Feasibility of in-situ elastic mechanical characterisation of masonry using the virtual fields method

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Abstract. The use of the virtual fields method (VFM) is explored to conduct detailed mechanical characterisation of masonry structures in-situ. By creating deformations in a masonry wall using flat jacks, it is possible to estimate the Young's moduli and Poisson's ratios of both brick and mortar in a single in-situ test. Numerical results, obtained using finite element (FE) models and VFM, prove the feasibility of the proposed approach and indicate that the identification is robust against loading uncertainties and measurement noise.

Introduction. Determining the material properties of existing masonry structures by collecting and testing multiple core samples can be invasive and is often unfeasible. As an alternative, minor-destructive in-situ testing techniques have been developed, such as the double flat jack test [1]. This test is routinely adopted to determine the elastic stiffness of masonry in the vertical direction. Resorting to full field optical measurements and the VFM [3], it is possible to obtain a more detailed mechanical characterisation of masonry in-situ. The feasibility of using this technique to identify the orthotropic properties of bricks and the isotropic properties of mortar is explored in this study. An in-situ flat jack test is simulated numerically using FE models, outputting strains. These strains are polluted with random Gaussian noise. Mechanical properties of both bricks and mortar are then identified with VFM, using the noisy strain fields**.**

FE Model. A plane stress 2D FE model of a masonry wall was implemented in DIANA FEA. A simple micromechanical representation was adopted for the masonry, where brick and mortar were explicitly modelled. The masonry wall, arranged in a single stretcher bond, measured 1530 x 2025 x 100mm with a brick size of 210 x 65 x 100mm and 10mm thick mortar joints. The linear elastic material properties assigned for brick (with density, $\boldsymbol{\rho}$ = 2125kg/m^3) and mortar ($\boldsymbol{\rho}$ = 1680kg/m^3) can be found in Table 1. An overburden pressure of 0.15MPa was applied to the wall. Different from the standard double flat jack test, three flat jacks (two horizontal and one vertical) were considered. Flat jack loading was simulated by applying a pressure on cut slots in the mortar joints (Fig. 1a). The pressure distribution along the flat jack was assumed to have a quartic profile with 1.2 times average pressure (P_{avg}) in the centre and 0.2 times average pressure at the tips. An additional slot (#4) was included to increase deformation, as proposed by Calio [4]. While flat jacks #1 and #2 exert a pressure ($P_{avg,1/2}$ = 0.17MPa) that compensates for the vertical deformations after the horizontal cuts, two different average jack pressures ($P_{avg,3}$ = 0.17MPa and $P_{avg,3}$ = 1.7MPa) were considered for the vertical flat jack (#3).

Virtual Fields Method. The VFM is a numerical tool to retrieve constitutive parameters from strain fields [3]. The procedure makes use of virtual displacement fields, which can differ from the measured displacement field. Any kinematically admissible deformation field can be selected as a virtual field. As a rule of thumb, it is suggested to define virtual fields with at least twice as many degrees of freedom than coefficients to be determined [3]. The so-called *optimized* VFM was developed by Avril et al. [5] to automatically select virtual fields that reduce the influence of measurement noise on the mechanical identification results when dealing with linear elastic materials. Since the procedure relies on full-field measurements from Digital Image Correlation [2], which can feature significant measurement noise, mechanical identification robustness against measurement noise is important. The *optimized* VFM provides a sensitivity parameter $\boldsymbol{\eta}$ to assess the robustness to noise for a given set of virtual fields [5]. This allows the user to compare different test setups and select the one with the lowest overall sensitivity to noise [3]. Given these advantages, the results in this study are based on the *optimized* version of the VFM.

The method was performed on the region of interest (ROI) delimited by opposing mortar cuts (Fig. 1a). The application of VFM only requires knowledge of the strain field inside this ROI, the surrounding strains and boundary conditions do not need to be determined. The corresponding virtual fields were defined in a piecewise manner. Since bricks and mortar can experience different strain magnitudes, a regular virtual mesh whose nodes align with the edges of mortar cross, head and bed joint elements was chosen (Fig. 1b). This provides the ability for the virtual fields to adjust to strains in different materials. This approach performed more reliably in estimating the material parameters than virtual meshes defined independently of

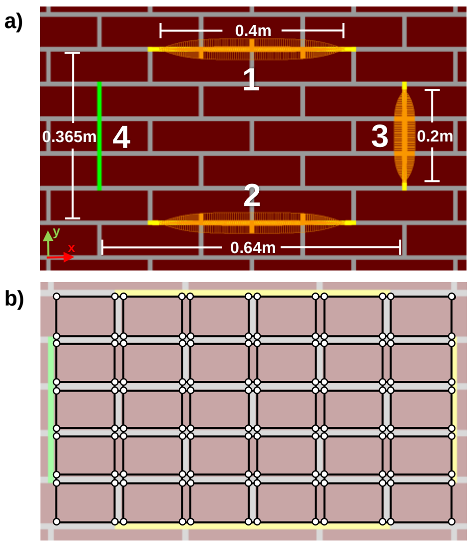

Figure 1. In-situ testing setup:
a) arrangement of the flat jacks (1-3) and the additional cut (4)
b) virtual mesh used for the VFM (dots indicate nodal points)

the masonry pattern. Furthermore, by specifying virtual fields with a constant displacement along the flat jack, the average pressure applied by the jack on the wall, rather than the specific pressure distribution, is required for determining the constitutive parameters. This is convenient for in-situ applications where the pressure distribution is unknown. The VFM identification was accordingly conducted using average pressure values. For brevity, only the results for a quartic pressure profile are presented in this paper. Other pressure distributions were also evaluated and returned similar results.

Results and Conclusion. The material parameters assigned to the FE-model were estimated with high accuracy using VFM (Table 1). Although mortar was modelled as an isotropic material, the orthotropic properties were determined using the VFM. The VFM clearly identified the isotropic behaviour of the mortar. Fig. 2 shows a high overall robustness to noise and matching values for the predicted (based on the $\boldsymbol{\eta}$-values) and measured coefficient of variation (CV) for each constitutive parameter. Fig. 3 further indicates that identification errors depend on the jack pressure magnitude. An increased average pressure of the vertical flat jack (#3), inducing higher horizontal strains in the masonry, shows less sensitivity to noise for parameters that resort to strains in the horizontal x-direction. With an increase of $P_{avg,3}$ from 0.17MPa to 1.7MPa, the CV for both Young's moduli in x-direction $CV(E_{x,brick})$ and $CV(E_{x,mortar})$ shows a reduction by a factor of 10. Material parameters based on strains in the vertical y-direction are less affected by this pressure increase.

These preliminary numerical results indicate the feasibility of the proposed method. Further numerical investigations and experimental tests will be conducted to investigate challenges for actual in-situ tests. By comparing the $\boldsymbol{\eta}$-values for different test setups, an optimised setup could be derived, paving the way towards Material testing 2.0 [6] for masonry in-situ identification.

	Material	E_x [MPa]	E_y [MPa]	ν_{xy} [-]	ν_{yx} [-]	G [MPa]
DIANA FEA	*Brick*	2600.0	2300.0	0.1600	0.1415	900.0
	Mortar	200.0	200.0	0.1500	0.1500	86.96
VFM	*Brick*	2593.1	2299.1	0.1600	0.1419	899.9
	Mortar	199.5	199.7	0.1500	0.1501	86.91

Table 1. Simulated material properties of brick and mortar and their corresponding values estimated by VFM, no noise was added to the strains ($P_{avg,3}$ = 0.17MPa)

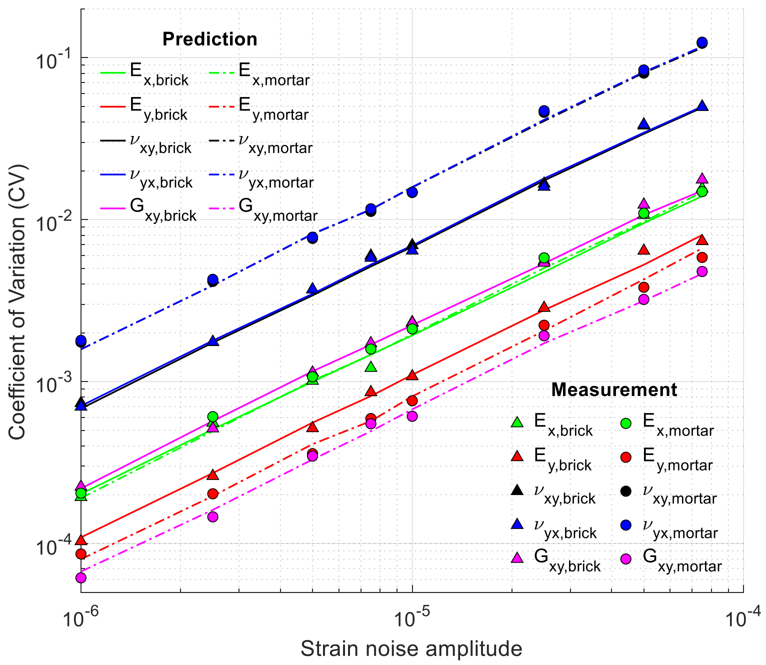

Figure 2. Predicted and measured coefficient of variation of the estimated constitutive parameters depending on the amplitude of the noise added to the strain values ($P_{avg,3}$ = 0.17MPa)

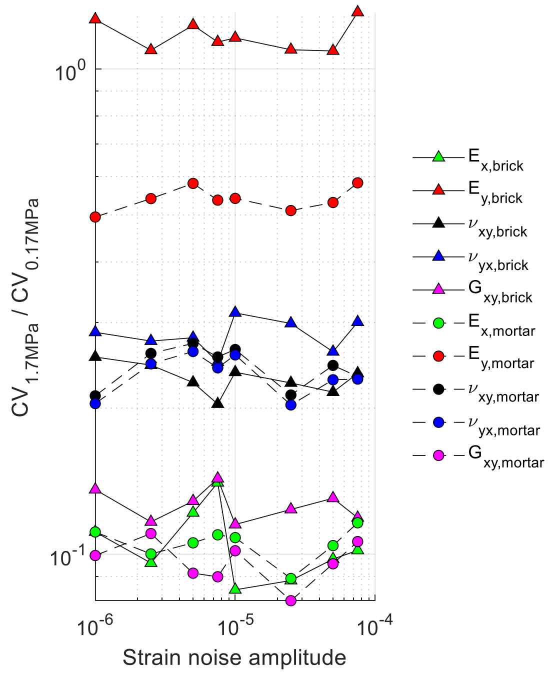

Figure 3. CV of the estimated constitutive parameters for a jack pressure of $P_{avg,3}$ = 1.7MPa divided by the corresponding CV for $P_{avg,3}$ = 0.17MPa

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