a transverse segment instead of the entire building. This reference segment has a length equal to the distance between two consecutive piers (Fig. 1).

This type of modelling, which constitutes an innovative aspect of the paper, strongly simplifies the analysis and lets to come quickly to the solution of the problem, without using complex and onerous computational tools.

2. The considered cathedral transverse modulus

The analysis considers a transverse segment of the cathedral having length equal to the longitudinal span of the piers flanking the nave. A wide cross vault, sustained by upper windowed walls, spans the central nave. These walls, in turn, are sustained by longitudinal arches spanning between piers bordering the nave. Figs. 4 and 5 show a three-dimensional view of the considered transverse modulus and of the windowed internal wall.

The heads of the piers and the springings of the central vault are both connected to large external buttresses through two orders of flyers. The lateral aisle vaults are sustained by piers and by external side walls. Fig. 6 shows the geometry of the considered sectional modulus with the corresponding measure lengths.

A pinnacle has been considered placed on the top of each buttress towards the outside. Even if the pinnacle does not produce a noteworthy effect on the overall stability of the underlying buttress, it increases the frictional strength contrasting the sliding failure of the top portion of the buttress [15].