Establishing a test-calculation dialogue for shear tests on masonry triplets.

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RESUME The development of digital image correlation techniques, particularly in the field of masonry, has allowed for the detection of crack evolution in joints and blocks over time. Recent studies further demonstrate the potential of these techniques for updating model parameters for masonry. Drawing inspiration from practices established in various mechanical domains, this article proposes an experimental-computational dialogue based on digital image correlation. In the initial phase, it serves to design and verify the experimental setup, and subsequently, it helps update and validate the parameters of the proposed model. By implementing this dialogue between experimental tests and numerical simulations, a more profound understanding of the mechanical behavior of masonry triplets should be achieved, thereby enabling improved prediction and interpretation of results.

Mots-clefs test-calculation dialogue, masonry, digital-image correlation, non-linear response

Modalité de présentation Poster

I.INTRODUCTION

The dialogue between testing and calculation serves as a bridge between numerical simulations and experimental campaigns conducted both before and after the tests. Initially, it aids in preparing for the experimental campaign by running virtual simulations, which validate the experimental setup and the entire measurement system through digital image correlation [VIT21]. An initial sensitivity analysis determines whether the experimental campaign can identify the parameters of the initially considered model. Subsequently, using displacement fields obtained through image correlation allows for the analysis and comparison of the model and calculations. Registration methods using FEMU are also possible [SOL18], offering a more detailed understanding of the behavior of the tested specimens by identifying local phenomena.

This article presents a novel approach to the dialogue between testing and calculation, utilizing digital image correlation. It begins with an explanation of the virtual design stage to facilitate the implementation of the experimental process, followed by an overview of a preliminary finite element modeling approach. Finally, the article presents the opportunities image correlation provides for model parameter identification and updates.

As a practical example illustrating this dialogue between testing and calculation, the article focuses on the shear testing of a masonry triplet. Specifically, a force F is applied to the middle block under varying levels of confinement σ to investigate the failure surface at the interface between mortar and bricks. The experimental device considered [Fig1] also allows for investigating the cyclic shear response [BAR20]. In the non-cyclic case, the vertical bar in the center is no longer necessary and will not be depicted further in the article.

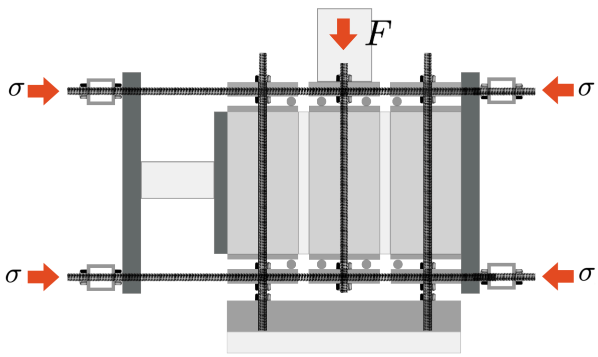

FIGURE 1.Experimental set-up according to [BAR20]

II.INTRODUCTION TO DIGITAL IMAGE CORRELATION

The emergence of Digital Image Correlation (DIC) in the early 1980s has significantly influenced the realms of solid mechanics and structural engineering. Leveraging its inherent contactless and non-intrusive attributes, DIC has emerged as an accessible, efficient, and economically viable technique [GRE12]. Particularly within masonry, DIC has proven instrumental in monitoring the progression of crack formations within joints and blocks over time [GUE14]. This article aims to exploit the extensive kinematic data provided by DIC to facilitate quantitative analysis using identification methodologies (refer to Section 6). Recent research highlights the potential of these techniques in refining model parameters for masonry structures [SCI23].

DIC involves analyzing two images of the same object under different loading conditions. The goal is to determine a displacement field $\underset{\sim}{u}(\underset{\sim}{x})$ that yields the reference image f when applied to the registered image g. The method is rooted in conserving the grey level throughout the deformation process [GRE12]. As early as 1981, Horn provided a robust formulation of this concept :

$$\forall \underset{\sim}{x} \in R, f(\underset{\sim}{x}) = g(\Phi_a(\underset{\sim}{x})) = g(\underset{\sim}{x} + \underset{\sim}{u}(\underset{\sim}{x}))$$

where $R \subset \mathbb{R}^2$ refers to the Region of Interest (ROI), f and g to the reference and deformed images respectively. Φ_a represents the apparent sought mechanical transformation.

DIC uses an optical device called the "camera," which captures scenes by converting various quantities into grey levels through an optical system. We introduce the pinhole model for the camera, utilizing established parameters to compute the spatial position of a point in the captured image. The following section provides a detailed explanation of designing an experiment by understanding these parameters.

A single-camera system confines measurements to in-plane displacements and strains on a flat object. The stereo-correlation technique (3D-DIC) overcomes these constraints, facilitating the assessment of 3D displacements and 2D strains on any three-dimensional object. [GRE12] In the employed model detailed in Section IV, the assumption is made of a solely planar loading. Therefore, stereo-correlation verifies this assumption at any point during the experimental campaign.

III.VIRTUAL DESIGN

Experimental Setup Validation

An initial opportunity in implementing the virtual design of an experiment is the ability to create a precise digital model of the test area, enabling the definition and validation of all components used. For example, all components comprising the supports and the pre-tensioning system in shear testing could be examined using Blender, an open-source software [https://www.blender.org/]. Additionally, Blender facilitated the configuration of the camera setup and lighting spots [Fig2] to be used for digital image correlation during the experiment. Upon observing Figure 2, it becomes apparent that the horizontal bars intended for confinement interfere with image correlation. Therefore, the 3D components were adjusted before machining to ensure they did not interfere with DIC again.

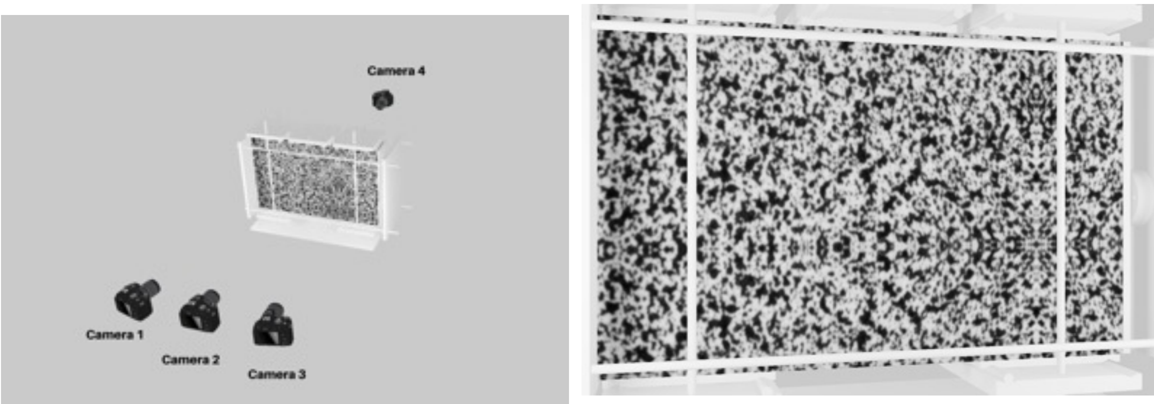

FIGURE 2.View of the experimental set-up (left) - Camera 1 view (right)

Python code enables studying the optical system and camera interactions based on their positions and parameters. Specifically, it facilitates the analysis of the coverage map [Fig3], indicating whether certain areas are obscured, particularly by the steel bars of the specimen's setup. Additionally, the code can determine maximum sensitivities along the X and Y directions [Fig3-4] and the size of the smallest observable crack [Fig4]. It also serves the purpose of optimizing camera placement, mainly to avoid shadowed areas.

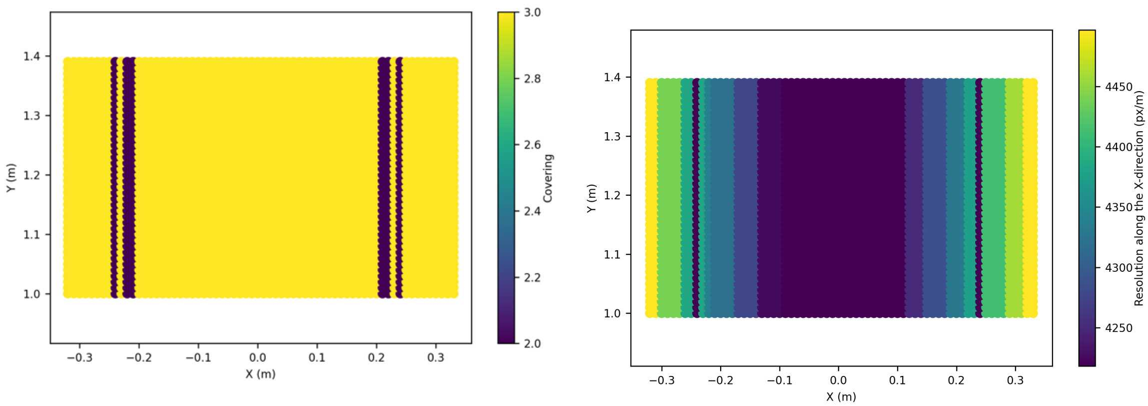

FIGURE 3.Coverage map (left) and sensitivity along the X-direction (right)

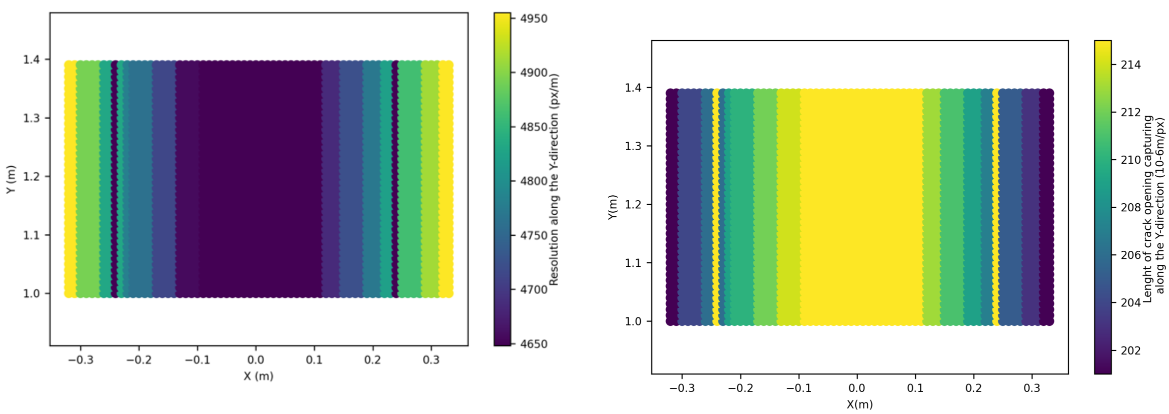

FIGURE 4.Sentitivity (left) and length of crack opening (right) along the Y-direction (right)

Virtual testing

A second opportunity, as outlined by Vitse et al. [VIT21], involves conducting virtual tests on the specimen. Digital testing is performed using the previously described model, generating displacement maps for various time intervals. Using BlenDIC, an open-source add-on for Blender [https://gitlab.com/sciviz/blendic], these maps can be imported to virtually deform the specimen (along with the applied speckle [Fig2]) while capturing these displacements through the pre-configured camera system. Consequently, virtual images are generated, replicating the expected outcomes of physically testing the specimen. These virtual images can be analyzed using Corelli [COR08] image correlation software. Several examples are presented below [Fig5].

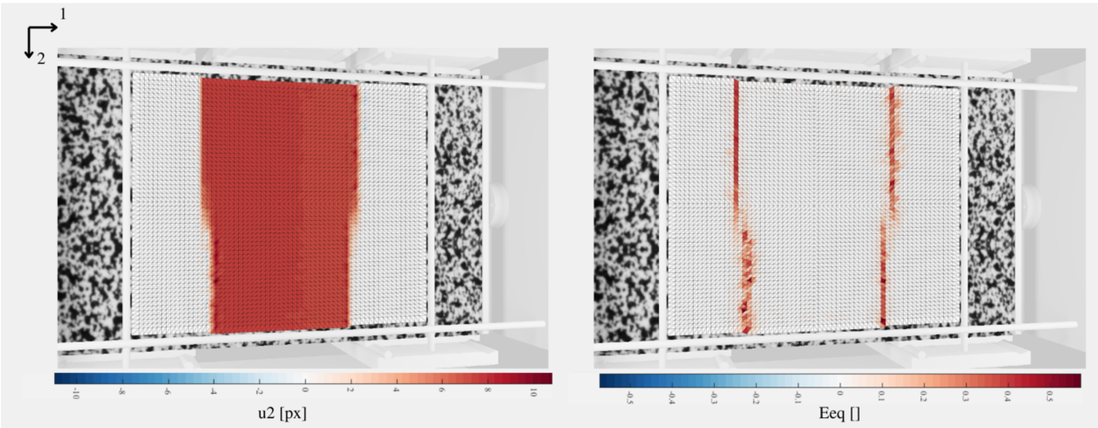

FIGURE 5.Displacement fields virtually measured (left) and equivalent stresses within the material (right).

One approach to consider involves simulating the experiment with various parameter configurations to assess the model's sensitivity to measurements, adjusting optics, speckle, lighting, and accounting for potential measurement noise. The difference between two simulated experiments with a 10% variation in the material joint's elastic limit constraint is presented here [Fig6]. The virtual image correlation results help verify the experiment's sensitivity to this parameter and ensure we can recalibrate it using the experimental results afterwards.

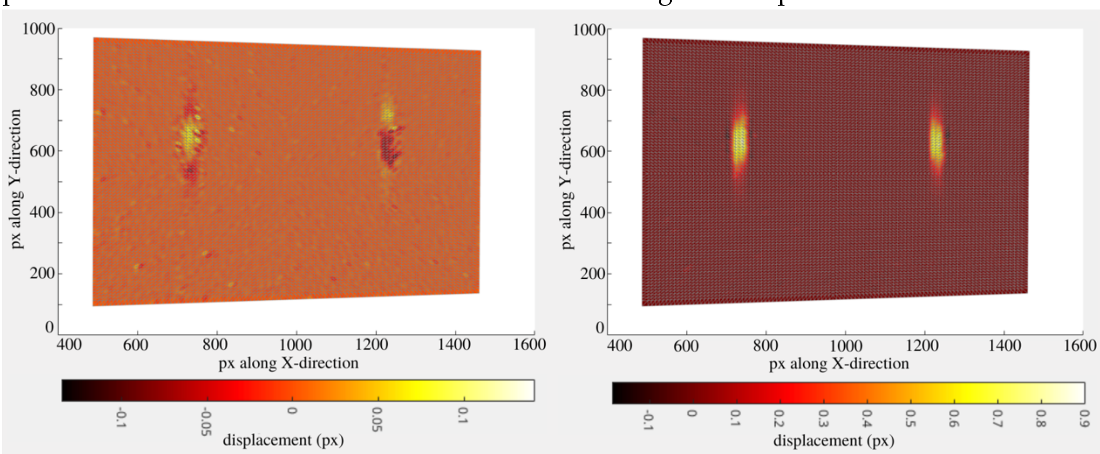

FIGURE 6.Difference between two displacement fields virtually measured along X (left) and Y (right) directions for a 10% variation in $\sigma_{t,j}$

Therefore, the virtual testing step is relevant, especially for establishing experimental plans and ensuring that all parameters are identifiable. However, its effectiveness strongly relies on the considered model. The following section introduces the selected model for simulating the shear triplet test.

IV.A FIRST MODELING APPROACH

On a micro-scale level, finite element modelling enables a detailed description of blocks and joints. At the same time, a homogenized model for the entire wall has been demonstrated by Rostagni et al. [ROS22]. Conversely, on a macro-scale, masonry walls can be simplified by representing them as assemblies of bar elements, which act as diagonal rods under compressive loads, especially in portal frame structures, as illustrated in the research by Combescure [COM96].

TABLE 1. Model Parameters

Parameter	E_j	ν_j	$\sigma_{t,j}$	$a_{tra,j}$	$q_{p,j}$	$c_{f,j}$	σ
Unit	Pa	/	Pa				MPa
Value	4E+06	0,13	1E+05	4E-03	6.5	2,89	0

During a shear test on a masonry triplet, our primary focus is on micro-scale modeling, using Finite Element Model Code Cast3M [https://www-cast3m.cea.fr/] The objective is to analyze the behavior of the joint elements using the non-linear Vassaux et al. model [VAS14], well-known for its adaptability in describing cyclic behavior. These joint elements exhibit elastic quasi-fragile properties, as specified in Table 1. Readers can find details regarding these parameters in [VAS14]. Parameters E_j and ν_j are typical parameters in the linear elastic behavior of a material. The introduction of non-linearity includes terms such as $\sigma_{t,j}$, representing the elastic limit; $a_{tra,j}$, controlling crack initiation energy; $q_{p,j}$, the crack closure rate; and $c_{f,j}$, the friction coefficient at the crack level. We adopt a RICRAG-type damage model [RIC10].

The parameter values used here align with those obtained experimentally by CSTB in tests on mortar elements with a similar composition and with those proposed in Concyc case-tests. These values are also consistent with what can be found in the literature. Simultaneously, we assume that the block elements remain within the linear domain. To achieve a uniform and coherent mesh at the joint level, we decide to mesh the entire structure with CUB8 elements of approximately

$5 \times 5 \times 5 mm^3$ dimensions. This corresponds to six cubic elements within the thickness of a 3 cm joint. The resulting mesh is illustrated below.

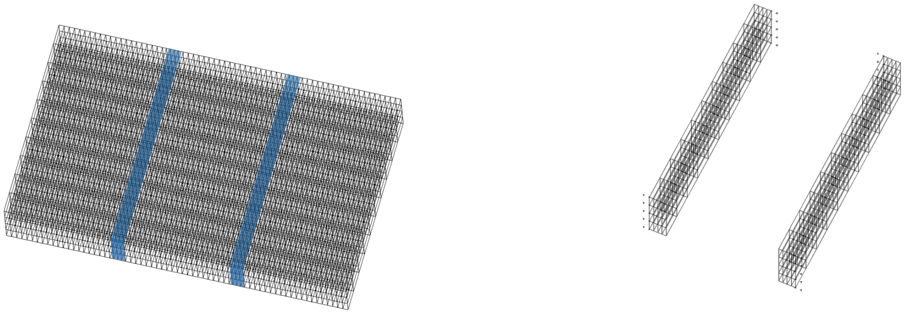

FIGURE7.Mesh of the triplet with joint elements in blue (left) and master nodes considered for static condensation (right)

A uniform displacement is applied to the central block, from 0 to 3.5 mm at the final stage. The displacements of the blocks at the ends are numerically fixed at the level of the hinges. A uniform normal stress is finally applied along the specimen. The choice of these boundary conditions will be further discussed in section 6. The challenge at hand is to achieve a detailed analysis of the joint elements without a substantial increase in computational time. Using a model reduction technique - static condensation -solves the problem only at designated master nodes for the block elements, and the displacement at slave nodes is subsequently derived. The chosen approach involves condensing the problem at the interface between the block and joint elements and at the support and loading points. The shape of the obtained curve [Fig8] and the magnitudes align with what can be observed in the literature and our first results. By focusing on the damage map obtained at the end of imposed loading [Fig9], a distribution along the block-joint interfaces is noticeable.
This stress concentration can be mitigated by non-local regularization and by modeling the joint at the interface separately, for instance, using a joint element following a rupture law at a specified tensile threshold.

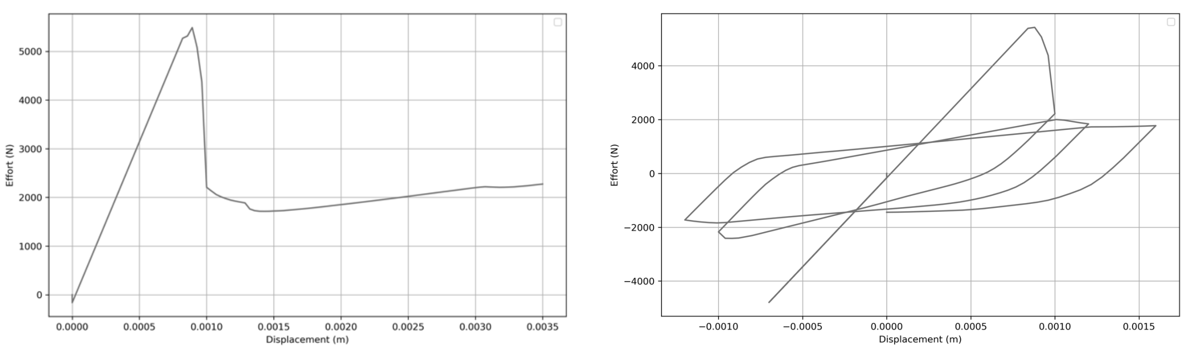

FIGURE 8.Force displacement curve for monotonic (left) and cyclic (right) triplet shear tests

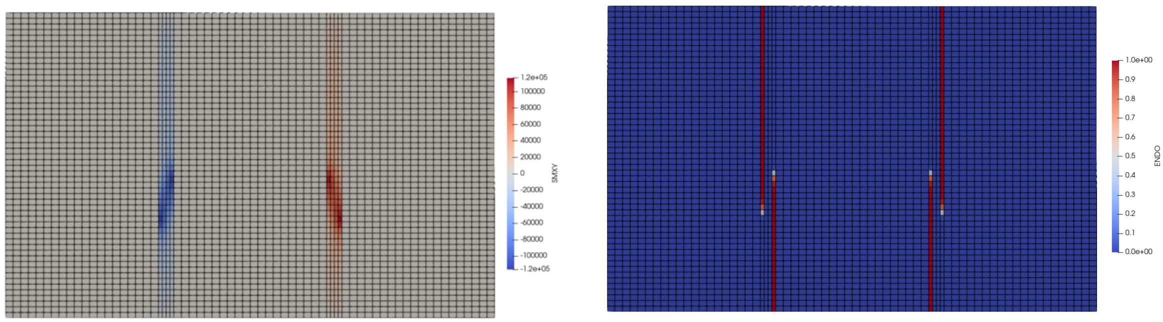

FIGURE 9.Shear stress distribution in the joint (left) and damage value (right) for a load of 4000 N.

At this stage, a more traditional sensitivity analysis is also carried out to determine the impact of model parameters on the force-displacement curve. The Sobol method is utilized with 2^5samples, varying all parameters except for $c_{f,j}$. This yields the average curve as well as the 95% prediction interval envelope. Similar to virtual testing, we can examine the influence of the $\sigma_{t,j}$ parameter on the overall displacement response [Fig10].

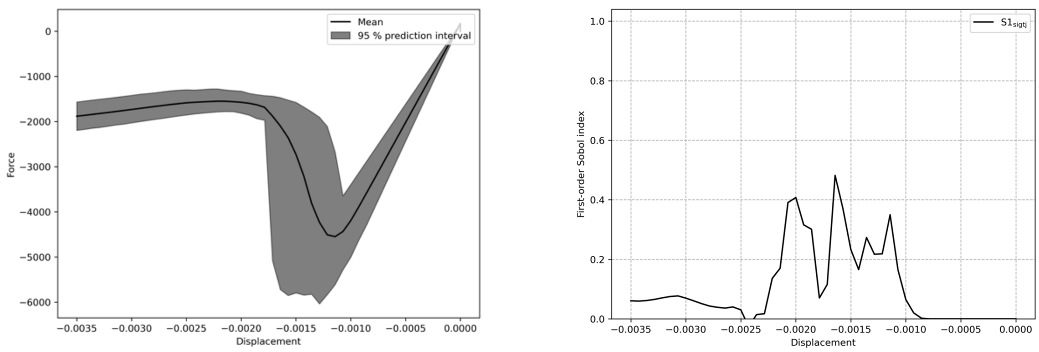

FIGURE 10.Average force-displacement curve (left) and evolution of First order Sobol Index for Sigtj parameter (right)

V.EXPERIMENTAL CAMPAIGN

It is important to note that the testing campaign is currently underway. Therefore, the planned steps are outlined here, but the first results, which will be presented in the poster, still need to be included.

Materials

Triplet tests, following the European standard [EN1052-3], were adopted as the standard method for conducting shear tests at masonry joints. Eight assemblies, each consisting of a single row of solid concrete blocks, are tested. Each assembly [Fig11] comprised a stack of three solid blocks with dimensions of 400 × 200 × 100 mm, and their characteristics are predetermined. A 2 cm thick joint between the blocks is created using CP/CEM II B-M-32.5 R, 0/2mm sand, and water. The constructed specimens have the same dimensions (400 × 640 × 100 mm) and are then inclined at 90° for shear tests.


FIGURE 11.Conditioning of blocks (left) and triplets after fabrication (right).

Experimental Setup

Shear tests will be conducted on the Zwick Z100 universal testing machine with a 100kN load cell, coupled with a horizontal loading arrangement to apply the pre-compression load σ perpendicular to the bed joints of the samples. Normal and shear stresses will be measured and recorded by horizontal and vertical load cells.

Loading

Tests will be performed with four different pre-compression stresses σ = 0.05, 0.10, 0.15, and 0.20 MPa. A stress cell verifies that the level of confinement remains stable until failure. The chosen pre-compression stresses are within the specified range to avoid exceeding the maximum compression strengths of the masonry. In total, four different specimen configurations are defined, and two tests will be conducted for each configuration. Table 2 summarizes the characteristics of the tested specimens and the loading levels.

Two specimens, CISAIL_9 and CISAIL_10, will also be subjected to cyclic loading to study crack opening/closing phenomena friction and identify certain parameters of the model, as suggested by S. Barattucci et al. [BAR20] and P.K. Dhir et al. [DHI22].

Experimental Results

The initial sets of triplets will undergo testing in March as part of the trial campaign. The outcomes will be presented in the context of the poster.

TABLE 2. Characteristics of the tested specimens

Test	Specimen			
	Length (mm)	Height (mm)	Thickness (mm)	σ (MPa)
CISAIL_1	400	640	100	0.05
CISAIL_2	400	640	100	0.05

CISAIL_3	400	640	100	0.10
CISAIL_4	400	640	100	0.10
CISAIL_5	400	640	100	0.15
CISAIL_6	400	640	100	0.15
CISAIL_7	400	640	100	0.20
CISAIL_8	400	640	100	0.20

VI.MODEL UPDATING

Upon completion of the experiment, image correlation provides a more profound understanding of the imposed boundary conditions and applied loading. Enforcing the observed displacements on each boundary onto the mesh makes it possible to approach the simulation conditions closer to reality. To save time, displacement fields on each mesh face can be interpolated using second-order functions.

A comprehensive understanding of the displacement field during testing enables a more accurate calibration of model parameters compared to relying solely on the experimental force-displacement curve. At this stage, Finite Element Model Updating is employed, which involves minimizing an objective cost function, such as minimizing the Frechet distance for the force-displacement curve and reducing the error in displacement at each point for the numerical/experimental displacement fields. Readers can find several applications of this method in the works of [SOL18].

Ultimately, a well-designed experimental campaign should facilitate the identification of the best-estimate set of parameters.

VI.CONCLUSION

This article explores the possibilities offered by digital image correlation for designing tests that may prove to be complex. The phase of virtual testing preceding the experiments enables the precise design of the experimental setup and ensures that the model's parameters may be identifiable through displacement field measurements. This local sensitivity analysis complements the one that can be performed by a Sobol method on the force-displacement response. Once the experiments are conducted, the data provided by conventional measurements and image correlation should allow for better simulation of real boundary conditions and precise identification of the sought-after parameter set through methods such as FEMU.

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