Study of mechanical compatibility at the mortar-block interface in a heritage building

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Résumé :

Ce travail a pour objectif de modéliser l'ensemble mortier/bloc et d'analyser la potentielle occurrence de problèmes mécaniques aux interfaces en présence d'une éventuelle incompatibilité. L'étude prend comme support un bâtiment historique au Maroc. Les auteurs choisissent une cellule représentative de la construction et procèdent à une simulation numérique, étudiant la répartition des contraintes dans la maçonnerie. Pour mener à bien ces analyses, les caractéristiques mécaniques (Module de Résistance et Module d'Elasticité) sont obtenues au moyen de techniques non-conventionnelles adaptées au domaine de la Conservation du Patrimoine qui sont brièvement décrites. Le scenario retenu pour l'étude concerne un mur porteur restauré au moyen d'un mortier non adéquat. Le but des simulations est de comparer la répartition des sollicitations internes entre la situation d'origine et la situation restaurée afin de quantifier les risques, pour les matériaux devant être conservés, liés au phénomène de « déviation de contraintes » et justifier ou non l'attention particulière à porter sur le choix d'un mortier spécifique à la restauration de ce bâtiment.

Abstract :

This research work aims at modeling the mortar-block assembly for analyzing the potential occurrence of mechanical problems at interfaces as the consequence of an eventual incompatibility. The study considers a heritage building located in Morocco. The authors focus their attention on a representative part of the building and perform numerical simulations, studying the stress repartition inside the masonry. For carrying out efficient analysis, the mechanical characteristics (Modulus of Resistance, Modulus of Elasticity) are collected through non conventional testing techniques dedicated to the field of Heritage Conservation that are briefly described. The scenario considered in the proposed study concerns a bearing wall restored with a non adequate mortar. The goal of the modeling works is to compare the repartition of internal solicitations between the original situation and the restored one in order to quantify the risk, for materials that should be conserved, associated with the "stress shielding" phenomenon and to justify the particular attention to be paid for the choice of a specific mortar for interventions to be carried out on the concerned building.

Mots clefs: masonry, numerical simulation, compatibility, stress shielding

1 Introduction

Masonry has been used for centuries in many places around the world. Most of the master pieces of our heritage are then erected with this material. For several reasons, these heritage structures should be preserved in order to be transmitted to following generations. Although they may appear trivial, restoration works are easily impacted by parasite problems associated with (essentially mechanical) incompatibilities between conserved and brought materials. These problems affect, economically and technically, the durability of the operations and constitute a point of interest for people engaged in structural mechanics.

2 Heritage masonry: specificities, weaknesses and challenge

Erectable with many types of bricks or stones with mortar joints according to varied patterns, the masonry concept concerns a wide range of building materials that are characterized by heterogeneous mechanical behavior [1]. Based on old constituents and ancient techniques (even if the know-how could be of advanced level at their construction period), heritage masonry may suffer of low mechanical properties still restricted by degradations induced by aggressive environments or exceptional conditions to which they are exposed [2,3]. In order to preserve ancient structures, restoration campaigns will generally opt for the replacement of altered parts by more reliable ones. Such kind of works carried out on masonries may sometimes concern bricks or stone but, in almost any case, will lead to partial mortar replacement (at least pointing operations). A specific attention should then be paid in the prescription of the works: contemporary elements should achieve a sufficient compatibility (mechanical, aesthetical, …) with the ones that are kept.

3 Non conventional data acquisition on materials in heritage buildings

In order to better document the problems of incompatibility between contemporary mortars and old masonries, the characterization of mechanical properties is of crucial interest in the approach of the subject. Nevertheless, extracting great quantities of materials within a structure whose value justifies the conservation in order to perform conventional characterization tests is a delicate and discussed spot. For the needs of the present research, the authors rely on experimental devices which make it possible to collect mechanical data on materials (compressive strength through the Modulus of Resistance and rigidity through the Modulus of Elasticity) through very few destructive approaches, namely:

1- “Translational Cutting Test” [3], to obtain the properties of resistance of materials. Not usual in classical material mechanics, it is widely used in the petroleum industry. It consists in tracing at the surface of a sample by removing successively thin layers of material with a rectangular Polymer Diamond Coated cutter of width w, a groove at constant shallow depth d. The cutter is inclined by an angle θ and is displaced at constant horizontal velocity v. The magnitude and inclination of the force F acting on the cutter are accurately measured and recorded during the test. Thanks to a dedicated phenomenological model, the Modulus of Resistance of the tested material may be computed from the relationship between the recorded force and the destroyed section. This technique is characterized by its simplicity, its time efficiency, the measuring accuracy and the main characters of the test which is relatively not very destructive due to the limited quantity of the necessary sample for the realization of the test as well as not dependent on the experimental procedures and analysis compared to the type of studied materials.

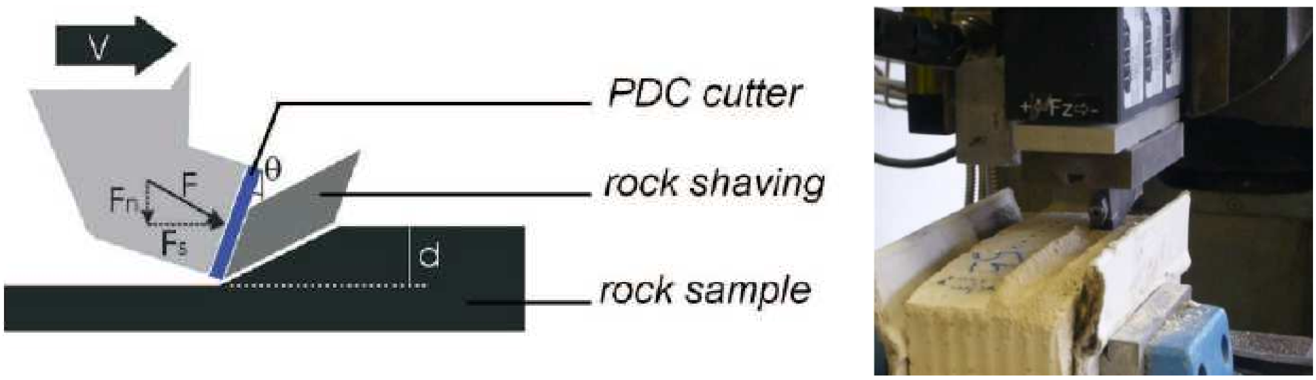

FIG. 1 - Schematic action of the PDC cutter (left) and experimental device at UMONS (right)

2- “Pulse Sonic Test” [4], to obtain the properties of rigidity of materials. Usually encountered in classical material mechanics where it is used in many fields, it relies on the well-known relationship linking the sound velocity inside a material with the dynamic version of the Modulus of Elasticity. Many experimental devices are commercially available: an emitter sends a sonic pulse on a given location at the surface of the material, a receiver detects it at another place and embedded computer-aided facilities allow determining the sound velocity based on the distance between emitter and receiver.

4 Masonry typology for present study

Typical of systems that may be encountered in Morocco, the masonry pattern constituting the minaret walls of AL MASJID AL AADAM Mosque in the old medina of Safi town (Figure 2) is chosen as starting point for the present study, focusing on potential restorations that would affect the front wall. In its preliminary shape, the proposed parametric study will rely on numerical simulations carried out on an elementary cell that is representative of the masonry encountered in the minaret wall (Figure 3).

FIG. 2 - Al Masjid Al Aadam rebuilt in 1807

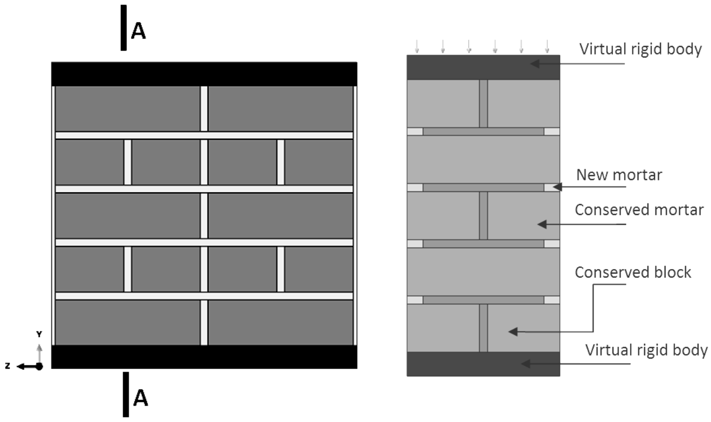

FIG. 3 – elementary cell: front view (left), section (right)

The proposed method is general: once developed, it is directly transposable to any other masonry pattern concerned by restoration operations where contemporary mortar is brought. The elementary cell is composed of the conserved elements (block and mortar) and of the new mortar that is used for pointing both faces of the considered wall after weathered mortar material has been removed on a 2 cm depth. The preserved blocks are parallelepiped elements of 9 x 6 x 19 cm^3 and all the joints (head joints and bed joints) present a thickness of 1 cm. Due to its position inside the minaret wall, the cell is assumed to be impacted by a static load pressure of 10 daN/cm^2, taking the weight of above elements (wall and flagstone) into account. For replicating the natural confinement acting on the cell while circumventing edge effects, rigid plates are placed on the superior and under the inferior face of the elementary cell with hard contact and friction without sliding conditions and continuity conditions are imposed on lateral facets of the cell. Numerical simulations are performed with SIMULIA ABAQUS software [4], coupled with Matlab which manages the parametric study (see below) and controls the ABAQUS calculation files. A tridimensional model is considered. In this preliminary approach, homogeneous and isotropic linear materials are considered for the simulations although more complicated studies (even with damage for blocks and/or mortar) are in progress.

5 Simulated scenario

In classical conservation approaches, repointing is a restoration operation that will concern joints (usual weak point of the structure) once they will have reach a given degree of alteration. The intervention consists of the digging of the joints manually or with a mechanical tool. According to their cohesion, the adherence and the state of degradation, the joints are dismantled on 1 to 3 cm of depth (in our scenario 2 cm) in order to guaranty a satisfying embedding for the new mortar that will be brought. Before repointing, masonry will be washed by brushing and often vacuum-cleaned with compressed air or high-pressure water flows depending on the friability of materials. Once the surface of the joint humidified, the filling must be made following distinct steps to maximize adherence and avoid any possible shrinking of the new mortar.

Mechanical incompatibility problems associated with repointing operations intervenes in relationship with the recourse to great resistance and/or great stiffness contemporary mortars compared to those of old block and mortar. The usage of inappropriate binders (nervous cement, industrial limes, …) in mortar mixes is the crucial problem of the 20th and 21st centuries. It may give birth to mortars that are not adapted to the “work” of the old buildings. In the short-term, the stress shielding phenomena has to be feared as it creates zones with stress increase and can potentially promote damages in sensitive blocks (Figure 4). In the long-term, a mortar that is too rigid will not be able to follow the displacement of the structures over the years; tensions will appear between the blocks and the mortar, mechanically affecting the structural behavior of masonry.

For helping practitioners to orientate their day-to-day practice, the authors undertook to determine range of parameters associated with limit state configurations. Based on such boundary knowledge, it becomes possible to quantify practical risks associated with situations that are faced. In the proposed parametric study, the fixed morphology of the masonry cell will be considered under fixed loading but the Modulus of Elasticity of the new mortar will be modified (between 1 and 30 times the MOE of conserved mortar) for several values of MOE for the conserved block (between 40 and 120 times the MOE of conserved mortar). Such an approach is likely to highlight the occurrence of the stress shielding phenomenon.

Designation of Material	Modulus of Elasticity [daN/cm^2]	Poisson's ratio[-]	Density [kg/cm^3]
Conserved mortar	3 000	0.25	0.0020
Conserved block	40 x 3000 → 120 x 3000	0.25	0.0020
New mortar	1 x 3000 → 30 x 3000	0.25	0.0020

Tab. 1 – Mechanical properties of various materials used in the parametric modeling

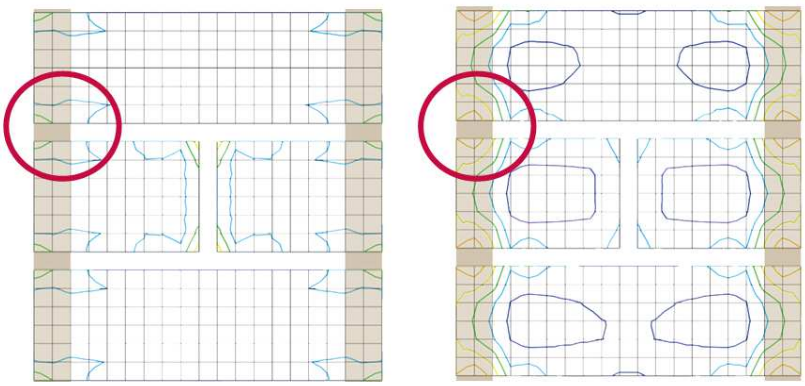

FIG. 4 – Stress shielding scheme: masonry repointed with identical mortar (left) or too rigid mortar (right)

6 Preliminary Results

With regard to field observations, the present study presents evolution of results around edges of blocks concerned by the restoration process. The treatment of the results of the simulation are involved for a local interest volume on the corner of the block, see (figure 5)

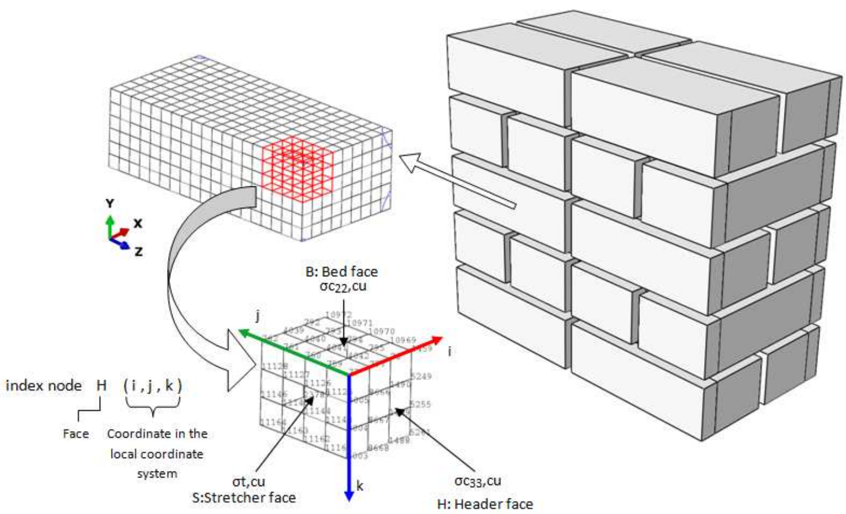

FIG. 5 – schematic view of the elementary cell and local interest volume for results visualization

For each pertinent face of the local interest volume, the evolution of stresses associated with specific damage patterns are plotted in Figure 6, Figure 7 and Figure 8. The maximal tensile stress on the Stretcher face may be responsible for crack initiations while compressive stresses for Head and Bed faces could eventually lead to crushing if blocks are composed with weak or weathered material. The presented results of these preliminary investigations outline the stress shielding phenomenon may take place under specific range of properties and, further than some boundaries, no critical evolution should be feared any more. Such considerations may now be used as guidelines for the setup of advanced simulations that are now in progress, namely taking damage into account with the Barcelona Model implemented in ABAQUS SIMULIA.

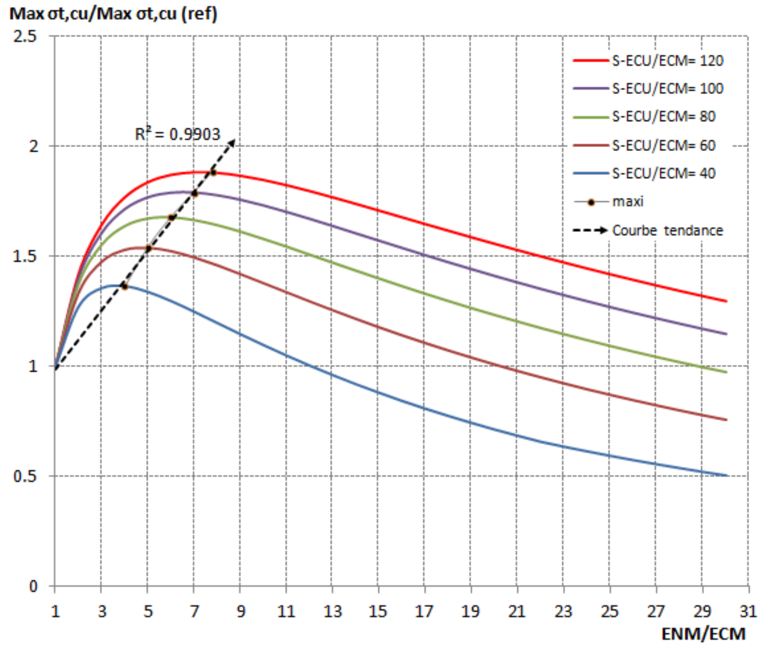

FIG. 6 - Evolution of ratio “max tensile stress / max tensile stress (ref before restoration)” for Stretcher face (S) of local volume, with the ratio E_{NM} / E_{CM} for several E_{CU}/E_{CM} values and under fixed loading

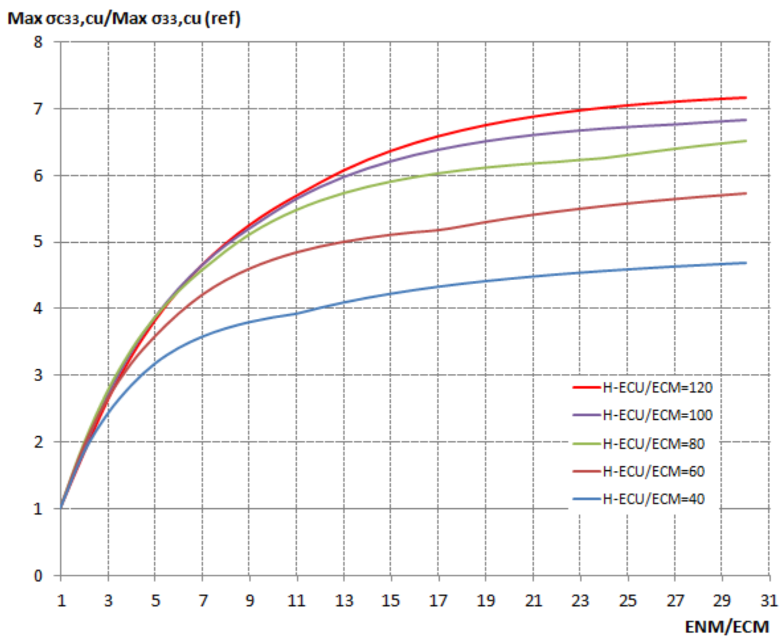

FIG. 7 - Evolution of the ratio “compress stress max / compress stress max (ref before restoration)” for Header face (H) of local volume, with the ratio E_{NM}/ E_{CM} for several E_{CU}/E_{CM} values and under fixed loading

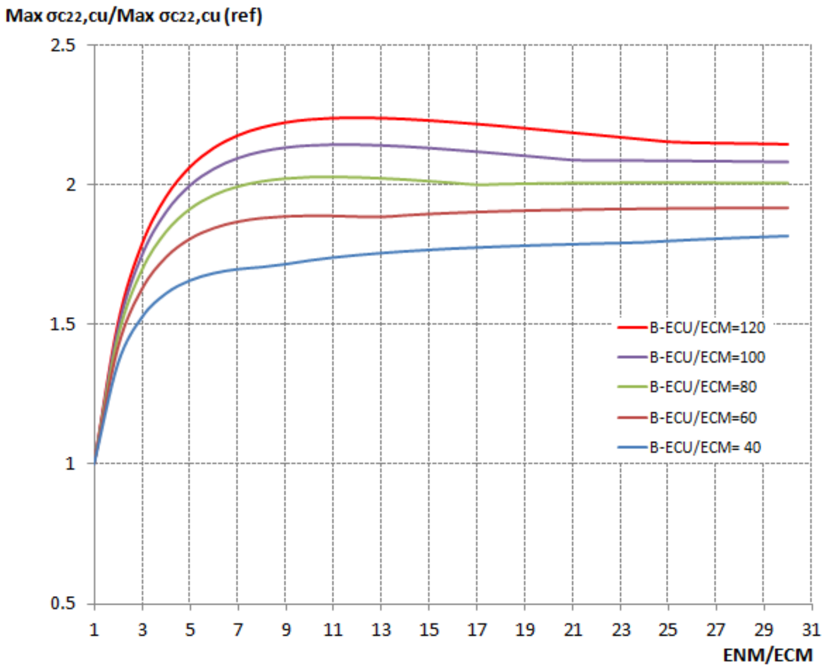

FIG. 8 - Evolution of the ratio "compress stress max / compress stress max (ref before restoration)" for Bed face (B) of local volume, with the ratio E_{NM}/ E_{CM} for several E_{CU}/E_{CM} values and under fixed loading

7 Conclusions and further works

Although mechanical incompatibility plays a great role in the durability associated to restoration operations carried out on heritage masonry, the current recourse to trial & error approaches is not a fatality. The present work proposes preliminary results showing that numerical simulation may be used for documenting the situation faced by practitioners. Since these results are still partial, no strong conclusion may be edited. Nevertheless, encouraged by the presented observations, further investigations are now in progress. They rely on damageable material models for the blocks and will help establishing practical tools, usable on the building sites for risk estimation.

8 Acknowledgement

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