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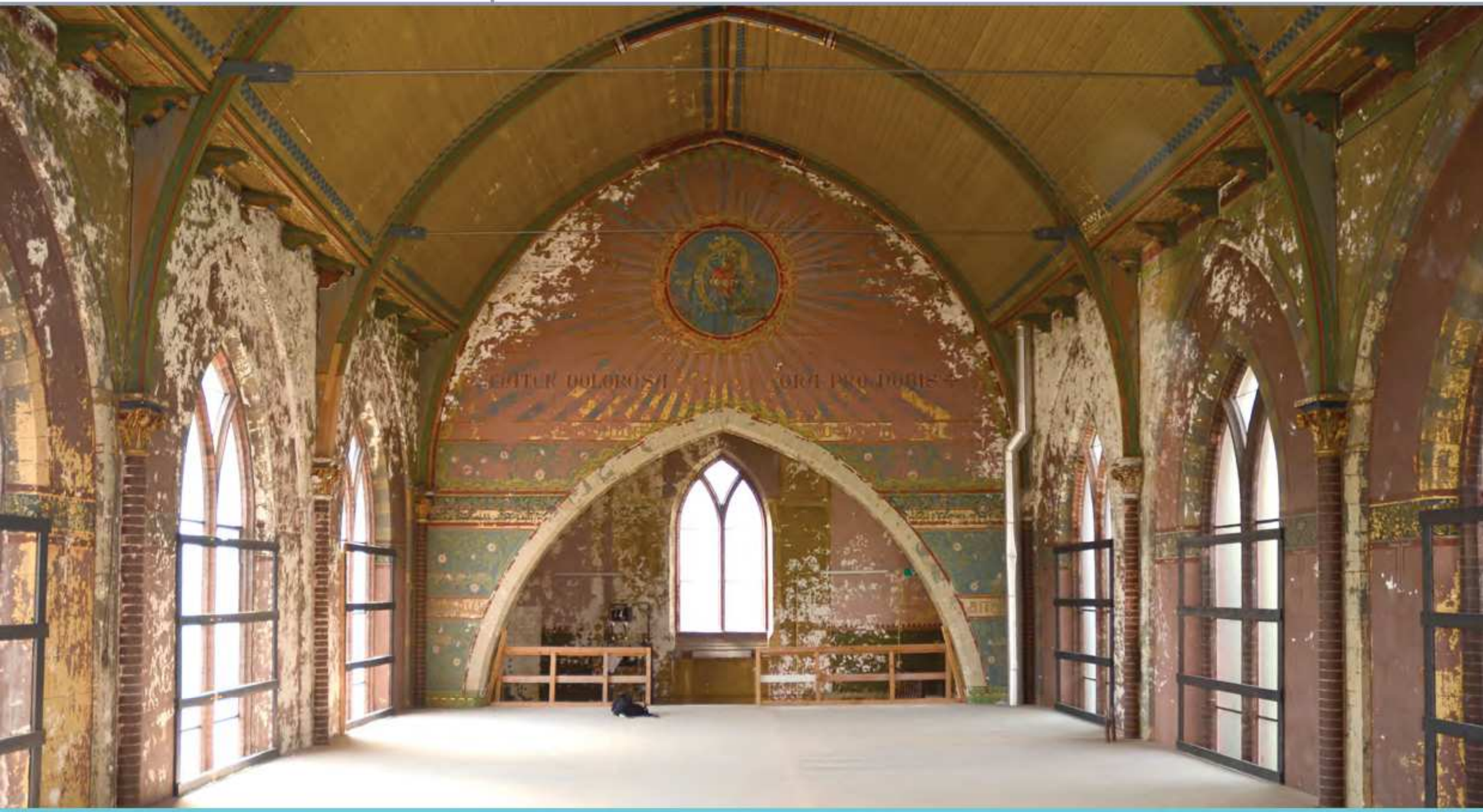

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COMPUTATIONAL MODELING OF THE CYCLIC PUSHOVER TEST ON A CALCIUM SILICATE ELEMENT MASONRY ASSEMBLAGE

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KEYWORDS

Calcium Silicate Elements, Masonry, Finite Element Modelling

ABSTRACT

Induced seismicity in the Groningen region of the Netherlands has led to a large scale testing campaign on Calcium silicate element masonry structures at Delft University of Technology. An overview of the finite element analysis (FEA) using an implicit solver, on the full scale quasi-static cyclic pushover test performed on a two-storey calcium silicate element masonry assemblage is presented in this paper. Tests have been performed in the experimental campaign at material, component, and structural level, of which the material tests like bond wrench tests, compression tests and shear tests are also briefed in this paper.

The pushover case study has been modelled using a total strain based rotating crack modelling approach for the Calcium silicate masonry and a discrete cracking / coulomb friction model along the connections in the assemblage. The material parameters used in the FEA for the pushover case study are obtained from the aforementioned material level tests. In this study, monotonic analyses are performed along both directions of the cyclic loading and the loading protocol is simulated using a displacement controlled approach. Comparisons are made with the experiment in terms of force-displacement curve, crack pattern and drift ratios.

The use of an implicit solver for quasi-brittle materials comes with convergence issues, and these have been elucidated in this study. If material parameters calibrated on the basis of the material tests are used, a significant overestimation of the capacity in both loading direction of the test is found. Therefore, there is need for better correlation between material level tests and the behavior observed at the structural level to understand the true behavior of the masonry. The computed maximum displacements have been severely under predicted in both directions reiterating the need for most robust solution procedures to realize global softening behavior in masonry structures.

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INTRODUCTION

Calcium-silicate blocks (also known as 'elements' or 'CASIELS') have been in use in the Netherlands since the 1970's. A steady increase in size from traditional brick format (in Dutch 'waalformaat') in the early 1960's [1], towards large elements can be observed in Dutch construction practice since the early 1960's [1]. Although the blocks in the 1970's had smaller sizes, the need for speed and efficiency in construction practices have led to elements (CASIELS) that are now roughly 90 x 65 x 10 cm^3. The calcium silicate (CS) elements are generally used only as internal leaf, finished on the interior side with plaster and on the exterior side with insulation, a cavity and finally a baked clay brick as external (aesthetic) leaf. These elements, to this date, are frequently applied for the construction of terraced houses in the Netherlands including the seismic region of Groningen.

Thus, a research campaign (also extended to tests on Calcium silicate elements masonry) was performed at TU Delft to address the seismic situation in Groningen at material, component and building level. The material tests and the quasi-static cyclic pushover test are briefed upon in the next two sections of this article followed by the finite element modelling of the pushover test. The macro modelling approach, combined with non-linear interfaces at connections, is used in this study owing to the size of the structure being analyzed. Subsequently, the results and conclusions drawn are presented.

MATERIAL TESTS ON CALCIUM SILICATE ELEMENT MASONRY

As far as the properties of calcium silicate (CS) element masonry at material level are concerned, strength, stiffness and softening properties for compression, bending and shear are the matter of importance. These tests provide valuable information to define the input parameters as well as the constitutive material law for nonlinear finite element analyses. Consequently, a series of tests was performed to fully characterize the mechanical properties. The obtained material properties are listed in Table *1*.

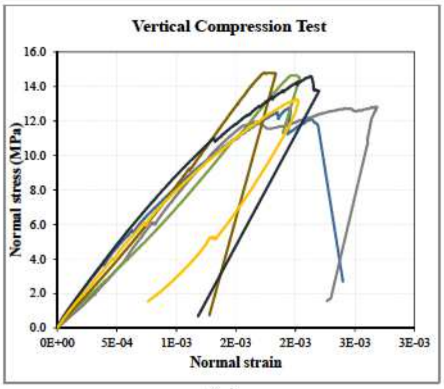
Material property	Unit	Average	Std. dev.
Compressive strength of masonry perpendicular to the bed joints	MPa	13.93	1.03
Compressive strength of masonry parallel to the bed joints	MPa	9.42	1.63
Elastic modulus of masonry in the direction perpendicular to bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	MPa	8801	958
Elastic modulus of masonry in the direction parallel to the bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	MPa	7400	929
Out-of-plane masonry flexural strength parallel with the bed joint	MPa	0.58	0.08
Out-of-plane masonry flexural strength perpendicular to the bed joint	MPa	0.73	0.03
Flexural bond strength	MPa	0.56	0.12
Masonry initial shear strength of masonry interface	MPa	0.83	-
Masonry shear friction coefficient of masonry interface	-	1.48	-

Table 1: Material properties of replicated calcium silicate element masonry.

The orthotropic behavior of masonry in compression was investigated by performing compression tests on masonry wallets both in the direction perpendicular and parallel to the bed joint following EN 1052-1 [5]. The CS element masonry showed an orthotropic behavior meaning that its compressive strength and elastic modulus are higher in the direction perpendicular to the bed joint. The orthogonality ratio for the compressive strength and the Young's modulus was found equal to 1.5 and 1.2, respectively.

An adopted displacement-control procedure allowed studying the post-peak behavior under compression. However, differently than other masonry types, the CS element masonry showed a brittle failure without almost any post peak phase. A typical observed crack pattern and stress versus strain curve for the vertical compression tests, where the applied load was perpendicular to the bed joint, are shown in Figure 1.

(a)



(b)

Figure 1: Compression test load was applied perpendicular to the bed joints: (a) typical observed crack pattern; (b) stress-strain curve.

The bending behavior of masonry was determined in agreement with EN 1052-2 [6]. The flexural strength perpendicular to the bed joint was obtained 1.3 times higher than the one which was parallel to the bed joints. The bond wrench test, performed in agreement with EN 1052-5 [7], showed the bond strength value of 0.56 MPa, similar to the flexural strength parallel to the bed joint.

The shear behavior of masonry interface was studied by means of couplets. The shear-compression tests on couplets were performed in agreement with EN 1052-3 [8]. The shear properties were derived following the Coulomb friction criterion. The masonry showed an initial shear strength of 0.83 MPa and a friction coefficient of 1.48.

CYCLIC PUSHOVER TEST ON CA-SI ELEMENT MASONRY ASSEMBLAGE

The two-storey calcium silicate element masonry assemblage with concrete floors has been tested in quasi-static cyclic pushover regime, and is intended to represent a typical Dutch terraced house built between 1960 and 1980. Such a house is characterized by large openings in the facades, slender piers and load bearing cavity walls. Since the test would serve as a benchmark for validation of analytical and numerical models, the built house includes only the load bearing parts of the typical Dutch terraced house. In accordance with the quasi-static pushover test performed on a calcium silicate brick house performed in 2015 [2], this test is steered in a displacement controlled approach where the second floor displacement is controlled using actuators that are hydraulically coupled to the first floor actuators to have an equal force distribution to both floors. That is to say the ratio of forces exerted at the first to second floor is 1:1 (F1+F3 = F2+F4). The scheme of the experiment is shown in Figure 2.

The CS element assemblage has been so designed to investigate the effect of aforementioned slender piers and the presence of large openings in the facades, in combination with long transversal walls. The standard element size was 897x643x100 mm^3 for the piers and 897x643x120 mm^3 for the transversal walls. A kicker course of CS bricks (in Dutch *"kimlaag")*, glued to the steel foundation at the ground level using sikadur glue and to the floor at the first floor level using a general purpose mortar, was placed under each wall to ensure the construction begins at a uniform level. The piers at the west are wider compared to the ones in the east. Both the top and the first prefabricated concrete floors were supported by the load-bearing transverse walls as well as by the piers. In contrast to traditional brick masonry buildings, the connection between the transversal walls and the piers is not guaranteed by regular running bond; instead the connection was made using steel anchor strips at all bed joints except the ones between the piers and the kicker layers. For detailed overview, refer to [1].

The overall force displacement curve is shown in Figure 2. The thick black line denotes the backbone/envelope curve for the cyclic response.

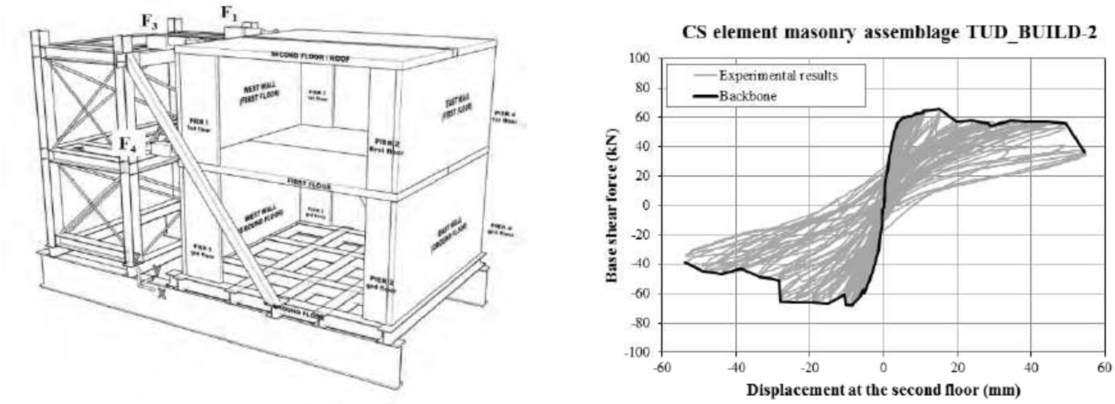


Figure 2: Experimental scheme of the cyclic pushover test on the Ca-Si Masonry assemblage at TU Delft and the capacity curve [1].

The first cracking was observed, in the potentiometers, in the wall-floor connections primarily in the facades but also in the transversal walls. In the pre-peak phase, these cracks were visible to naked eye and this was followed by the rocking of the piers on both storeys, thereby bringing about a reduction in the stiffness of the structure. In the following cycles, the rocking of piers at both storeys continued along with cracking in the transversal walls until the peak load was reached in the positive direction. During the post peak phase, a soft storey mechanism was observed: the rocking becomes highly localized and cracking propagates in the transversal walls. Furthermore, wider piers at ground floor in the façades showed cracking along the joints between the CS elements and splitting cracks, and also an out-of-plane deformation in this phase. The test was continued until collapse of both the wide piers (first on the North side, later on the South side), at an imposed displacement of the top floor equal to 55 mm which translates to a reduction of approximatively 45% of the base shear force. The crack patterns at different levels of imposed displacement at the second floor level (d2) are shown in Figure 3.

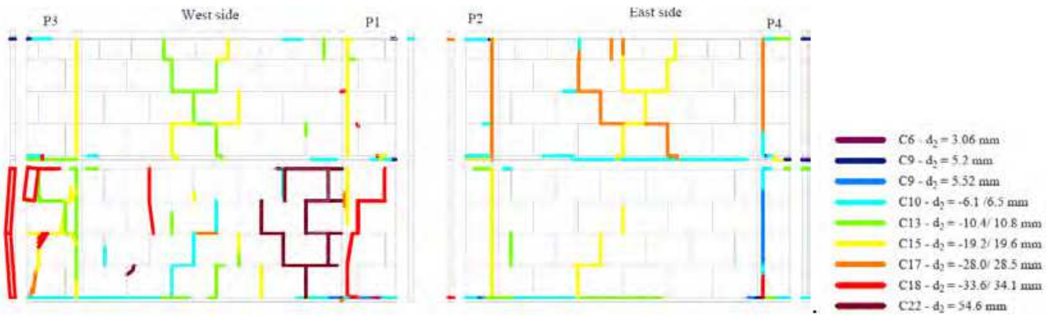


Figure 3: Crack patterns observed during the test for different levels of second floor imposed displacements by visual inspection [1].

FINITE ELEMENT MODEL

This section details the FEM model used for the prediction studies of cyclic pushover test on the CS masonry assemblage. Eight-noded quadrilateral iso-parametric shell elements, 0.2m x 0.2m in size, were used to model the calcium silicate elements in the analysis. The horizontal joints between piers, walls, kicker layers and floors are all represented by quadratic interface elements with discrete cracking and the vertical joints between walls and piers are represented by quadratic interface elements with coulomb friction models.

A total strain based rotating smeared crack model with linear tension softening and parabolic compression softening was used for the constitutive model of the shell continuum elements. A discrete cracking or coulomb friction model with gapping criterion was employed for the interfaces. The tensile strength and fracture energy for Mode-I failure for the shell elements and discrete cracking interfaces, compressive strength and fracture energy in compression for shell elements, and the cohesion and friction properties for the vertical interface are obtained from the bond wrench, compression and shear tests respectively and are summarised in Table 2. Geometric non-linearity is also included.

The loading is applied by means of an auxiliary frame to simulate the application of equal force ratio at the two floor levels by the actuators and the analysis is kept displacement controlled along the centre line of the frame (along its height). Tyings are used to couple the displacements in the direction of loading between the nodes of frame and those of the floors which are at the positions of the actuators. The bottom of the house is kept fully clamped. A detailed overview of the modelling approach with assumptions and material properties is presented in Table 2. 7 integration points are used in the direction of thickness of the shell elements.

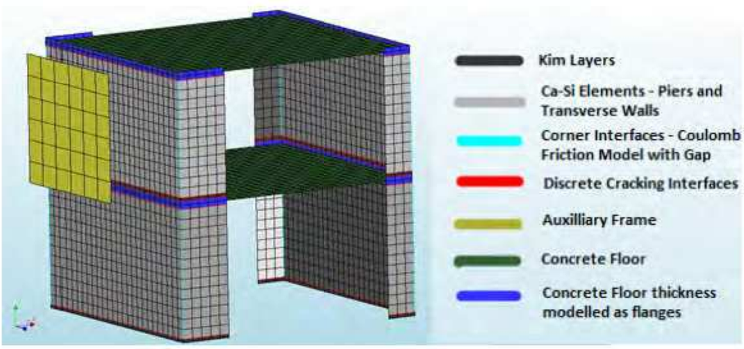


Figure 4: FEM Model of the Ca-Si Masonry assemblage pushover test

Element type	Constitutive model	Material parameters
CS Masonry - Shell elements	Tension softening (linear)	f_t = 0.4 MPa, G_{f1} = 100 N/m
	Compression softening (parabolic)	f_c = 10 MPa, G_{fc} = 10000 N/m
Horizontal joints - interfaces	Tension softening (linear)	f_t = 0.4 MPa, G_{f1} = 100 N/m
Vertical joints - interfaces	Coulomb friction with tension cut-off	Cohesion (c) = 0.68 MPa, friction angle φ =6°, Cut-off (f_t) = 0.4 MPa

Table 2: Material parameters for the FEA obtained from material level tests

RESULTS & DISCUSSION

The force displacement curves obtained from the numerical simulations of the monotonic pushover in the positive and negative directions are as shown in Figure 5 for properties based on the material level tests. Significant overestimation of the capacity is found and analyses terminate prematurely at lower displacement levels compared to the experiment. The overestimation of capacity stresses the need for variation studies on material parameters and premature termination is due to numerical issues associated with nonlinear finite element analysis of brittle materials with the traditional incremental iterative procedure. Also, extreme localization of damage at certain locations lead to the stiffness of certain elements being reduced to extremely low values (close to zero), consequently resulting in the ill conditioning of the finite element formulation and the premature termination of analysis.

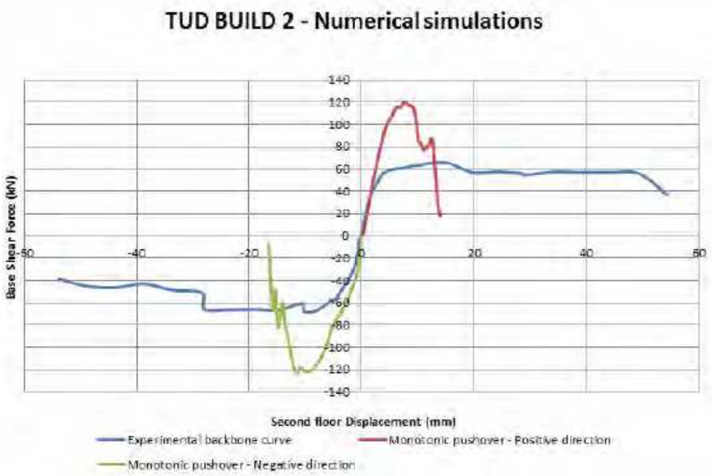


Figure 5: Capacity curve with parameters from material test properties

Parametric studies were performed, by reducing the values of the cohesion (c) and the tensile strength cut-off in coulomb friction interface and of the tensile strength in the discrete interfaces. The capacity curve obtained for c = 0.3 MPa and cut-off of 0.1 MPa for coulomb friction interface and tensile strength of 0.05 MPa for discrete cracking is shown in Figure 6. The simulation in positive direction of loading shows good agreement with capacity of experiment, while the negative direction shows a small overestimation. This can be attributed to the fact that the analysis is purely monotonic and the accumulated damage from the cyclic is not truly captured. The use of reduced values induces first cracking along the interface elements along horizontal connections followed by pronounced rocking of the piers and sliding along the vertical joints. Cracking is also observed in the transversal walls, but the cracking pattern is not accurate as the discontinuities between the CS elements, i.e. the head and bed joints, are not modelled in the macro-modelling approach. The soft storey mechanism just begins to appear and the piers show instability in the out of plane direction but the analysis stops prematurely due to the aforementioned reasons. The post peak phase is thus not captured where splitting cracks in ground floor wide piers was observed in the experiment. The evolution of crack patterns and interface relative displacements are shown in Figure 7 and 8.

The parametric study shows the relevance of the calibration of the material parameters. Even when they are obtained from tests at material level, some corrective factor may be needed to be applied in the Finite Element analysis, due to the limitations of the material models and, secondarily, the different behavior that masonry may have at structural level. In any case, it should be remarked, that only one case and a single model have been considered in this study.

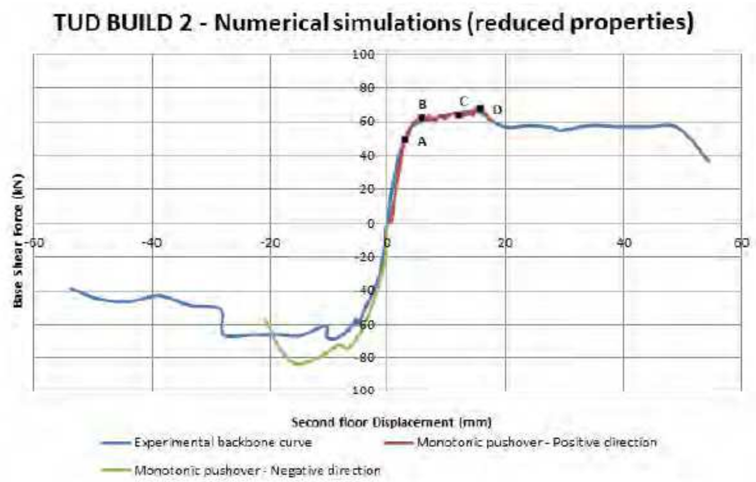


Figure 6: Capacity curve with reduced material parameters

Alternatively, to the standard total strain based rotating smeared crack model, the use of the Engineering masonry model [3], an anisotropic smeared failure model along with a shear failure mechanism based on coulomb friction criterion, may be considered. However, it would probably not lead to significant improvements as the CS element masonry is different from traditional brick masonry and the purpose of the differentiation of failure directions along the head and bed joints, the crux of the model, is lost. The choice of a compromise between a total strain based cracking approach and the provision of interfaces at locations of head and bed joints modelled using the composite interface model [4] is a promising one, but again the model becomes quite complex and it becomes even more unstable from a numerical point of view considering the implicit nature of the solution procedure being adopted. Therefore, this option is left out of the scope of this study, however investigation with an explicit solver is being considered. An alternate total approach, called Sequentially Linear Analysis [3], has been in development over the last decade and is currently being investigated for applications to cyclic loading and extensions to the engineering masonry model.

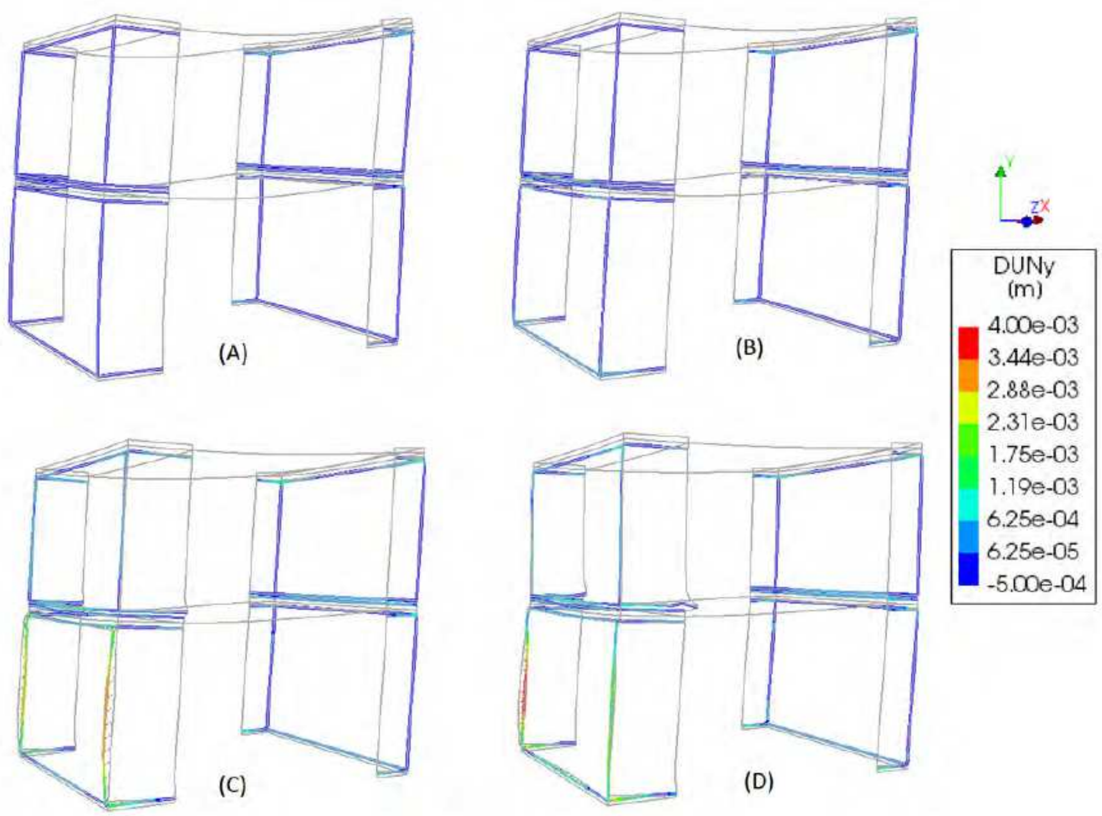


Figure 7: Interface relative normal displacement (at points A, B, C and D on the curve) that shows the rocking behavior and also opening of the vertical interface after initially sliding, - with reduced material properties based on parametric studies (Mesh not shown for clarity)

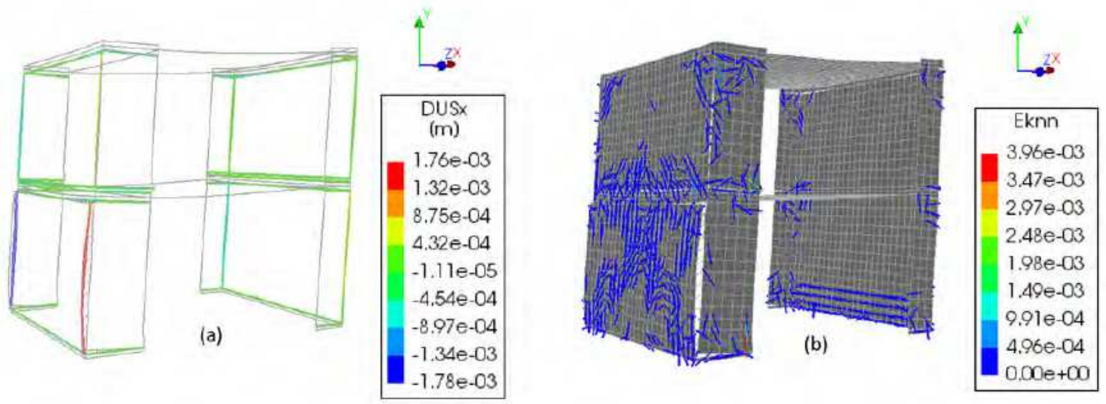


Figure 8: DUSx shows the interface tangential relative displacement at point C of the capacity curve indicating sliding has already happened before C (a) and the crack strains showing cracking pattern for point C of the capacity curve (b)

CONCLUSIONS

This paper presents the finite element analyses of the quasi-static cyclic pushover test of a calcium silicate masonry assemblage. The pushover test has been modelled monotonically in both the pushing directions using a total strain based rotating cracking model for continuum elements representing the calcium silicate elements and a discrete/coulomb friction model for interface elements representing connections. The material parameters are obtained from tests at material level and the model overestimated the capacity in the simulation. A parametric study was performed on the material properties and reduced tensile strength and cohesion values for the interfaces showed good agreement to the experiment. The need for appropriate calibration of material properties while using FEA is thus illustrated. The problems associated with stability of the incremental-iterative procedure, post peak, using an implicit solver have also been elucidated in this study. This reiterates the need for more robust and stable solution procedures for non-linear analysis concerning brittle materials like masonry. Explicit schemes may be used but are computationally very intensive.

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